INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) BRIDGE DECKS: DURABILITY AND CRACKING PERFORMANCE

By
Alireza Bahadori
David Darwin
Matthew O'Reilly

A Report on Research Sponsored by

Construction of Low-Cracking High-Performance
Bridge Decks Incorporating New Technology
Transportation Pooled-Fund Program
Project NO. TPF-5(392)

Structural Engineering and Engineering Materials
SM Report No. 149
January 2023

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

The laboratory portion of this study investigates the effects of internal curing (IC) water in pre-wetted lightweight aggregates (LWA) between 8.2 and 9.0% and between 12.0 and 13.1% by weight of binder and total internal (TI) water in all aggregates between 3.4 and 12.5% by weight of binder on freeze-thaw durability, scaling resistance, shrinkage, and ion transport properties of concrete mixtures with different binder compositions (100% portland cement or a ternary composition with 30% slag cement and 3% silica fume as partial replacements for portland cement [by total weight of cementitious materials]), paste as a percentage of concrete volume (23.7, 24.6, 26.7, or 33.7%), and water-to-cementitious material ratios (*w/cm*, 0.45 or 0.41). Normalweight aggregates consisted of three types of coarse aggregates and river sand.

The results show that for paste contents between 23.7 and 33.7% of concrete volume, the freeze-thaw durability of internally-cured concrete mixtures is a function of the percentage of IC water by the weight of binder, rather than total IC water per unit volume of concrete; all IC mixtures assessed for freeze-thaw durability in accordance with ASTM C666-Procedure A exhibited durability factors below 90% and failed the freeze-thaw test and would not be considered acceptable under MnDOT specifications, while some mixtures at *w/c* ratio of 0.45 and all mixtures at a *w/c* ratio of 0.41satisfied the requirements of ASTM C666-Procedure B and KTMR-22 and would be considered acceptable under KDOT specifications. The results also demonstrate that the freeze-thaw resistance of the mixtures decreased markedly when the TI water exceeded 12.0% by the weight of binder. Scaling test results show that as the paste content increases from 23.7 to 33.7%, the scaling resistance of the specimens decreases. At a *w/cm* ratio of 0.45 and a paste content of 23.7%, mixtures with an IC water content of 8.8% passed the scaling test; at a *w/cm* ratio of 0.41 and a paste content of 23.7%, mixtures with IC water contents less than or equal to 13% passed the scaling test. None of the mixtures with a paste content of 33.7% passed the scaling

test at either *w/cm* ratio. Moreover, for a given binder composition and type of coarse aggregate, increased TI water resulted in higher scaling resistance. The type of coarse aggregate also had effects on scaling resistance. The ternary mixtures with granite as the coarse aggregate, had lower mass losses than the ternary mixtures with low-absorption limestone and similar quantities of TI water. As the TI water content increased, shrinkage decreased for concretes with both binder compositions. Mixtures with IC water exhibited more expansion at the end of the curing period than mixtures with no IC water. Increases in the TI water content in mixtures did not affect the rapid chloride permeability or surface resistivity measurements, while the binder composition did, with the ternary mixtures, on average, showing higher and lower SRM and RCP values, respectively, than mixtures containing 100% portland cement.

The second portion of the study involved the construction, crack surveys, and evaluation of 12 bridge decks (nine in Minnesota and three in Kansas) containing IC water and supplementary cementitious materials (SCMs) that were constructed between 2016 and 2021 following IC-LC-HPC specifications (of Minnesota or Kansas) and two associated Control decks without IC. The decks were monolithic with the exception of three of the Minnesota decks, which had overlays. The results show that the use of overlays on bridge decks results in high crack densities and should be avoided. Low-cracking bridge decks require concrete with a paste content of 27.2% or less based on concrete volume. Paste contents above 27.2% correlate with increased cracking, and for decks with paste contents greater than 27.2%, the addition of IC and SCMs does not overcome the negative effects of high paste content. The results also indicate that the combination of low paste, internal curing, and good construction procedures offer the potential to reduce cracking. Under circumstances, good construction practices are needed for low-cracking decks. If poor construction practices are employed, even decks with low paste content and IC can exhibit high cracking and scaling damage.

Key Words: bridge decks, construction practices, cracking, crack density, durability, internal curing, internally-cured low-cracking high-performance concrete, lightweight aggregate, paste content, supplementary cementitious materials, total internal water.

ACKNOWLEDGEMENTS

This report is based on a thesis presented by Alireza Bahadori in partial fulfillment of the requirements for the Ph.D. degree from the University of Kansas. Funding for this research was provided by the Kansas Department of Transportation (KDOT) and the Minnesota Department of Transportation (MnDOT) for the "Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology" Transportation Pooled Fund Study, Project No. TPF-5(392). Ash Grove Cement provided the chemical on the cementitious materials. The Indiana Department of Transportation (INDOT) provided time and resources for two years of bridge deck crack surveys in their state. Additional funding for this research was provided by the ACI Foundation and sponsoring organizations: ABC Polymers, the ACI Foundation's Strategic Development Council (SDC), Active Minerals International, the American Society of Concrete Contractors, Baker Concrete Construction, BASF Corporation, FORTA Corporation, the Expanded Shale, Clay and Slate Institute, the Euclid Chemical Company, GCP Applied Technologies, the University of Kansas Transportation Research Institute, PNA Construction Technologies, Inc., Premier Construction Products, Sika Corporation, and Structural Group, Inc.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 – INTRODUCTION

1.1 GENERAL

Bridges are essential components of the U.S. infrastructure, allowing for vehicles to move across the country to areas that would be otherwise inaccessible. There are more than 617,000 bridges in the United States. Forty-two percent of these bridges are over 50 years old and will most likely need to be rehabilitated or replaced (ASCE 2021). In 2021, the American Society of Civil Engineers (ASCE) reported that 7.5% of U.S. bridges were structurally deficient (ASCE 2021). Furthermore, for years, travel demands and the costs associated with bridge rehabilitation and replacement have increased while funding has been limited (Koch et al. 2002). As a result, the federal government estimates a backlog of bridge rehabilitation and replacement of $125 billion (ASCE 2021).

In 2004, a nationwide survey of state transportation agencies by the Federal Highway Administration's (FHWA) High-Performance Concrete Technology Delivery Team (HPC TDT) indicated that cracking of concrete decks, corrosion of reinforcing steel, cracking of girders and substructures, and freeze-thaw damage of concrete were the topmost bridge deficiencies (Triandafilou 2005).

For many years transportation agencies have been concerned with cracking in bridge decks. As a result, they have attempted to minimize cracking by improving mixture proportions, concrete properties, and construction procedures, as well as implementing crack-reducing technologies (Pendergrass and Darwin 2014). The initial approach was to use concrete designated as "High-Performance" to help reduce crack-related problems in bridge decks. The term High-Performance Concrete (HPC), in most cases, is translated into mixture proportions with high binder (cementitious materials) contents and low water-to-cementitious material (*w/cm*) ratios. As such, HPC mixtures have low permeability, protecting reinforcing steel from corrosion. Although HPC mixtures were meant to improve concrete durability and limit cracking tendency, these early HPC mixtures were associated with high compressive strengths and high paste contents, resulting in increased cracking (Schmitt and Darwin 1995, 1999, Russell 2004, Lindquist et al. 2005, 2006, Darwin et al. 2016).

Based on research at the University of Kansas (Schmitt and Darwin 1995, 1999, Darwin et al. 2004, Lindquist et al. 2005), low-cracking high-performance concrete (LC-HPC) specifications were established to improve the cracking performance of bridge decks. The LC-HPC is distinguished from conventional high-performance concrete in that it is specifically designed to minimize cracking. The LC-HPC specifications were implemented in a two-phase Pooled-Fund study, entitled *Construction of Crack-Free Bridge Decks,* involving the construction of 16 bridge decks between 2005 and 2011 in Kansas. Thirteen of these bridge decks were associated with control decks, constructed following standard Kansas Department of Transportation (KDOT) specifications. Annual cracking surveys performed on the LC-HPC decks demonstrated improved cracking performance in comparison with the control decks (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Alhmood et al. 2015, Darwin et al. 2016).

The mixture proportions used in the LC-HPC decks and the subdecks of the paired control bridge decks contained portland cement as the only binder. The LC-HPC specifications included requirements for aggregates, concrete, construction, and were constructed with low cement paste contents, low slump concrete, limitation on maximum compressive strength, enforced concrete temperature control, minimum finishing, adequate and thorough consolidation, and immediate and extended curing. The LC-HPC bridge decks exhibited improved cracking performance, which is attributed to the modifications in the mixture proportions and construction practices. The specifications did not include other crack-reducing technologies such as internal curing (IC), fiber-reinforced concrete (FRC), and shrinkage-reducing admixtures (SRAs). The LC-HPC specifications developed in Kansas have been modified over the years based on lessons learned in the laboratory and in the field.

In recent years, other crack-reducing technologies, including internal curing (IC), fiber-reinforced concrete, shrinkage-reducing admixtures, with or without incorporating supplementary cementitious materials (SCMs) as partial replacements of portland cement, have been employed by state Departments of Transportation (DOTs) in an effort to reduce further cracking (Bitnoff 2014, Barrett et al. 2015, Rupnow et al. 2016, Lafikes et al. 2020, Feng and Darwin 2020).

As observed in prior research, the effectiveness of crack-reducing technologies in achieving low-cracking and durable concrete is not always guaranteed, especially when it is applied under bad construction practices in the field (McLeod et al. 2009, Khajehdehi and Darwin 2018, Feng and Darwin 2020). Therefore, the importance of following construction procedures is also discussed in this study.

Despite the well-documented benefits of crack-reducing technologies such as IC and SCMs, there is a research gap concerning the combinatorial effects of these approaches to construct durable and low-cracking concrete bridge decks. In addition, only a number of limited studies have investigated the effects of the quantity of IC water[1] at the moderate *w/cm* ratios (values between 0.43 and 0.45) that are used for most bridge decks, especially on freeze-thaw durability. The current study builds on previous work by bridging these research gaps to determine appropriate quantities of IC water for constructing IC-LC-HPC bridge decks. Additionally, this study aims to

[1] The term internal curing (IC) water in generally understood to represent water contained in absorbent materials, such as fine lightweight aggregate that replaces a portion of normalweight aggregate or super-absorbent polymers that are added to concrete. The term is not usually used to also include absorbed water in normalweight aggregates.

evaluate the shrinkage, transport properties, and durability of concrete mixtures incorporating IC water with or without SCMs with further evaluation of the effects of total internal water (provided by all aggregates) on internally-cured concrete mixtures. Research is conducted in the laboratory and in the field, with the goal of constructing low-shrinkage and durable bridge decks with an emphasis on following construction procedures properly.

This chapter provides the background and establishes the objective and scope of this study.

1.2 SIGNIFICANCE OF BRIDGE DECK CRACKING

The principal mechanisms of cracking in bridge decks involve restrained shrinkage and thermal stresses. Concrete shrinks due to a loss of moisture in hydrated cement paste (cementitious materials and water). In bridge decks, where a high level of restraint exists, tensile stresses develop. Cracking initiates once the tensile stresses exceed the tensile strength of the concrete. Additionally, at early ages when the tensile strength of concrete is low, thermal stresses caused by a temperature differential between the concrete and the girders may lead to cracking (Krauss and Rogalla 1996).

Cracks facilitate the penetration of oxygen, moisture, and deicing chemicals into bridge decks, leading to the corrosion of reinforcing steel, which results in concrete spalling and considerably shortens the service life of the decks (Mehta and Monteiro 2006, Lindquist et al. 2005, 2006, Darwin et al. 2016). The penetration of moisture and deicing chemicals can also increase the potential for scaling and freeze-thaw damage. To make matters worse, the use of deicing chemicals in the U.S. has been increasing since the 1960s (Russel 2004).

As shown in Figure 1.1, the expansive corrosion products increase tensile stresses in the concrete, which eventually cause cracking, deterioration, and concrete spalling (PCA 2002). Bridge deck cracking, followed by corrosion of reinforcing steel, is considered to be the primary cause of bridge deck deterioration (Russell 2004).

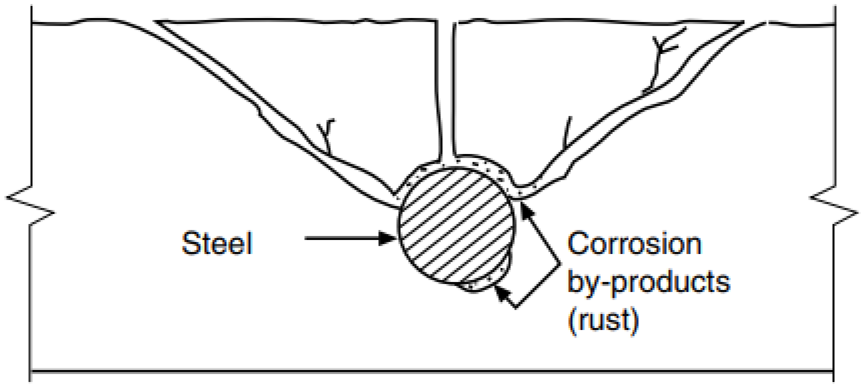


Figure 1.1. Schematic of cracking in concrete due to corrosion of reinforcing steel (PCA 2002)

Lindquist et al. (2006) reported that at crack locations, the concentration of chlorides at the level of the top reinforcing steel [3.0 in. (76.2 mm) from the surface] exceeded 1.0 lb/yd^3 (0.6 kg/m^3), the lower limit of corrosion threshold of conventional reinforcement, within the first two years after construction. In uncracked concrete, however, the concentration of chlorides remained below the corrosion threshold for a minimum of twelve years and considerably longer for most bridge decks.

Cracking, as the main factor that leads to corrosion of reinforcement, also promotes freeze-thaw damage in bridge decks, a significant concern for decks located in the northern U.S. As will be discussed, freeze-thaw damage can occur in different forms, such as concrete spalling due to extreme cement paste expansion as well as surface scaling in the presence of deicing chemicals/salts and moisture. Improving freeze-thaw resistance, therefore, has the potential to prolong the service life of bridge decks significantly.

1.3 CAUSES OF CRACKING IN BRIDGE DECKS

Cracks develop in bridge decks when the induced tensile stresses are greater than the tensile strength of the concrete. Tensile stresses can be induced as a result of restrained shrinkage, temperature changes, and external loading. External loading, however, has a relatively small effect when compared to concrete shrinkage and thermally-induced stresses (Krauss and Rogalla 1996). Concrete with no restraint can change volume without developing tensile stresses, while restrained concrete is susceptible to cracking.

Cracks are typically classified into two main categories: 1) cracks that occur prior to setting, when the concrete is still plastic – these include plastic shrinkage cracking and plastic settlement cracking; and 2) cracks that occur after the concrete has hardened – these include autogenous shrinkage cracking, drying shrinkage cracking, thermal cracking, and external loading cracking. This section reviews the factors that cause cracking in plastic and hardened concrete and the development of tensile stresses in bridge decks.

1.3.1 Concrete Shrinkage Cracking

While cracking in bridge decks results from an interaction of multiple factors, restrained volume change is the major contributor to early-age and long-term bridge deck cracking. The subsequent sections review different types of concrete shrinkage cracking that occur in plastic and hardened concrete.

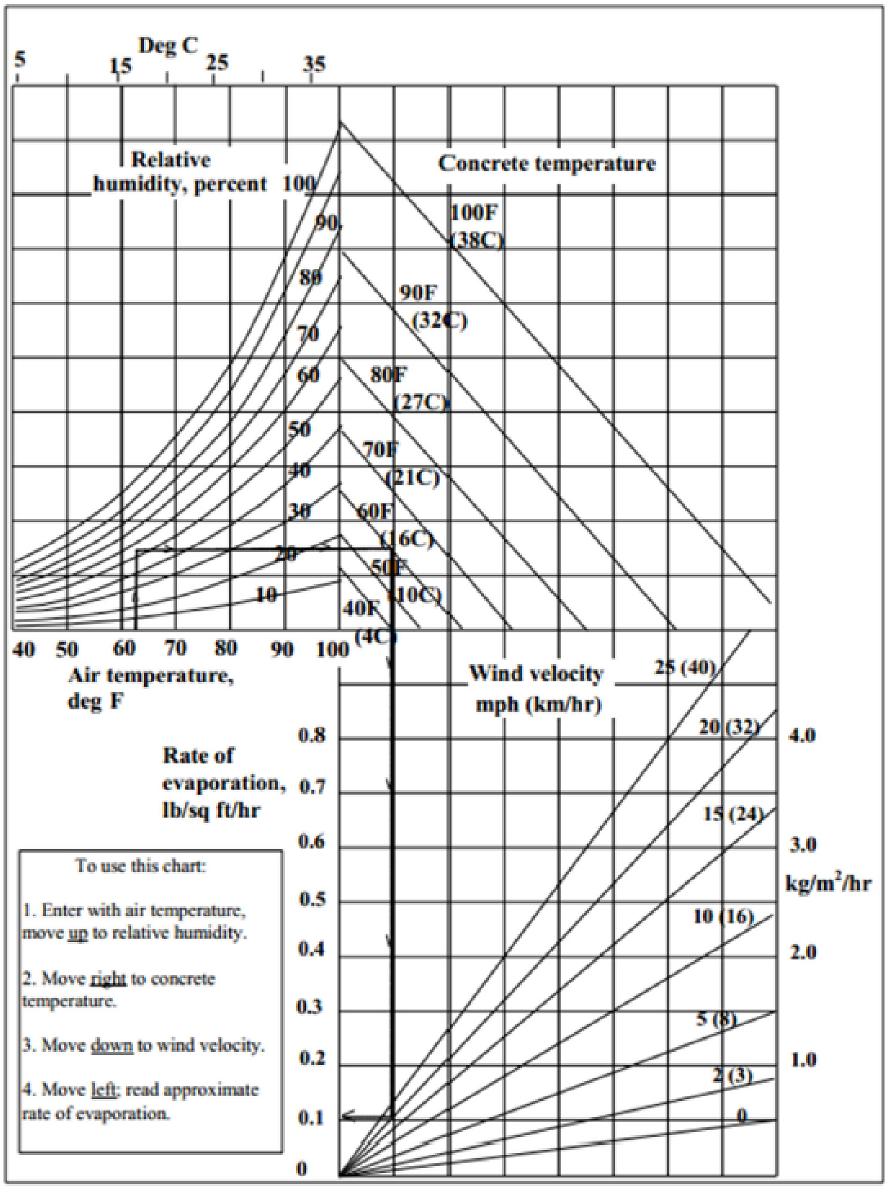
1.3.1.1 Cracking in Plastic Concrete

Plastic shrinkage cracking occurs in fresh concrete, while it is still plastic and before it gains strength, when the concrete loses water through evaporation at the surface and suction by formwork or the subgrade (Mindess et al. 2003). As a result, menisci are formed between particles at the surface as the rate of evaporation exceeds that of the bleed water reaching the surface. The formation of menisci results in the development of negative capillary pressures, leading to a reduction in the cement paste volume. In addition, since the surface is open to the environment while the underlying concrete is not, the shrinkage rate at the surface is higher than that of the underlying concrete. As a result, the differential shrinkage developed between the surface and the underlying concrete generates tensile stresses and leads to cracking at the surface (Mindess et al. 2003). In bridge decks, particularly, the area exposed to the environment is greater than other structures due to larger surface area-to-volume ratios and, if not protected, is more prone to plastic shrinkage and cracking (Mora-Ruacho et al. 2009, Pendergrass and Darwin 2014).

An increase in the evaporation rate at the surface of the concrete as well as a decrease in the bleeding rate are two primary factors leading to plastic shrinkage cracking. These factors can be mitigated by a number of strategies.

High concrete and air temperatures, low relative humidity, and high wind velocity are the major factors contributing to an increase in the evaporation rate at the surface of concrete. ACI Committee 308 (2016) provides a nomograph, shown in Figure 1.2, to estimate the surface evaporation rate, which is often used by state DOTs. Although the evaporation rate can be estimated using Figure 1.2, the bleeding rate is not easy to determine. In practice, many state DOTs specify a maximum limit of 0.1 or 0.2 lb/ft^2/hr (0.5 or 1.0 kg/m^2/hr) for the evaporation rate and encourage the use of protective measures, such as cooling the concrete by replacing some of the mix water with ice, providing early application of wet curing, and using windbreaks to protect the concrete from direct wind to reduce the potential for plastic shrinkage cracking (Mindess et al. 2003, Lindquist et al. 2008, Kansas Department of Transportation 2015, Minnesota Department of Transportation 2018). Additionally, pre-wetting the formwork just before placing fresh concrete on bridge decks can limit water loss (Mindess et al. 2003), reducing plastic shrinkage as well.

A decrease in the bleeding rate in concrete increases the potential for plastic shrinkage cracking. Many factors influence the bleeding rate. An accelerated rate of hydration or increase in the surface area of the solid constituents of concrete due to the use of very fine cementitious materials (cement and SCMs, especially silica fume), the use of air-entraining and high-range water-reducing admixtures, a reduced water content, and the use of low *w/cm* ratio mixtures may decrease the bleeding rate (Soroka and Ravina 1998, Mindess et al. 2003, Pendergrass and Darwin 2014). Plastic shrinkage cracks typically form in random patterns and are frequently wide at the surface but shallow in depth (Krauss and Rogalla 1996).



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

Figure 1.2. Evaporation rate nomograph (ACI Committee 308 2016)

Plastic settlement cracking, also called subsidence cracking, occurs in freshly placed concrete. As bleed water reaches the surface, solid particles in plastic concrete, which have a greater density than water, continue to settle around top reinforcing bars after placement and consolidation. As the reinforcing bars restrain the movement of concrete, a weakened vertical zone is created on top of the reinforcement (Powers 1968, Babaei and Purvis 1995, Schmitt and Darwin 1995). The tensile stresses induced above the reinforcing bars may result in cracking in the plastic concrete above and parallel to the top reinforcing bars.

Dakhil et al. (1975) reported that plastic settlement cracking increases with an increase in concrete slump, greater reinforcing bar size, and primarily, a decrease in the top cover thickness. In addition, poor construction procedures, such as insufficient consolidation, also increase the potential of plastic settlement cracking (Khajehdehi and Darwin 2018). A number of studies have demonstrated that the use of crack-reducing technologies, including FRC, SRA, and IC in conjunction with SCMs, mitigate plastic settlement cracking (Henkensiefken et al. 2010, Al-Qassag et al. 2015, Ibrahim et al. 2019). Research performed by Al-Qassag et al. (2015) showed that the addition of synthetic fibers and rheology modifying admixtures (RMAs) to concrete mixtures noticeably reduces plastic settlement cracking. Ibrahim et al. (2019) investigated the effects of shrinkage-reducing technologies, including SRA, IC, and SCMs, in optimized aggregate gradation concrete mixtures on plastic settlement cracking. They showed that the plastic settlement was significantly reduced using these technologies compared to similar concrete mixtures that did not incorporate these technologies.

1.3.1.2 Cracking in Hardened Concrete

Autogenous shrinkage cracking occurs in hardened concrete due to self-desiccation within paste in a sealed system in the absence of water loss to the environment (Radlińska 2008).

This type of shrinkage is of concern for concrete mixtures with *w/cm* ratios less than 0.42, such as for high-strength concrete mixtures, where due to their low permeability, the penetration of external curing water to concrete comes with difficulty. As water is consumed in the hydration process, menisci form in the capillaries and the partially-filled pores, leading to an increase in internal tensile stresses. The resulting capillary stresses developing from water drawing out from capillary pores lead to autogenous shrinkage (Holt 2001).

Several techniques have been developed to limit autogenous shrinkage by providing curing water internally, principally by using pre-wetted lightweight aggregate (LWA) and superabsorbent polymer particles (SAPs). Internal curing can provide internal water reservoirs at early ages to gradually release water into the surrounding cement paste, mitigate self-desiccation, improve hydration, and reduce permeability (Bentz and Snyder 1999, Geiker et al. 2004, Cusson and Hoogeveen 2008, Pendergrass and Darwin 2014).

Because bridge deck concretes rarely have *w/cm* ratios much below 0.42, autogenous shrinkage is not an issue for most decks. As will be discussed in Section 1.6, however, internal curing can reduce drying shrinkage at early ages, even *w/cm* ratios above 0.42 and, thus, is a viable technique for minimizing cracking in bridge decks.

Drying shrinkage cracking occurs in hardened concrete due to the loss of water to the environment, resulting in capillary stress development and induced volume changes. Drying shrinkage of concrete in the presence of restraint is the principal cause of cracking in bridge decks (Vergas 2012). Restraint in bridge decks results from external and internal sources. External restraint is provided by the structural components, including the composite action between the concrete, girders, and abutments. Internal restraint is provided by the reinforcing bars and the shrinkage gradient within concrete (as a result of preferential drying at the concrete surface).

Internal restraint can increase tensile stresses due to the generation of a non-uniform shrinkage strain profile through the deck thickness (Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018). Although drying shrinkage takes place over a more extended period compared to other types of shrinkage, a major portion occurs at early ages (Holt 2001).

As will be discussed, concrete material properties and mixture proportions are the primary factors contributing to drying shrinkage. Factors such as type and fineness of cement, aggregates, admixtures, and *w/cm* ratio affect the amount of drying shrinkage; however, cement paste content is the dominant factor affecting drying shrinkage (Mindess et al. 2003, Miller and Darwin 2000, Khajehdehi and Darwin 2018).

Thermal cracking in bridge decks results from restrained thermally-induced volume changes. The reaction of water with cement components, hydration, is exothermic, resulting in an increase in plastic concrete temperature in the first few hours after placement. Initially, expansion resulting from the increase in temperature caused by the heat of hydration results in little or no significant stresses in concrete, mainly due to the low modulus of elasticity at early ages. As hydration progresses, the concrete temperature reaches its peak and the concrete gets harder. If the hardened concrete is restrained by reinforcing steel, girders, and abutments, subsequent cooling to the ambient temperature (leading to contraction) can induce tensile stresses in concrete and may cause cracking (Babaei and Fouladgar 1997).

The primary factor contributing to thermal cracking is the temperature differential between the concrete bridge deck and the girders (Krauss and Rogalla 1996, Babaei and Fouladgar 1997). Babaei and Purvis (1996) and Babaei and Fouladgar (1997) suggested that thermal cracking can be avoided by maintaining the temperature differential between the concrete and the girders below 22 °F (12 °C) for a minimum of 24 hours after placement.

The potential for thermal cracking is greater in decks with higher initial concrete temperatures than the girders. This is, particularly, the case for placing warm concrete in cold weather where the girder temperatures are as low as the ambient temperature. In this situation, an effective way to control the thermal stresses is to increase the temperature of the girders by heating the air underneath the deck (Babaei and Fouladgar 1997).

Previous studies have also shown a correlation between plastic concrete temperature and high air temperature (Khajehdehi and Darwin 2018). Khajehdehi and Darwin (2018) showed that on hot days with a high air temperature between 78 and 88 °F (26 and 31 °C), placement of concrete with controlled temperatures ranging from 58 to 72 °F (14 to 22 °C) was correlated with lower cracking in steel girder bridge decks. While the concrete maintains its volume, the contraction of girders upon a drop in air temperature induces compression stresses within the concrete, reduces tensile stresses caused by drying shrinkage. Khajehdehi and Darwin (2018), however, did not observe any advantage of high air temperature in placing decks without controlling the concrete temperature. Shading the materials, cooling the aggregates using sprinklers, replacing a portion of mixing water with ice, or injecting liquid nitrogen are measures that can be taken to control the concrete temperature for placing in hot weather conditions (Kansas Department of Transportation 2015).

Externally applied loading includes construction load, dead load, and live load, which can produce tensile stresses in bridge decks. Although the induced tensile stresses can cause flexural cracking in decks, studies have shown that these tensile stresses are only a small percentage of the stresses that cause cracking when compared to concrete shrinkage and thermal cracking (Krauss and Rogalla 1996). An example of external loading under an unusual condition addressed in previous studies includes an individual traffic lane that was greatly cracked due to heavily loaded equipment/vehicles, such as construction equipment or heavily loaded trucks transferring minerals from nearby mines, as documented by Darwin et al. (2016) and Lafikes et al. (2020).

1.4 TYPES OF BRIDGE DECK CRACKING

Cracks in bridge decks can be divided into five main groups based on orientation and pattern: transverse, longitudinal, diagonal, pattern/map cracking, and random cracking (*Durability of Concrete Bridge Decks* 1970, Schmitt and Darwin 1995). The orientation and type of cracks may be used to identify the cause of cracking and the possible exposure of the reinforcement to the environment. Cracks formed perpendicular to the reinforcement will only expose a small area on the steel bar to the surrounding environment. This results in localized corrosion. Cracks formed above and parallel to the reinforcement, however, can expose a large steel area, increasing the risk of corrosion. Transverse, longitudinal, diagonal, and pattern/map cracking are shown in Figure 1.3.

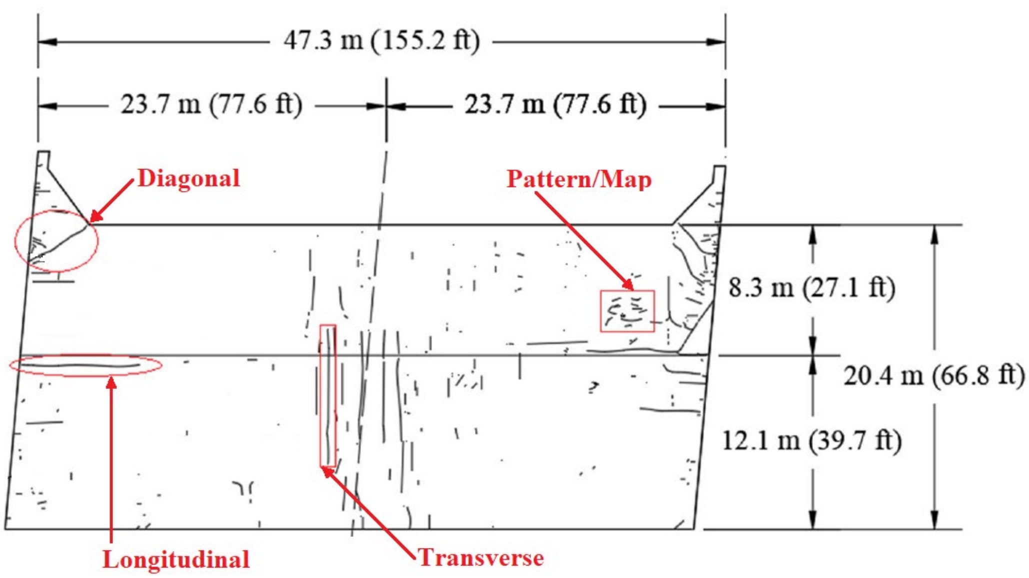


Figure 1.3. Transverse, Longitudinal, Diagonal, and Pattern/Map Cracking (Darwin et al. 2016)-*modified*

Transverse cracks in bridge decks are perpendicular to the direction of traffic flow (longitudinal axis) and are the most prevalent type of cracks observed on concrete bridge decks (Ramey et al. 1997). Transverse cracks typically form above and parallel to the transverse reinforcement. Transverse cracks can also extend entirely through the deck thickness, accelerating the penetration of corrosion enablers to the level of the reinforcing steel. Therefore, transverse cracks significantly increase the likelihood of corrosion of the reinforcing steel (*Durability of Concrete Bridge Decks* 1970, Schmitt and Darwin 1995, Krauss and Rogalla 1996).

Longitudinal cracks form parallel to the bridge deck centerline. These cracks are typically straight, with variations in length. In bridge decks with integral abutments, longitudinal cracks may form near the ends of the deck, mainly because of the transverse restraint imposed on the deck by the abutments (Schmitt and Darwin 1995, Miller and Darwin 2000, Khajehdehi and Darwin 2018). Full-depth longitudinal cracks have been observed in bridge decks supported by prestressed box girders due to differential settlement of one girder to the next (Frosch et al. 2003, Lafikes et al. 2020).

Diagonal cracks typically form in skewed bridge decks, near integral abutments or over the piers. They are typically oriented perpendicular to the skew angle of the deck. The formation of this type of crack can be attributed to drying shrinkage and external loads (Pendergrass and Darwin 2014).

Pattern or map cracks can form as an interconnected system in all types of bridge decks. These cracks are short, narrow, and shallow in depth and can extend in any direction on the deck surface. Increased moisture evaporation rate at the surface resulting from a failure to apply early curing increases the potential of map cracking in bridge decks (*Durability of Concrete Bridge Decks* 1970, Schmitt and Darwin 1995). In addition, overfinishing the concrete surface may result in map cracking by bringing excess paste to the surface (Pendergrass and Darwin 2014). Bridge decks with concrete overlays are also susceptible to map cracking.

Random cracks comprise those types of cracks that do not fall into any of the categories mentioned above. These cracks can have various orientations and forms due to many variables (Pendergrass and Darwin 2014).

1.5 FACTORS AFFECTING BRIDGE DECK CRACKING

Although the primary contributors to bridge deck cracking are restrained shrinkage and thermal stresses, previous studies have shown that many factors are involved in bridge deck cracking. These factors are a function of the concrete material properties, construction procedures, environmental conditions, and structural design, all of which can influence the cracking performance of bridge decks (*Durability of Concrete Bridge Decks* 1970, Schmitt and Darwin 1995, Pendergrass and Darwin 2014). The following sections summarize these factors.

1.5.1 Concrete Material Properties

Numerous studies have shown that concrete material properties, such as cement paste content, water-to-cementitious material ratio, aggregate content, supplementary cementitious materials, chemical admixtures, and concrete slump, can play a crucial role in the durability and cracking performance of bridge decks.

The cement paste content of concrete mixtures is the dominant factor in concrete shrinkage (Bissonnette et al. 1999, Khajehdehi et al. 2021), and thus, bridge deck cracking. The effects of paste content on the cracking performance of bridge decks have been addressed in numerous studies (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2020, Khajehdehi et al. 2021). In a study that included 32 monolithic bridge decks, Schmitt and Darwin

(1999) observed that concrete decks with a cement paste content greater than 27% (by concrete volume) exhibited significantly greater cracking compared to decks with lower paste contents. In a somewhat broader study, Khajehdehi and Darwin (2018) and Khajehdehi et al. (2021) observed that the cracking of bridge decks containing more than 27.2% paste was significantly higher than that of the bridge decks with less than 26.4% paste, but that reductions below 26.4% provided no additional advantage. Other researchers have also shown that lower cement paste content is more important than incorporating other shrinkage-reducing technologies, such as SRAs and IC water (Feng and Darwin 2020, Lafikes et al. 2020). Lafikes et al. (2020) reported that paste contents greater than 27%, even when using incorporating IC with SCMs, results in a higher cracking than decks constructed with lower paste contents.

Krauss and Rogalla (1996) investigated the effects of cement content and water-to-cement (*w/c*) ratio (portland cement was the only binder) on the cracking tendency of concrete mixtures using a restrained shrinkage test. The results showed that the mixtures with the highest cement content [846 lb/yd^3 (500 kg/m^3)] with *w/c* ratios of either 0.3 or 0.35 exhibited higher cracking than that of the mixtures with the lowest cement content [470 lb/yd^3 (280 kg/m^3)] with *w/c* ratios of either 0.3 or 0.35. An increase in cement content leads to increased paste content, increasing the potential for concrete shrinkage. Additionally, increasing the cement content generates more heat of hydration, resulting in increased thermal stresses (Brown et al. 2001).

Some studies have shown that a reduction in *w/cm* ratio results in slightly increased bridge deck cracking (Schmitt and Darwin 1999, Brown et al. 2001, Darwin et al. 2004). This decrease in the *w/cm* ratio improves the durability of concrete due to a decrease in concrete permeability. The decrease in the *w/cm* ratio, however, also leads to an increase in concrete compressive strength, resulting in a decrease in concrete creep, which limits the alleviation of tensile stresses induced when shrinkage is restrained (Krauss and Rogalla 1996). As discussed earlier in Section 1.3.1.2, a *w/cm* ratio less than 0.42 can result in autogenous shrinkage, which can also result in cracking (Krauss and Rogalla 1996). Khajehdehi and Darwin (2018), however, observed that independent of the *w/cm* ratio, paste content remains the dominant effect. They found that concrete strength did have an effect, but the correlation between strength and cracking was not statistically significant.

Concrete shrinkage can be influenced by aggregate volume, size, and type. In contrast to cement paste, most aggregates are dimensionally stable and can restrict volume changes. As the aggregate content increases, cement paste content decreases and shrinkage decreases (Mindess et al. 2003). The use of a large aggregate size can be beneficial in decreasing the amount of concrete shrinkage. Larger aggregates have a smaller surface area-to-volume ratio, decreasing the amount of cement paste needed to provide a given workability. In addition, the use of aggregates with a low coefficient of thermal expansion and modulus of elasticity can result in decreased thermal stresses and concrete shrinkage (Krauss and Rogalla 1996, French et al. 1999).

As will be discussed in Section 1.7, the addition of supplementary cementitious materials as a partial replacement for portland cement can have an impact on concrete shrinkage. The impact that additional SCMs have on shrinkage is related to curing. Yuan et al. (2015) investigated the effects of different replacement levels of portland cement with slag cement on drying shrinkage with different curing periods (between 3 and 28 days). They observed that, for a constant paste content, when cured for 14 days, mixtures containing a 30% volume replacement of portland cement with slag cement exhibited lower drying shrinkage compared to the paired mixtures with 100% portland cement; these mixtures, however, when cured for seven days showed similar shrinkage. Yuan et al. (2011) also observed that mixtures containing 40% volume replacement of portland cement with Class F fly ash exhibited lower drying shrinkage when cured for at least 28 days compared to the paired mixtures with 100% portland cement. These mixtures, however, when cured for 14 and 7 days, showed similar and more shrinkage, respectively, than mixtures with 100% portland cement.

The use of air-entraining agents (AEAs), water-reducing admixtures (WRAs), shrinkage-reducing admixtures (SRAs), and shrinkage-compensating admixtures (SCAs) can influence the shrinkage of concrete. The addition of AEAs to concrete mixtures promotes workability by decreasing the friction between solid particles. Schmitt and Darwin (1995, 1999) concluded that the cracking of bridge decks decreases when the air content is at least 6.0%. Water-reducing admixtures are commonly used to decrease water demand and achieve the desired slump. Adding WRAs containing hydroxylated carboxylic acid can also increase bleeding and, thus, reduce plastic shrinkage cracking (Krauss and Rogalla 1996). The addition of SRAs can reduce plastic and drying shrinkage cracking by decreasing capillary pressures in concrete due to the reduced surface tension of the pore solution (Lura et al. 2007, Mora-Ruacho et al. 2009). Ibrahim et al. (2019) also observed decreased settlement cracking for mixtures with a wide range of slumps containing SRAs. SRAs also reduce early-age and long-term drying shrinkage (Yuan et al. 2011, Ardeshirilajimi et al. 2016, Pendergrass et al. 2017). The reaction between calcium oxide (CaO) and magnesium oxide (MgO), two primary components of SCAs, with water forms hydroxides, resulting in an expansion in concrete. In bridge decks, where a high level of restraint exists, the expansion of concrete helps to induce compressive stresses, counteracting tensile stresses caused by restrained shrinkage. Khajehdehi and Darwin (2018) investigated the effects of SCAs on drying shrinkage for a series of concrete mixtures. They reported that mixtures incorporating SCAs consisting of CaO or MgO exhibited lower shrinkage than mixtures with no SCAs through 180 days after casting.

The effect of slump on early-age cracking has been investigated in several studies. Many researchers have reported that as the concrete slump increases, the potential for settlement cracking increases (Schmitt and Darwin 1999, Lindquist et al. 2005, McLeod et al. 2009, Yuan et al. 2011, Al-Qassag et al. 2015, Ibrahim et al. 2019). Ibrahim et al. (2019) reported that in a laboratory study, settlement cracking increased as slump increased for all mixtures. In mixtures containing portland cement as the only binder, crack widths increased as slump increased, while in mixtures incorporating SCMs (slag cement and silica fume) with or without IC, crack widths increased only slightly. Crack widths in mixtures incorporating an SRA did not change as the slump increased.

1.5.2 Environmental Conditions, Construction Procedures

In addition to concrete material properties, environmental conditions and construction procedures can impact the cracking performance of bridge decks, regardless of the crack-reducing technologies implemented in the mixtures (Krauss and Rogalla 1996, McLeod et al. 2009, Pendergrass and Darwin 2014, Hopper et al. 2015, Khajehdehi and Darwin 2018, Feng and Darwin 2020).

1.5.2.1 Weather and Time of Casting

As discussed in Section 1.3.1.1, an increased evaporation rate is a primary issue that affects plastic shrinkage cracking. Schmitt and Darwin (1995) and Miller and Darwin (2000) reported that an increase in the air temperature, as well as a greater temperature range on the day of placement, resulted in increased cracking in bridge decks. Bridge decks placed in the late morning or early afternoon experience higher cracking than decks placed in the early evening or at night (Krauss and Rogalla 1996, Khajehdehi and Darwin 2018).

Although the rate of evaporation at the concrete surface increases as the relative humidity decreases, resulting in increased plastic shrinkage cracking, prompt application of curing can mitigate this problem (Lindquist et al. 2008, McLeod et al. 2009, Darwin et al. 2010, Yuan et al. 2011, Darwin et al. 2012, Pendergrass and Darwin 2014, Darwin et al. 2016). Concrete should be protected in windy conditions to minimize surface drying using windbreakers and water fogging procedures during construction (Krauss and Rogalla 1996), although the latter is far from a perfect solution and may cause problems of its own (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011).

1.5.2.2 Consolidation

Thorough consolidation of freshly placed concrete is vital to minimize cracking of bridge decks. The risk of settlement cracking in decks with low concrete cover increases when concrete is inadequately consolidated (Issa 1999). Disturbing freshly consolidated concrete can also significantly increase the potential of cracking on bridge decks even with cover as great as 3 in. (75 mm) (Khajehdehi and Darwin 2018). One effective method of consolidation is by using vertically mounted gang vibrators spaced at 1 ft (0.3 m), which are commonly used in Kansas. Precautions, however, should be taken when spring-loaded gang vibrators are used because abrupt removal of vibrators from the concrete leaves a series of holes in the deck that are not closed by the finishing equipment, leaving the concrete susceptible to settlement cracking (McLeod et al. 2009, Khajehdehi and Darwin 2018).

1.5.2.3 Finishing

Finishing procedures are another factor affecting bridge deck cracking. While early finishing can reduce the number and width of cracks (Horn et al. 1975, Stewart and Gunderson 1969), overfinishing concrete through excessive screeding or bullfloating tends to bring excessive cement paste to the surface while pushing coarse aggregate to lower depths, which can result in increased cracking. Delays in finishing concrete may, in turn, postpone the early application of curing, exposing concrete to the environment, resulting in increased plastic bridge deck cracking (Lindquist et al. 2008, McLeod et al. 2009, Darwin et al. 2010, Yuan et al. 2011, Darwin et al. 2012, Pendergrass and Darwin 2014, Darwin et al. 2016). Furthermore, overfinishing concrete in an attempt to remove excess bleed water works the bleed water back into the surface, leading to a paste layer with a high *w/cm* ratio that may lead to freeze-thaw and scaling damage. A similar issue can result from the use of a finishing aid on the concrete.

1.5.2.4 Curing

The early application of curing can influence the cracking performance of bridge decks by minimizing plastic shrinkage and aiding the hydration process (Krauss and Rogalla 1996, Darwin et al. 2016). Application of curing in accordance with the KDOT LC-HPC specifications includes applying two layers of pre-soaked burlap on the deck surface. The first layer is applied within 15 minutes of strikeoff by the screed. The second layer is applied within 10 minutes of the first layer (Kansas Department of Transportation 2015). Application of curing in accordance with Minnesota Department of Transportation (MnDOT) IC-LC-HPC specifications includes applying a layer of pre-soaked burlap covered with white plastic sheeting on the deck surface. Wet curing is required within 20 minutes of strikeoff. According to MnDOT IC-LC-HPC specifications, the use of a membrane curing compound is allowed where marring of a broomed or tined surface is a concern and should be applied within 30 minutes of concrete placement, followed by the wet curing.

The duration of curing can also affect the cracking performance of bridge decks. An increase in the curing period should reduce shrinkage because it permits continued hydration of the cementitious materials, which permanently ties up water that cannot subsequently evaporate. KDOT LC-HPC specifications require a 14-day curing period, while MnDOT IC-LC-HPC specifications require a minimum of a 7-day curing period. A number of researchers have reported the beneficial effect of extending the curing period on decreasing the drying shrinkage of concrete. Lindquist et al. (2008) found that increasing the curing period from 7 to 14 days reduced drying shrinkage of concrete mixtures with SCMs. Reynolds et al. (2009) and Browning et al. (2011) reported similar observations for concrete mixtures with IC provided by pre-wetted fine lightweight aggregate with partial replacements of portland cement with slag cement. Similarly, Yuan et al. (2015) observed a decrease in drying shrinkage for mixtures containing slag cement when the curing period was extended from 7 to 14 days. Therrien et al. (2000) investigated the effects of curing time and relative humidity on moisture loss of mortar mixtures with a *w/c* ratio of 0.40. They observed that, at a relative humidity of 53%, increasing curing duration from 1 to 28 days decreased moisture loss and drying shrinkage by approximately 33 and 67%, respectively.

In another study, West et al. (2010) investigated the effect of varying curing periods on the drying shrinkage of concrete mixtures containing either Type I/II or Type II coarse-ground cement with and without air-entraining admixtures. A series of concrete specimens were cast and cured for 3, 7, 14, and 28 days in lime-saturated water in accordance with ASTM C511. They found that among the mixtures with different curing durations, the mixtures cured for 28 days exhibited the lowest shrinkage.

1.5.3 Structural Design Factors

As discussed earlier, although material properties and construction procedures contribute significantly to bridge deck deterioration, cracking in bridge decks can also be influenced by structural design. The primary factors include type of deck, degree of restraint and type of girder, span length, deck thickness, reinforcing bar size and spacing, and top cover thickness.

Type of Deck

Russell (2004) reported the increased potential for the formation of reflective cracks in the concrete toppings above the discontinuities in the panels. Wenzlick (2005) reported that partial-depth precast deck panels supported by prestressed concrete girders exhibited higher cracking (almost double) than cast-in-place decks in Missouri. Bitnoff (2014) investigated the cracking performance of a series of partial-depth precast concrete deck panels supported by prestressed girders in Utah. The crack densities of the decks ranged from 0.430 to 1.148 m/m^2 at 24 months, exhibiting poor cracking performance. The poor cracking performance of decks surveyed by Bitnoff, however, can likely be attributed to the high quantity of paste (28%) in the mixture since, as prior studies have demonstrated, a high paste content (at or above 27%) is the dominant factor affecting bridge deck cracking (Khajehdehi and Darwin 2018, Feng and Darwin 2020, Lafikes et al. 2020).

In contrast to studies reporting increased cracking in decks with partial-depth precast panels, Harley et al. (2011), Shrestha et al. (2013), and Khajehdehi and Darwin (2018) observed much lower crack densities for a series of decks supported by partial-depth precast panels in Kansas. The cracking performance of these decks was attributed mainly to the low paste content (lower than 25%) of the concrete topping (Khajehdehi and Darwin 2018).

The use of overlays can also increase bridge deck cracking. Miller and Darwin (2000) and Lindquist et al. (2005) reported greater cracking in decks with concrete overlays containing 100% portland cement (conventional) and in decks containing silica fume than in monolithic decks with similar characteristics.

Degree of Restraint and Type of Girder

Stresses in a bridge deck can be affected by the degree of restraint and the composite action between the deck, girders, and abutments. A composite deck is externally restrained by the girders and abutments, which can result in transverse cracks (Krauss and Rogalla 1996). Decks supported by steel girders are more prone to cracking than decks supported by prestressed concrete girders (Krauss and Rogalla 1996, Frosch et al. 2003, Hopper et al. 2015, Darwin et al. 2016, Khajehdehi and Darwin 2018). This observation can be attributed to differences between the thermal expansion coefficient of steel and concrete girders, as well as the fact that the steel girders do not creep while concrete girders do (Pendergrass and Darwin 2014).

Span Length

Krauss and Rogalla (1996) observed that cracking increases as the span length increases. They indicate that decks with longer spans, in contrast with shorter spans, are supported by longer girders that induce a higher degree of restraint, leading to more cracking. Other studies, however, have shown no correlations between span length and cracking (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005).

Deck Thickness

Deck thickness can affect cracking in two ways, one of which will decrease cracking and one of which will increase cracking. Some studies have shown that increasing the deck thickness results in decreased cracking (Horn et al. 1972, Kochanski et al. 1990, French et al. 1999). A thicker deck, in theory, can increase the resistance to tensile forces and reduce cracking. Krauss and Rogalla (1996) and Brown et al. (2001), however, reported that thicker decks on smaller girders are susceptible to develop non-uniform shrinkage, which may result in increased deck stresses and cracking.

Reinforcing Bar Size and Spacing

Reinforcing bar size and spacing can affect bridge deck cracking. Dakhil et al. (1975) and Babaei and Fouladgar (1997) reported that settlement cracking increases with an increase in bar size. Schmitt and Darwin (1995) investigated cracking in bridge decks and suggested limiting the top transverse bars to No. 4 or No. 5 (No. 13 or No. 16) with a maximum spacing of 6 in. (150 mm). In another study, Krauss and Rogalla (1996) recommended the use of No. 4 (No. 13) bars with a maximum spacing of 6 in. (150 mm) to mitigate stresses and decrease crack widths.

Top Cover Thickness

An increase in top concrete cover helps to reduce settlement cracking (Dakhil et al. 1975). Departments of transportation often require a minimum top cover of 2 in. (50 mm). Higher cover thickness minimizes the effect of penetration of the deicing salts even in the presence of cracks (Lindquist et al. 2005, 2006).

1.6 INTERNAL CURING

Internal water provided through the use of pre-wetted absorptive materials to enhance cement hydration is referred to as internal curing (IC) (ACI Committee 308 2013). By employing internal curing, the absorbed water stored within the water-carrying reservoirs is provided to the cement paste. As hydration begins and water is consumed in the cement paste and as drying begins, the absorbed water is released into the cement paste to promote further hydration and to replace the water lost to evaporation (Bentz and Weiss 2011).

The benefits of IC on concrete performance have been addressed in a number of studies (Weber and Reinhardt 1997, Bentz and Snyder 1999, Cusson and Hoogeveen 2008, Lindquist et al. 2008, Wei and Hansen 2008, Reynolds et al. 2009, Browning et al. 2011, Bentz and Weiss 2011, Castro 2011, Browning et al. 2011, Pendergrass and Darwin 2014, Lafikes et al. 2020 to name a few). These include reduced autogenous and drying shrinkage, reduced plastic settlement cracking, reduced permeability, enhanced cement hydration, and enhanced strength development.

Internal curing can be provided by the use of pre-wetted lightweight aggregate (LWA), superabsorbent polymers (SAPs), saturated recycled crushed concrete aggregates (CCAs), and saturated wood fibers. Among these water-carrying reservoirs, the use of pre-wetted LWA has been the most common method to provide internal curing (Bentz and Weiss 2011). The focus of this study is to evaluate the effects of IC water content on the shrinkage and durability of concrete mixtures and bridge decks through the use of pre-wetted LWA.

The use of internal curing, through the use of pre-wetted lightweight aggregates, was first proposed by Philleo (1991) for high-strength concrete mixtures. Since then, the use of internal curing has been increasing as its benefits have become better recognized. Lightweight aggregate is highly porous, with relatively large pores compared to normalweight aggregates. The absorption of LWA is one of the key properties determining its effectiveness as an internal curing agent, the value of which is highly dependent on the pre-wetting method and duration (Barrett et al. 2015).

As discussed in Section 1.3.1.2, autogenous shrinkage occurs due to self-desiccation within paste in a sealed system in the absence of water loss to the environment (Radlińska 2008). Autogenous shrinkage is of particular concern in mixtures with low *w/cm* ratios (below 0.42), where external wet-curing cannot provide enough water for cement hydration (Mindess et al. 2003). Internal curing can mitigate autogenous shrinkage and improve cement hydration. Cusson and Hoogeveen (2008) studied the effects of internal curing on autogenous shrinkage, using different amounts of IC water on two pairs of prismatic high-performance concrete specimens with dimensions of 7¾×7¾×39¼ in. (200×200×1000 mm). They reported that the inclusion of internal water resulted in a reduction in autogenous shrinkage, which corresponded to a reduction in the generation of tensile stresses.

Recent studies have shown the benefits of internal curing for mitigating drying shrinkage. Henkensiefken et al. (2009) examined internally-cured mortar mixtures (with different volumes of LWA) with a *w/c* ratio of 0.30 on free shrinkage tests (cured under sealed and unsealed conditions).

They observed that increasing the quantities of pre-wetted LWA resulted in decreased drying shrinkage. Browning et al. (2011) investigated the effects of vacuum-saturated LWA containing 5.4, 7.4, and 10.3% of IC water by the weight of binder on drying shrinkage in concrete. They reported that mixtures with IC exhibited less drying shrinkage during the first year after casting than mixtures without IC.

Another benefit of internal curing is in mitigating plastic settlement cracking (Henkensiefken et al. 2010, Ibrahim et al. 2019). Henkensiefken et al. (2010) examined the settlement of internally-cured mortar mixtures with IC contents ranging from 0 to 7.4% (by the weight of binder). They observed less settlement for mixtures containing IC than for a mixture without IC; the reduction of settlement increases with increasing the quantities of IC. In another study. Ibrahim et al. (2019) investigated the effects of internal curing water on settlement cracking of mixtures with slumps ranging from 3 to 8½ in. (75 to 215 mm). They concluded that IC using pre-wetted fine LWA decreased settlement cracking by 37% compared to mixtures without pre-wetted fine LWA throughout the range of slumps investigated. They also observed that the use of different LWA particle sizes (one with fine size LWA and one with pea-gravel size LWA) had a similar effect on reducing settlement cracking for the same total IC water content.

Although the effects have not been investigated extensively, limited studies suggest that internal curing limits ionic transport, which is affected by the volume and connectivity of concrete pores (Castro et al. 2011). In particular, using the rapid chloride permeability test (RCPT), Thomas (2006) and Lafikes et al. (2020) showed that ion permeability was lower in concrete with internal curing than in concrete without internal curing. Khayat et al. (2018) and Lafikes et al. (2020) also reported that the surface resistivity of mixtures increased when IC was used.

Studies indicate that improved cement hydration and strength development occurs in concretes that incorporate internal curing (Bentz and Weiss 2011, Castro 2011). The improved cement hydration is due to an increase in the available water; the improved hydration in turn increases the compressive strength of the concrete. Villarreal and Crocker (2007) reported that the compressive strength of IC mixtures was approximately 1000 psi (6.8 MPa) higher than that of mixtures without IC, suggesting that IC enhances cement hydration.

The amount of LWA required for IC depends on several factors, including the target quantity of IC water and the LWA absorption and desorption values, where absorption is the water holding capacity of LWA as a function of time and desorption is the loss of water from the pores of the LWA during drying as a function of relative humidity at a constant temperature (Castro 2011). Bentz and Snyder (1999) proposed an equation, Eq. (1.1), to estimate the amount of LWA required for IC mixtures.

The design quantity of W_{LWA} can be calculated as:

$$W_{LWA} = \frac{C_f \times IC}{\alpha \times \beta} \tag{1.1}$$

where C_f = Cementitious materials content (lb/yd^3)

IC = Target internal curing water (fraction of cementitious materials weight)

α = LWA absorption

β = LWA desorption at specified RH

The concept behind the proposed equation was to reduce the effects of autogenous shrinkage. ASTM C1761-17 includes a recommendation that IC water equal to 7% by weight of cementitious material to limit autogenous shrinkage. Although autogenous shrinkage is not common in bridge decks, where the *w/cm* ratio is usually above 0.42 (Mindess et al. 2003), an IC water content of 7 or 8% by weight of cementitious material is often used (Bentz and Weiss 2011, Bitnoff 2014, Barrett et al. 2015, Kansas Department of Transportation 2015, Lafikes et al. 2018).

As will be discussed in Section 1.8, the freeze-thaw durability and scaling resistance of internally-cured concrete can be compromised if an excessive quantity of IC water is used.

1.7 SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS)

The use of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (now described as slag cement), fly ash, and silica fume as partial replacements of portland cement, has become popular as means to improve durability, reduce chloride penetration, and reduce life cycle costs, including in concrete bridge deck construction (Russell 2004).

1.7.1 Slag Cement

Slag cement is a recovered industrial byproduct from pig iron production. It is rich in lime, silica, and alumina, with relatively higher silica content than portland cement. As molten slag is diverted from the blast furnace, it is rapidly chilled by quenching with water, forming hydraulically active calcium aluminosilicate glassy granules that have reactive cementitious properties when ground to cement fineness (Mindess et al. 2003). Based on the slag activity index, per ASTM C989-18, slag cement is categorized into three grades–80, 100, and 120. The slag activity index is calculated at 7 and 28 days and is defined as the ratio between the compressive strength of mortars made with a blend of 50% slag cement and 50% portland cement (by weight) to that of mortars made with 100% portland cement.

A partial replacement of portland cement with slag cement in concrete provides benefits to both fresh and hardened concrete properties. These include improved workability and pumpability, increased setting time, greater long-term strength gain, and decreased permeability compared to mixtures with 100% portland cement (Russell 2004).

Concrete with slag cement initially gains strength more slowly than concrete with 100% portland cement, raising the importance of adequate curing (Russell 2004). Tazawa et al. (1989)

reported when cured for 28 days, mixtures containing slag cement exhibited less shrinkage than mixtures containing portland cement as the only binder. They also observed that slag cement mixtures cured for 3 and 7 days exhibited greater shrinkage than the same mixtures cured for 28 days at the same drying time, as is true, in general, for all concretes. Autogenous shrinkage and early-age cracking have been observed in mixtures with high replacement volumes of slag cement without sufficient curing (Bentz and Weiss 2011, Shen et al. 2019). Li et al. (1999), however, reported no significant change in shrinkage strain of concrete containing a 50% replacement by weight of portland cement by slag cement, when compared to concrete containing portland cement as the only binder.

Hooton et al. (2009) examined the effect of slag cement on the drying shrinkage of concrete. They reported that, on an equal paste content basis, mixtures containing slag cement exhibited slightly less shrinkage (about 3%) than those containing portland cement as the only cementitious material, regardless of the slag cement content of the mixtures. Yuan et al. (2015) investigated different curing periods (7 and 14) for mixtures with a 60% volume replacement of portland cement by slag cement. They reported that the mixtures containing slag cement cured for 7 and 14 days exhibited lower shrinkage after 365 days of drying (12 and 19%, respectively) than those containing portland cement as the only binder.

The combined effects of internal curing water and slag cement have also been evaluated in a number of studies (Bentz 2007, Lindquist et al. 2008, Browning et al. 2011). Bentz (2007) reported that when IC was used in mixtures with a 20% replacement of portland cement with slag cement (by weight of binder) and *w/cm* ratio of 0.3, autogenous shrinkage was reduced significantly. For moderate *w/cm* ratios (0.43 to 0.45), which is the case for bridge decks, autogenous shrinkage is not an issue, and the combination of IC and SCMs can be used to reduce plastic and drying shrinkage cracking. Lindquist et al. (2008) found that for mixtures containing slag cement, those containing saturated high-absorption limestone as the coarse aggregate exhibited less shrinkage than mixtures containing a low-absorption coarse aggregate. Similar observations were made by Yuan et al. (2015).

1.7.2 Fly Ash

Fly ash, a by-product of the burning of pulverized coal in power plants, is used as a supplementary cementitious material in conjunction with portland cement (ACI Committee 232 2018). Fly ash can improve both fresh and hardened concrete properties. The benefits of using fly ash in plastic concrete include improved workability and pumpability without the addition of water, increased cohesiveness, reduced segregation, and improved finishability (Mindess et al. 2003, Russell 2004). The benefits of using fly ash in hardened concrete include reduced permeability and chloride penetration, increased resistivity, and resistance to acid sulfate attack (Russell 2004).

Based on chemical composition and the source of origin, fly ash is divided into two classes in accordance with ASTM C618-19: Class F and C. Class F and Class C fly ash are distinguished based on the major acidic contents (silicon dioxide [SiO_2], aluminum oxide [Al_2O_3], and iron oxide [Fe_2O_3]) as well as calcium oxide content (CaO). Class F fly ash is produced from bituminous and anthracite coals. It has pozzolanic properties and contains a minimum acidic oxide content of 50% as well as a maximum calcium oxide content of 18%. Class C fly ash, also known as high-lime ash, is produced from burning lignite or subbituminous coal. It has both pozzolanic and cementitious properties and contains a minimum acidic oxide content of 50% as well as a minimum calcium oxide content of 18% (Mindess et al. 2003, ASTM C618-19).

Yuan et al. (2011) evaluated the effects of the curing period on the free shrinkage of mixtures containing 40% fly ash by volume as a partial replacement of portland cement and mixtures containing portland cement as the only binder. They reported that Class F fly ash mixtures cured for at least 28 days exhibited less shrinkage than 100% portland cement mixtures. These mixtures, when cured for 7 and 14 days, however, exhibited higher and similar, respectively, shrinkage as corresponding mixtures without fly ash.

De la Varga et al. (2012) investigated the effects of IC in conjunction with mortar mixtures with low *w/cm* ratios containing different volumes (20, 40, and 60% by volume) of Class C fly ash. They reported that the combination of IC and fly ash resulted in increased compressive strength, decreased autogenous shrinkage and heat of hydration.

1.7.3 Silica Fume

Silica fume consists primarily of amorphous silicon dioxide (SiO_2) and is a by-product of the production of silicon and ferrosilicon. It consists of spherical particles with diameters approximately one hundredth the size of portland cement particles (Mindess et al. 2003). Due to the chemical and physical properties of silica fume, it is a highly reactive pozzolan that is often used to enhance the strength and reduce the permeability of concrete, reducing the corrosion of reinforcing steel (Maage and Sellevold 1987). In addition, the extremely small particles enhance the denseness of the pore structure by filling the gaps between the larger cement particles, particularly near the paste-aggregate interface.

Khatri and Sirivivatnanon (1995) evaluated drying shrinkage of mixtures containing silica fume and Class F fly ash. They reported that the combination of fly ash and silica fume increased drying shrinkage compared to a mixture containing only silica fume. Lindquist et al. (2008) observed that for mixtures containing a high-absorption coarse aggregate, the addition of silica fume or slag cement resulted in reduced drying shrinkage at all ages when the curing period was increased from 7 to 14 days. When cured for seven days, mixtures containing a low-absorption coarse aggregate in conjunction with either silica fume or slag cement exhibited increased early-age shrinkage. For these mixtures extending the curing period from 7 to 14 days resulted in a similar or slight reduction in both early-age and long-term shrinkage.

Pendergrass and Darwin (2014), Khajehdehi and Darwin (2018), and Feng and Darwin (2020) reported decreased drying shrinkage in concrete mixtures containing slag cement and silica fume as partial replacements of portland cement compared to mixtures containing portland cement as the only cementitious material. Additionally, Feng and Darwin (2020) reported that IC water in the range of 5.3 to 9.7% by the weight of binder to mixtures containing slag cement and silica fume reduced shrinkage after 365 days of drying, with decreases associated with an increasing the quantity of IC water.

1.8 FREEZE-THAW DURABILITY OF CONCRETE

Concrete subjected to periodic freezing-thawing cycles in moist conditions can deteriorate due to several mechanisms. The presence of cracks can also contribute to freeze-thaw damage as they expose a greater surface area of the concrete to moisture and chlorides from deicing salts. Deicing chemicals, commonly used during winter months to ensure road safety in icy conditions, increase the risk of concrete surfaced scaling (Esmaeeli et al. 2017).

Concrete durability can be improved by increasing the curing period, which leads to increased hydration, compressive strength, and lower permeability. Unfortunately, this is not always attainable in the field. Bridge decks constructed a few months before winter are at particular risk if they have not fully cured and dried before being subjected to deicing salts and freezing-thawing cycles. The following sections highlight the primary mechanisms of freeze-thaw damage in the cement paste and aggregates and discuss the phenomenon of surface scaling caused by deicing salts.

1.8.1 Cement Paste Freeze-Thaw Damage Mechanism

The freeze-thaw resistance of cement paste is affected by porosity, capillary pore sizes, and solute concentration in pore water, as well as the pore water movement within the paste (Mindess et al. 2003). Two primary causes of freeze-thaw damage (frost damage) in cement paste are osmotic pressure and the desorption of water (Powers and Helmuth 1953, Mindess et al. 2003, Mehta and Monteiro 2006).

In contrast with ice, water in capillary pores is not pure–instead it contains various solute compounds such as chlorides and alkalis. With the formation of ice in larger capillary pores, the concentration of the remaining pore solution increases, resulting in a concentration differential near the freezing site and smaller pores. As a result, water flows from more dilute pores (smaller pores with a lower concentration solution) to the freezing sites due to osmotic pressure (Mindess et al. 2003). This caused tensile stresses in the surrounding paste produced by local dilation, which can subsequently lead to cracking.

The desorption of water, which promotes an additional movement of water through a separate mechanism, was proposed by Litvan (1970). The freezing point of the water in the capillary pores depends on the size of the pore (more specifically, the diameter of the pore neck). Gel pore diameter is so small that the adsorbed water on the surface of calcium silicate hydrate (C-S-H) cannot freeze at temperatures above -108 °F (-78 ºC) (Mehta and Monteiro 2006). As a result, water in the smaller pores will supercool rather than freeze at temperatures below 32 °F (0 ºC). On the other hand, water in larger pores can freeze. At temperatures below 32 °F (0 ºC), water has a higher chemical potential than ice; therefore, water will flow from smaller pores towards freezing sites (with larger pores) to maintain equilibrium. As such, unfrozen areas experience shrinkage while frozen sites expand as water moves to the site and more ice forms. If sufficient water flows to capillaries and freezes, internal pressure develops, eventually leading to cracking (Powers 1975, Mindess et al. 2003, Mehta and Monteiro 2006).

As discussed next in Section 1.8.1.1, air entrainment, where small air bubbles are intentionally formed in concrete, and the use of a low water-to-cementitious material (*w/cm*) ratio within specified limits, can effectively protect cement paste from freeze-thaw damage.

1.8.1.1 Durability Effects of Air Entrainment

The use of air entrainment is an effective way to increase the durability of concrete in the presence of water and deicing salts, as entrained air produces extra empty spaces (air voids) within the paste for excess water to travel and freeze without causing stress within the cement paste. Klieger and Hanson (1961) observed that air-entrained mixtures exhibit significantly higher freeze-thaw and scaling resistance than non-air-entrained mixtures. Entrained air voids serve as a reservoir for ice and pore solution such that they allow water to freeze inside them (instead of capillary pores) at or near 32 °F (0 °C) due to their larger sizes compared to the capillary pores, reducing damage. Additionally, through osmosis pressure and desorption water mechanisms, the saturation level of surrounding paste decreases as water moves into adjacent voids (Mindess et al. 2003). Mindess et al. (2003) reported that air contents ranging from 2 to 8% (based on the maximum size of coarse aggregate, by concrete volume) are required to provide satisfactory frost resistance.

An important aspect to note is that concrete with a higher air content alone is not necessarily protected from freeze-thaw damage. The air void system must provide small, closely spaced, uniformly distributed air voids. The primary parameters, also known as air-void parameters, representing an air void system include the spacing factor, specific surface area, and air content

(ASTM C457-16). The air void spacing factor is defined as an approximation of the average distance that pore water must travel from anywhere in the cement paste to reach the nearest air void. The specific surface area is defined as the ratio of the surface area of air voids to the air void volume (ASTM C457-16).

Studies suggest an air-void spacing factor of 0.008 in. (0.20 mm) or less and a specific surface area greater than 600 in.$^{-1}$ (25 mm^{-1}) are needed to improve frost resistance (Mindess et al. 2003, Russell 2004). In addition to the recommended values for spacing factor and specific surface area, ACI Committee 201 (2016) suggests that air contents be a function of the nominal maximum size aggregate for different freezing-thawing exposure classes. For example, it is suggested an air content between 5 and 8% for mixtures with a nominal maximum size aggregate of ¾ or 1 in. (19 or 25 mm) under moderate exposure to freezing-thawing cycles to provide satisfactory frost protection. LC-HPC specifications for bridge deck construction, however, require higher air contents (6.5 to 9.5%), not only to provide adequate durability and strength but also to reduce cracking (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Kansas Department of Transportation 2015). It is also important to note that some types of admixtures used in conjunction with air-entraining admixtures may affect the air void system by reducing air-void stability, leading to reduced freeze-thaw resistance (Pendergrass and Darwin 2014).

1.8.1.2 Durability Effects of Water-to-Cementitious Material Ratio

In addition to an adequate air void system, the water-to-cementitious material ratio (*w/cm*) also impacts the durability of concrete subjected to freezing-thawing cycles. A higher *w/cm* ratio, results in higher permeability due to an increase in the volume and size of capillary and gel pores. The effects of the *w/cm* ratio on permeability, however, are influenced more by larger capillary pores than gel pores (Mindess et al. 2003). Similarly, a lower *w/cm* ratio results in decreased permeability due to a reduction in the porosity of the paste as well as improvement in the pore structure. A lower *w/cm* ratio also leads to increased compressive strength and enhanced durability (Mindess et al. 2003). Many bridge deck specifications often list a maximum *w/cm* ratio limit to ensure adequate freeze-thaw resistance and permeability (Russell 2004). According to LC-HPC specifications, the *w/cm* ratio may not exceed 0.45 (Kansas Department of Transportation 2015).

1.8.2 Aggregate Freeze-Thaw Damage Mechanisms

The durability of concrete can be compromised even in properly air-entrained concrete with a dense pore structure due to the failure of saturated aggregate particles (Powers 1975). Most aggregates typically have larger pores than those in cement paste that are most easily filled with water. Additionally, due to the larger pore sizes, the freezing point of water in aggregate pores is at or near 32 °F (0 °C). In contrast to the freeze-thaw damage mechanism in cement paste, osmosis pressure and desorption water play less of a role in the water movement of concrete containing larger aggregate pores.

The primary contributor to freeze-thaw damage in aggregates is hydraulic pressure, resulting from ice formation within the aggregate pores (ACI Committee 201 2016). When water freezes, it undergoes a volumetric expansion of nearly 9%, which will push the excess water away from the freezing sites, inducing hydraulic pressure within the aggregate. The pore water must flow through a distance within the aggregate to reach an exterior boundary to relieve the hydraulic pressure. Freeze-thaw damage and fractures within the aggregates occur when this distance is too great or when the degree of saturation of the aggregate is too high (Mindess et al. 2003). The critical degree of saturation is defined as the ratio of the absolute volume of absorbed water to the total volume of concrete pores, beyond which damage initiates upon freezing (Li et al. 2012). The hydraulic pressure can also expel the excess water from the aggregate pores and pressurize the surrounding cement paste. This pressure can cause cracking at the interfacial transition zone (ITZ) between paste and aggregate (Mindess et al. 2003).

The potential for freeze-thaw damage is more pronounced for aggregates with fine pores, high absorption, and high permeability. One particular concern about internal curing using pre-wetted LWAs is that a greater amount of absorbed water is released and forced into the surrounding paste once frozen (Cusson and Margeson 2010, Jones et al. 2014). Klieger and Hanson (1961) reported that the freeze-thaw durability of mixtures with air-dried lightweight aggregates is similar to that of mixtures with normalweight aggregates when adequately air-entrained. They observed, however, that for non-air entrained mixtures containing pre-wetted LWA (soaked between 18 and 24 hours), the freeze-thaw damage increased.

The freeze-thaw durability of concrete mixtures with a *w/cm* ratio of 0.42 with and without IC was assessed by Jones et al. (2014). They observed that for a *w/cm* ratio of 0.42, the dynamic modulus of elasticity of mixtures with more IC water than needed to reduce autogenous shrinkage dropped in fewer cycles than it did for mixtures without IC and with IC water content that was just adequate to mitigate autogenous shrinkage. The latter mixtures exhibited satisfactory freeze-thaw performance after 300 cycles at a *w/cm* ratio of 0.42. A complementary study by Feng and Darwin (2020) showed that the freeze-thaw durability of IC mixtures containing slag cement and silica fume decreased as the quantity of IC water increased from 5.3 to 9.7% (by total weight of binder).

1.8.3 Salt Scaling

The scaling resistance of concrete can be compromised in the presence of deicing salts and freezing-thawing cycles, even with durable aggregates or air-entrained concrete. Scaling refers to the loss of mortar and surface aggregates as a result of damage to the surface layer of concrete. While deicing salts are used to ensure safe road driving conditions in cold weather, salt solutions (due to having a lower vapor pressure than pure water) at the concrete surface create an environment with a lower evaporation rate and a higher degree of saturation compared to the concrete surface without exposure to deicing salts (Esmaeeli et al. 2017). The increased amount of free moisture at the surface further accelerates the growth of ice lenses, which fracture the concrete surface and mortar particles.

Deicing salts can also cause a rapid drop in temperature just below the concrete surface. Damage can occur due to induced thermal strains, which lead to increased tensile stresses and cracking (Mindess et al. 2003). Additionally, the increased solute content of the concrete pore solution causes concrete surface damage due to osmotic pressures (Mindess et al. 2003). Unfortunately, scaling damage is a progressive phenomenon. Small flakes from the concrete surface expose fine and coarse aggregates, resulting in larger pop-outs over time. Valenza and Scherer (2007a) reported that surface scaling resistance could be improved by providing proper air entrainment, which enhances freeze-thaw resistance and decreases bleeding water at the surface.

One of the primary mechanisms that causes concrete scaling is termed "Glue Spall," which gains its name from a technique used in the epoxy-coated glass industry (Valenza and Scherer 2007b). According to the "Glue Spall" theory, as the salt solution freezes, a brine/ice layer is formed at the concrete surface. As temperature drops below the melting point of the solution, the ice layer breaks into small shards as it contracts. Due to the difference in the coefficients of thermal expansion between ice and underlying concrete (ice has a thermal expansion coefficient about five times greater than that of concrete), tensile stresses are induced, resulting in cracking on the concrete surface (Valenza and Scherer 2007b).

In addition to the mechanism described above, concrete durability can be compromised due to reactions between deicing salts (such as calcium chloride) and concrete as the result of the formation of calcium oxychloride. Calcium oxychloride ($3Ca(OH)_2.CaCl_2.12H_2O$) forms when the calcium hydroxide ($Ca(OH)_2$) produced during the hydration of portland cement reacts with the salt solutions, as shown in Eq. (1.2) (Collepardi et al. 1994).

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow 3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O \tag{1.2}$$

For concretes exposed to calcium chloride deicers, the formation of calcium oxychloride is dependent on the concentration of the $CaCl_2$ solution and the temperature. Figure 1.4 shows an isopleth for the calcium oxychloride phase diagram constructed by Qiao et al. (2017). Calcium oxychloride is expansive and causes tensile stresses and deterioration in concrete (Sutter et al. 2008). This is specifically the case for scaling tests such as ASTM C672 that use calcium chloride ($CaCl_2$) as a deicing salt, which really tests both scaling and calcium oxychloride resistance. Consequently, the scaling tests conducted in accordance with ASTM C672 appear to exhibit increased damage due to both scaling and formation of calcium oxychloride. Although ASTM C672 has been withdrawn, the common tests used in the U.S. and Canada to assess the scaling resistance of concrete are still ASTM C672 and Quebec standard BNQ NQ 2621-900. As described in Chapter 2, a 4% $CaCl_2$ solution is used for ASTM C672 and a 3% NaCl solution is used for Quebec standard BNQ 2621-900 test.

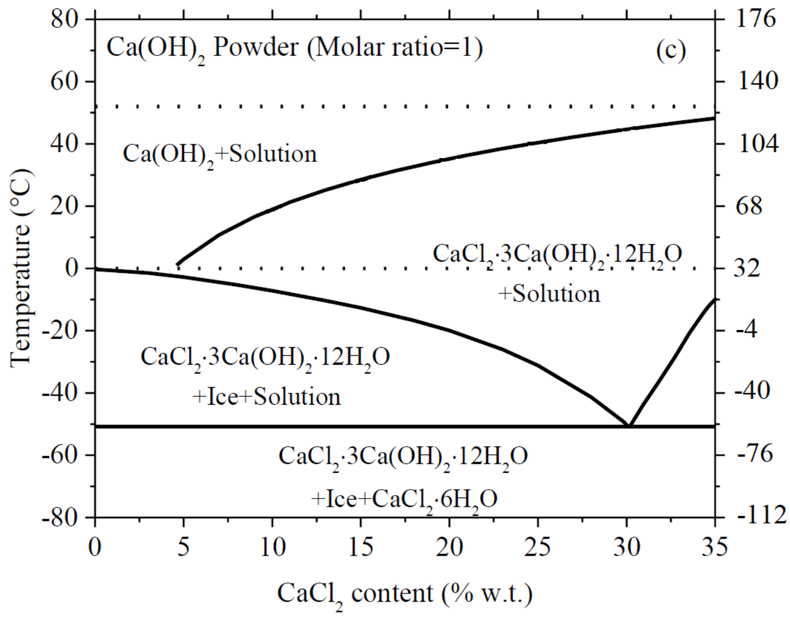


Figure 1.4. The isopleth of the phase diagram of calcium oxychloride (Qiao et al. 2017) - *modified*

The use of SCMs in concrete can impact scaling resistance and calcium oxychloride formation, where the extent of scaling and calcium oxychloride reductions depend on the type of SCM and the replacement level. Although the effects of binder composition, deicing salt, salt concentration, and exposure conditions on the durability of concrete have been investigated by many researchers, a consensus has yet to be reached about scaling resistance of concretes containing SCMs as a partial replacement of portland cement (Talbot et al. 2000, Sutter et al. 2008, Bouzoubaâ et al. 2008, Hooton and Vassilev 2012, Abdul Baki et al. 2020).

In some studies, concretes with SCMs have shown reduced scaling resistance when tested in accordance with ASTM C672. This reduction has been attributed to the fact that SCMs develop their properties slowly and do not reach maturity when exposed to freezing-thawing cycles as rapidly as concretes containing portland cement as the only binder (Hooton and Vassilev 2012). Other studies, however, have reported improved durability for concretes with SCMs by mitigating alkali-silica reaction, reducing permeability, and improving resistance to sulfate attack (Mindess et al. 2003). Additionally, studies have found that for concretes containing SCMs, the decreased quantity of calcium hydroxide available to react with calcium chloride reduces calcium oxychloride formation (Sutter et al. 2008).

Talbot et al. (2000) and Bouzoubaâ et al. (2008) found that the addition of fly ash to mixtures leads to more scaling compared to control mixtures (without fly ash), with increased fly ash levels leading to even more scaling. The scaling resistance of concrete with two different slag cements (Grade 100 and 120) and different replacement levels (0, 20, 35, and 50% by weight of binder) was investigated by Hooton and Vassilev (2012). The scaling testing was performed in accordance with ASTM C672 and a modified BNQ 2621-900 incorporating similar freeze-thaw increments/cycles as ASTM C672 (5, 10, 15, 25, and 50 cycles). They reported that reducing the *w/cm* ratio from 0.42 to 0.38 improved scaling resistance, regardless of slag grade, slag cement content, and salt solution. They also reported that mixtures containing portland cement as the only binder exhibited a higher mass loss when tested according to ASTM C672 than when tested per the modified BNQ 2621-900. Mixtures containing 50% slag cement contents, however, exhibited a lower mass loss when tested per ASTM C672 than when tested per the modified BNQ 2621-900. Abdul Baki et al. (2020) investigated the effects of different replacement levels of portland cement (0, 20, 35, and 50% by weight of binder) with either slag cement or Class C fly ash on concrete durability as affected by scaling and the formation of calcium oxychloride. They reported that for concrete mixtures with portland cement as the only binder and mixtures with a 20% volume replacement of portland cement with slag cement, $CaCl_2$ caused more scaling than NaCl. Moreover, for mixtures with a 50% volume replacement of portland cement with either slag cement or Class C fly ash, NaCl caused more scaling damage than $CaCl_2$. They suggested that a 35% volume replacement of portland cement with slag cement can serve as the maximum acceptable replacement level for having durable concrete potentially subjected to both NaCl and $CaCl_2$. These findings clearly show the role of deicing salts in the formation of calcium oxychlorides and deterioration in concrete.

In another study, Pendergrass and Darwin (2014) investigated the effects of silica fume on the scaling resistance of concrete specimens. They reported that the addition of 3% silica fume to mixtures containing 30% slag cement (by volume of binder) led to even more scaling, with higher amounts of silica fume (from 3% to 6%) worsening scaling damage.

Other factors, such as the use of internal curing with or without supplementary cementitious materials, the concentration of the salt solution, overfinishing, and over consolidation, also impact scaling. Pendergrass and Darwin (2014) and Feng and Darwin (2020) evaluated mixtures with IC in combination with SCMs and found they exhibited more scaling than mixtures containing portland cement as the only binder. Feng and Darwin (2020) showed that mixtures containing either 0 or 6.5% IC water (by the weight of the binder) with only portland cement as the binder exhibited satisfactory scaling resistance. They reported, however, that mixtures containing either 5.3% or 6.5% IC water (by weight of binder) with partial replacements of portland cement with slag cement and silica fume exhibited poor scaling performance and failed the test. In another study, Jones et al. (2014) reported no negative impact of internal curing on the scaling resistance of mixtures containing 20% replacement of portland cement with Class F fly ash.

The salt solution concentration can also have an impact on the extent of scaling in line with the mechanisms described above, with the greatest effects appearing with salt concentrations between 2 to 4% for both calcium and sodium chlorides (Verbeck and Klieger 1957). During construction, concrete can be significantly jeopardized to have a higher scaling risk due to overfishing or over consolidation procedures, resulting in excessive paste content, higher air-void spacing factors, and increased local *w/cm* ratio near the surface.

Similar to freeze-thaw mechanism, the most effective way to reduce scaling damage is by providing adequate air entrainment. The presence of air voids in concrete mitigates differences in vapor pressure between water and ice, reduces bleeding water in plastic concrete, and provides additional freezing spaces outside cement paste capillaries. Additionally, the use of low-permeability concrete through the use of low *w/cm* ratios can slow the rate of penetration of salt solutions into concrete, which further reduces scaling damage (Mindess et al. 2003, Valenza and Scherer 2007a).

Studies have demonstrated that different methods of testing durability (testing with different deicing salts and curing periods) can result in inconclusive findings regarding freeze-thaw durability and scaling resistance (Abdul Baki et al. 2020). Therefore, experimental investigations are required to evaluate the freeze-thaw durability and scaling resistance of IC mixtures under different testing procedures.

1.9 PREVIOUS WORK ON THE EFFECTS OF PASTE CONTENT AND INTERNAL CURING ON CRACKING AND DURABILITY OF BRIDGE DECKS

Based on research at the University of Kansas (KU) with the participation of nineteen state departments of transportation, the Federal Highway Administration (FHWA), and industry, low-cracking high-performance concrete (LC-HPC) specifications were established to improve the cracking performance of bridge decks (Schmitt and Darwin 1995 and 1999, Darwin et al. 2004, Lindquist et al. 2005, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Alhmood et al. 2015, and Darwin et al. 2016). The LC-HPC specifications were implemented in a two-phase Pooled-Fund study, *Construction of Crack-Free Bridge Decks,* which involved the construction of 16 bridge decks between 2005 and 2011 in Kansas. LC-HPC mixtures have low paste contents (below 24.6%) to reduce shrinkage, low slump (1½ to 3 in. [40 to 75 mm] to limit settlement cracking and limitations on both the maximum and the minimum compressive strengths (5500 and 3500 psi, respectively [37.9 and 24.1 MPa]). In bridge decks, where a high degree of restraint exists, the higher compressive strength decreases creep and increases tensile stresses. The LC-HPC specifications also require an air content between 6.5 to 9.5%. LC-HPC specifications also address construction procedures, including limitations on concrete temperature, and requirements for thorough consolidation, minimal finishing, and early initiation and an extended curing application (Darwin et al. 2016). Annual crack surveys performed on bridge decks constructed in accordance with LC-HPC specifications demonstrated improved cracking performance compared to control decks in the study (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Alhmood et al. 2015, Darwin et al. 2016).

Building upon the success of the LC-HPC decks, other crack reducing technologies are available for investigation. One of those technologies involves internal curing (IC) in conjunction with supplementary cementitious materials. Early application of IC involved mixtures with low *w/cm* ratios (below 0.42) that were susceptible to autogenous shrinkage (Castro et al. 2011, Barrett et al. 2015, and Jones et al. 2014). Only a few laboratory studies have investigated the effects of IC on the shrinkage and durability of concrete specimens with *w/cm* ratios between 0.43 and 0.45, values typically used in the construction of bridge decks, where self-desiccation and autogenous shrinkage are not of concern (Khayat et al. 2018, Lafikes et al. 2020).

The New York State Department of Transportation (NYSDOT) developed a program to investigate the benefits of internal curing along with SCMs (fly ash and silica fume) by constructing several bridges throughout the state (Streeter et al. 2012). Bridge decks with a ternary binder system (cement, slag cement, and silica fume, or cement, fly ash, and silica fume) in conjunction with IC have also been constructed in Ohio (Delatte et al. 2007).

Bitnoff (2014) conducted field crack surveys of four bridges, two with and two without IC (identified here as UT-IC and UT-Control, respectively), supported by prestressed girders with partial-depth precast concrete deck panels in Utah for two years. All decks had a *w/cm* ratio of 0.44, a binary system (with partial replacements of portland cement with fly ash), and a paste content of 28%. The two IC decks were proportioned to provide a nominal IC water content of 7% by the weight of binder. As shown in Figure 1.5, the 24-month crack densities reported by Bitnoff ranged from 0.43 to 1.148 m/m^2, representing poor cracking performance even when IC is used. In a parallel study, also illustrated in Figure 1.5, Shrestha et al. 2013 and Khajehdehi and Darwin 2018 investigated a series of bridge decks, also with partial-depth precast concrete deck panels, (KS-DP) in Kansas with paste contents of either 24.0 or 24.8%. The results show that the Kansas deck panels exhibited significantly less cracking than the UT decks at a similar age, demonstrating the dominant effect of paste content in cracking (Khajehdehi and Darwin 2018).

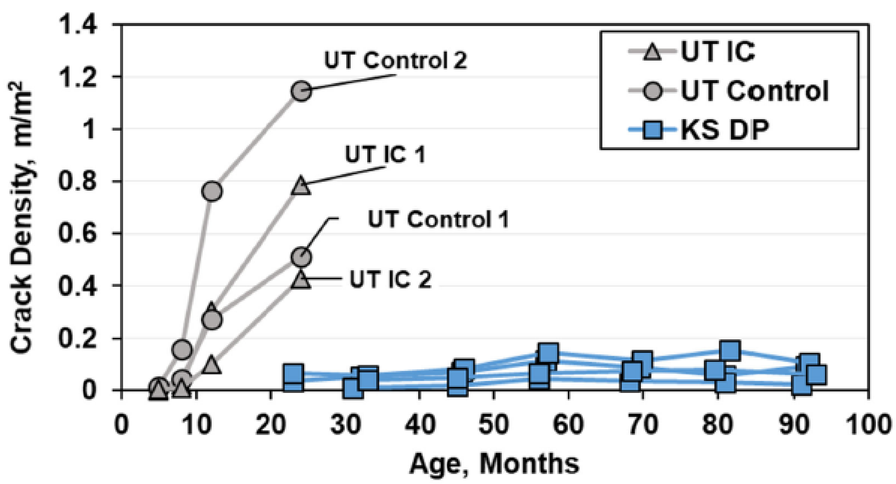


Figure 1.5. Crack density vs. age for deck panels in Kansas and Utah (Khajehdehi and Darwin 2018)

Schlitter et al. (2010) and the Indiana Department of Transportation (INDOT) investigated the development of internally-cured concrete for use in Indiana and evaluated the shrinkage and durability of the mixtures. They reported a considerable reduction in autogenous and drying shrinkage of IC mortar mixtures compared to mixtures without IC. Additionally, their results illustrated that the relative dynamic modulus of elasticity of mixtures with IC water contents of 2.7 and 5.3% by the weight of binder and a *w/c* ratio of 0.30 remained above 100% of the initial value through 300 freezing-thawing cycles. Using the findings of Schlitter et al., Di Bella et al. (2012) and Barrett et al. (2015) documented the construction of a series of IC and control (with no IC) decks in Indiana. One IC and one control deck containing portland cement as the only binder (identified here as IN-IC and IN-Control, respectively) were constructed in 2010. Both decks had a *w/cm* ratio of 0.39 and a paste content of 27.6%. The nominal quantity of IC water was 7% by the cement weight (Di Bella et al. 2012). In addition to these decks, four IC decks containing a ternary binder system (identified here as IN-IC-HPC, with partial replacements of portland cement with either slag cement and silica fume or fly ash and silica fume) were constructed between 2013 and 2015. These decks had *w/cm* ratios ranging from 0.40 to 0.43 and lower paste contents than the first decks, between 24.6 and 26.0%. They were designed for a nominal IC water content of 8% by total weight of binder (Barrett et al. 2015).

Although crack surveys were performed 12 and 20 months after the construction of the IC and control decks placed in 2010, Di Bella et al. did not report measured crack densities. Similarly, crack densities were not reported by Barrett et al. (2015). To quantify the cracking performance in the Indiana decks, Lafikes et al. (2018, 2020) conducted field surveys of these decks between 2016 and 2018. As shown in Figure 1.6, the results of those surveys, as well as the results of the crack surveys of the Utah IC decks (UT-IC), also shown in Figure 1.5, support the dominant effect of paste content on cracking. This observation is in line with the findings dating back over two decades ago by KU researchers who found that increased paste content, independent of other factors, results in increased cracking (Schmitt and Darwin 1995, Miller and Darwin 2000, Darwin et al. 2004, Lindquist et al. 2008, Khajehdehi and Darwin 2018, Khajehdehi et al. 2021). Decks with paste contents below 27% (by volume) exhibited less cracking than decks with higher paste contents (such as UT-IC, IN-IC, and IN-Control). Lafikes et al. (2018, 2020) reported that the decks in Indiana with a ternary binder system and IC exhibited less cracking than the IC and control decks constructed in 2010 (with portland cement as the only binder and higher total paste contents) within 36 months of construction.

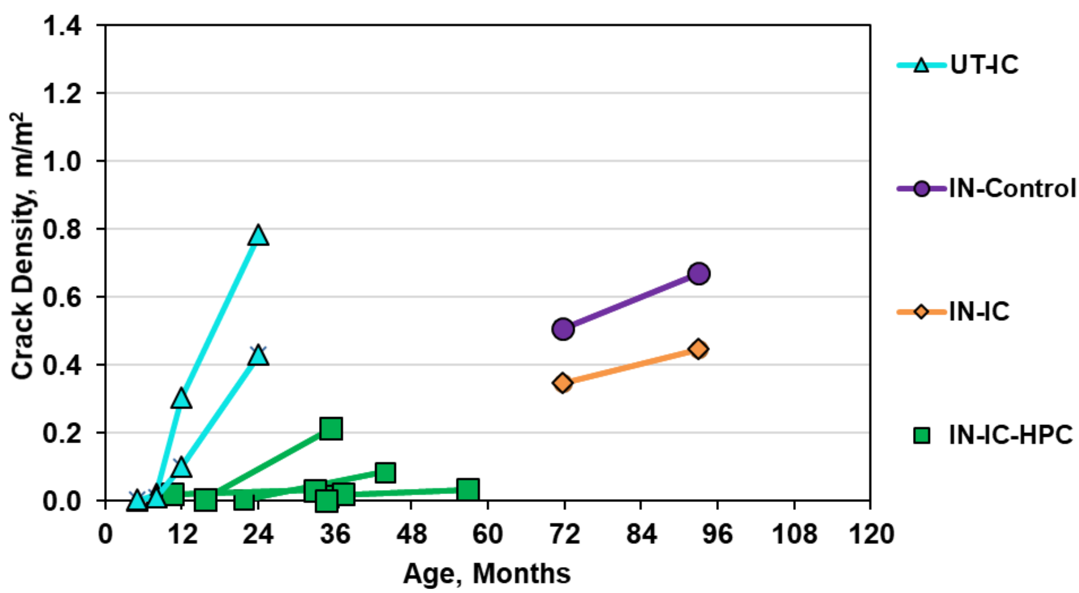


Figure 1.6. Crack density vs. age for Indiana decks (IC and control) and Utah IC decks (Lafikes et al. 2020)

Lafikes et al. (2020) conducted field surveys of two bridge decks without IC (as control decks) and four decks with IC and SCMs between 2017 and 2020 in Minnesota. All decks were supported by prestressed concrete girders. Three of the decks (two IC decks and one control deck) received a 2-in (51-mm) thick overlay that contained no IC. The IC decks had *w/cm* ratios ranging from 0.42 to 0.44, with quantities of IC water ranging from 6.5 to 8.6% by weight of cementitious material. The paste content of the sub-decks ranged from 25.0 to 25.8% (the 2-in. overlays had a paste content of 34.3%). Lafikes et al. observed that for decks without overlays, the use of IC and SCMs reduced bridge deck cracking compared to control decks. No improvement, however, was noted for the two IC bridge decks with an overlay, and higher amounts of cracking were reported for these decks than for the decks without an overlay. Previous studies have shown that due to higher restraint provided by steel girders, in general, decks supported by steel girders exhibit higher crack densities than those supported by prestressed concrete girders (Shrestha et al. 2013, Darwin et al. 2016, Lafikes et al. 2020). Although the decks in Minnesota were supported by prestressed concrete girders, the increased cracking on decks with overlays matches the observations by Miller and Darwin (2000), Lindquist et al. (2005), Yuan et al. (2011), Pendergrass and Darwin (2014), and Darwin et al. (2016) on decks with overlays supported by steel girders.

As discussed above, although bridge decks with IC and SCMs have been constructed recently in a number of states, only in this study has this technology been applied in conjunction with Kansas LC-HPC specifications. Also, although internal curing technology has been demonstrated to be beneficial in mitigating early-age and long-term shrinkage, concerns exist as to the freeze-thaw durability and scaling resistance of IC mixtures with or without SCMs as partial replacements of portland cement (Pendergrass and Darwin 2014, Jones and Weiss 2014, Khajehdehi and Darwin 2018, and Lafikes et al. 2020).

Jones and Weiss (2015) evaluated the freeze-thaw durability of internally-cured concrete mixtures in accordance with ASTM C666-Procedure A. The mixture proportions included a binary binder composition including 20% Class F fly ash (by weight of cementitious material) with *w/cm* ratios of 0.36, 0.48, and 0.56. The mixtures were designed to provide a nominal internal curing water content of 6% by weight of the binder, provided by pre-wetted fine lightweight aggregate.

They reported that the mixture with the *w/cm* ratio of 0.56 demonstrated poor freeze-thaw performance compared to the mixtures with *w/cm* ratios between 0.36 and 0.48. They also concluded that if sufficient air content is provided, IC mixtures with *w/cm* ratios up to 0.48 subjected to freezing-thawing cycles are durable.

In another study, Lafikes et al. (2020) evaluated the durability of 64 concrete mixtures with different binder composition systems (100% portland cement, binary [cement and slag], and ternary [cement, fly ash, and silica fume]). They found that the scaling resistance of IC mixtures with SCMs was compromised for mixtures with air contents below 7%. Additionally, they recommended that the freeze-thaw resistance of the IC specimens is better correlated with the total absorbed water content (water absorbed by all aggregates) than the quantity of IC water in the LWA. Lafikes et al. (2020) concluded that concrete mixtures with total absorbed water contents greater than 12% exhibit failures in fewer freeze-thaw cycles than mixtures with total absorbed water below 12% by weight of binder. This conclusion is in line with the observations of these researchers when they surveyed the IC decks constructed in Indiana, as mentioned earlier. Indiana IC decks had nominal IC water contents of 7 or 8%, but the actual IC water contents ranged from 7.2 to 12.0%, with total absorbed water content between 9.7 and 17.6% by weight of binder. They reported freeze-thaw and scaling damage in relatively young placements (approximately 33 to 57 months after the construction) with higher quantities of IC water (8.5 to 12% by weight of cementitious material) and *w/cm* ratios ranging from 0.40 to 0.43. The poor durability performance of these decks was attributed mainly to low air contents (mostly below 7%), date of placement (cured in cold ambient temperature), poor surface finishing, and high total absorbed water contents (14.7 to 17.6% by weight of cementitious material). No significant freeze-thaw or scaling damage, however, was observed for the IC deck with 7.2% IC water (9.7% total water content) and a *w/cm* ratio of 0.39, approximately 93 months after the construction.

1.10 OBJECTIVE AND SCOPE

The overall objective of this study is to investigate the cracking and durability of concrete bridge decks employing internal curing to determine the proper quantity of internal curing water needed to construct low-shrinkage and durable bridge decks based on binder composition, cement paste content, and water-to-cementitious material (*w/cm*) ratio. Concrete mixtures incorporating internal curing, used in conjunction with slag cement with or without small amounts of silica fume (as partial replacements of portland cement), are investigated in both the laboratory and the field.

In the lab, a number of concrete mixtures with different quantities of internal curing water, binder compositions, paste contents, and water-to-cementitious material ratios are cast and tested. The field evaluations involve construction observations and crack surveys of bridge decks in Kansas and Minnesota.

In prior work, when constructing bridge decks using concrete mixtures with internal curing, increasing the quantity of internal curing water as a function of binder weight, without an upper limit, has been considered an appropriate way to ensure that the advantages of internal curing are achieved. Recent studies involving freeze-thaw testing of internally-cured concrete mixtures, however, have shown that increasing the quantity of internal curing water as a function of binder weight decreases freeze-thaw durability in both the lab and the field (Lafikes et al. 2020). Additionally, in prior studies, few attempts have been made to investigate the effects of different total absorbed water content (absorbed water in all aggregates) on the freeze-thaw durability of concrete.

Laboratory evaluations in this study involve three test programs. To help establish an upper limit on IC water and determine if such a limit should be based on (1) IC water as a percentage of binder weight or (2) total weight of IC water per unit volume of concrete, the freeze-thaw durability of concrete mixtures with *w/cm* ratios typical of those used in bridge-deck construction and different paste contents were evaluated for 39 concrete mixtures in test Programs I and II. To determine the effects of total internal water or TI water (provided by all aggregates) in internally-cured concrete eight mixtures were evaluated in test Program III.

In the field studies, the effectiveness of internal curing (IC), along with supplementary cementitious materials (SCMs), is further evaluated, providing insight into the practical application of IC considering construction practices. As previous studies have indicated, the effectiveness of crack reducing technologies is not always achievable without following proper construction practices (Khajehdehi and Darwin 2018, Feng and Darwin 2020, Lafikes et al. 2020). Therefore, there is also a need to address construction issues related to IC, which are considered in relation to observations of previous studies.

1.10.1 Laboratory Evaluations of Internally-Cured Concrete Mixtures for Improved Durability and Decreased Shrinkage

In Program I, 27 concrete mixtures with paste contents of 23.7, 26.7, or 33.7%, containing 100% portland cement as the binder and nominal IC water contents of 9 or 13% by the weight of binder are evaluated for freeze-thaw durability following ASTM C666-Procedure A.

In Program II, 12 concrete mixtures, also with paste contents of 23.7, 26.7, or 33.7%, containing 100% portland cement as the binder, and nominal IC water contents of 9 or 13% by the weight of binder, are evaluated for both freeze-thaw durability and scaling resistance. The freeze-thaw performance of the mixtures is investigated following both ASTM C666-Procedure A and the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22, Resistance of Concrete to Rapid Freezing and Thawing, that includes the use of ASTM C666-

Procedure B. Scaling resistance is evaluated for eight of the mixtures in accordance with ASTM C672 and a modification of Canadian test BNQ NQ 2621-900. The testing modifications include minor differences in the temperature range during freezing-thawing periods and relative humidity, as well as a different screen size to measure mass loss. Using these two testing procedures provides an improved understanding of the effects of different quantities of IC water and different deicing salts on the freeze-thaw durability and scaling resistance of concrete and provides guidance for the development of future specifications.

Program III includes eight concrete mixtures (six IC and two control mixtures) and investigates shrinkage, freeze-thaw durability, scaling resistance, and permeability. The primary variables considered in this program include cementitious material compositions (two include only portland cement and six include a ternary binder composition including slag cement and silica fume), nominal quantities of internal curing water provided by pre-wetted lightweight aggregate (equal to 0, 6, and 9% by weight of binder), and different coarse aggregates (low absorption limestone, high absorption limestone, and granite). Mixtures without IC water serve as control mixtures. The quantity of total internal water for mixtures with only portland cement as the binder is either 3.4 or 8.7%. The quantities of total internal water for ternary binder composition mixtures range from 3.0 to 12.5%. The mixtures in this program are evaluated for free shrinkage in accordance with a modified version of ASTM C157 (readings begin just after final set), scaling resistance in accordance with ASTM C672, freeze-thaw durability in accordance with ASTM C666-Procedure A, rapid chloride permeability (RCP) in accordance with ASTM C1202, and surface resistivity measurement (SRM) per AASHTO TP-95 and Louisiana Department of Transportation and Development (LA DOTD TR 233-11). Results obtained from RCP and SRM testing are compared.

1.10.2 Field Studies: Construction and Evaluation of Internally-Cured Low-Cracking High-Performance Concrete Bridge Decks

The field studies aim to determine the effectiveness of internal curing (IC) along with supplementary cementitious materials (SCMs) used in five bridge decks in Minnesota constructed between 2018 and 2020 in accordance with Minnesota internally-cured high-performance concrete (IC-HPC) specifications and four bridge decks in Kansas constructed between 2019 and 2022 in accordance with Kansas internally-cured low-cracking high-performance concrete (IC-LC-HPC) specifications, to develop recommendations that help to minimize or prevent cracking of bridge decks. Crack surveys are conducted up to three years after the construction of the bridge decks, and cracking performance is reported in terms of crack density. The importance of following good construction procedures is discussed in light of previous research, which indicates that poor procedures can reduce the effectiveness of crack-reducing technology. The construction procedures, concrete properties, and documented field observations help provide guidance for the construction of future IC-LC-HPC decks.

CHAPTER 2 – LABORATORY TEST PROGRAM FOR INTERNALLY-CURED MIXTURES WITH OR WITHOUT SUPPLEMENTARY CEMENTITIOUS MATERIAL

2.1 GENERAL

For decades, cracking has been a major problem for transportation agencies that can increase maintenance costs and reduce the service life of bridge decks. Cracks expose the reinforcement to moisture and deicing salts, which accelerate corrosion of the steel bars and cause durability issues, such as freeze-thaw and scaling. As a result, a number of crack-reducing technologies have been employed with the goal of minimizing concrete shrinkage and cracking.

As discussed in Chapter 1, one technique for reducing cracking is internal curing (IC) using pre-wetted fine lightweight aggregate (LWA). By incorporating internal curing in concrete, the absorbed water stored within LWAs is provided to the cement paste. During hydration and drying periods, the absorbed water is released into the cement paste, promoting hydration, replacing the water lost to evaporation, and decreasing shrinkage (Bentz and Weiss 2011). Additionally, the combined effects of IC and selected supplementary cementitious materials (SCMs) as partial replacements of portland cement in mitigating shrinkage have been widely reported (Bentz 2007, Browning et al. 2011, De la Varga et al. 2012, Jones 2014, Pendergrass and Darwin 2014, Yuan et al. 2015, Khajehdehi and Darwin 2018, Feng and Darwin 2020 to name a few). As explained in Chapter 1, although bridge decks with binary or ternary binder compositions combined with IC have been constructed recently in some states, only in this study has this technology been applied in conjunction with Kansas LC-HPC specifications. Therefore, the efficiency of these technologies in reducing cracking needs to be determined when combined with the approach required by LC-HPC specifications.

As presented in Chapter 1, although employing IC is beneficial in mitigating shrinkage, the freeze-thaw durability of internally-cured concrete can be compromised if an excessive quantity of IC water is used. Limited studies, however, have been conducted on the effects of increasing the quantity of IC water above the recommended value of 7 or 8% by weight of binder (ASTM C1761-17, Bentz and Weiss 2011, Bitnoff 2014) on freeze-thaw durability. This recommendation, generally, is based on minimizing autogenous shrinkage, which is of concern in concretes with *w/cm* ratios below 0.42 (Mindess et al. 2003). Recommendations for the maximum allowable IC percentage vary considerably in prior research, yielding no clear conclusion. Jones and Weiss (2015) investigated the freeze-thaw durability of internally-cured concrete mixtures, with 20% Class F fly ash (by weight of cementitious materials) with *w/cm* ratios of 0.36, 0.48, and 0.56. They reported that mixtures with 6.4% of IC water content at *w/cm* ratios of 0.36 and 0.48 performed satisfactorily in freeze-thaw testing (in accordance with ASTM C666-Procedure A), while at *w/cm* ratio of 0.56 failed the test. In another study, Feng and Darwin (2020) studied the freeze-thaw durability of mixtures with slag cement and silica fume as partial replacements of portland cement, with IC water ranging from 5.3 to 9.7% by weight of cementitious materials at a *w/cm* ratio of 0.45. They reported that mixtures with 5.3 or 6.5% IC water by weight of cementitious materials performed well in the freeze-thaw testing, while the mixture with 9.7% IC water performed poorly and failed the test (in accordance with ASTM C666-Procedure B following the regime in Kansas Department of Transportation (KDOT) Test Method KTMR-22). In another study, Lafikes et al. (2020) studied the freeze-thaw durability of mixtures with portland cement as the only binder, with IC water ranging from 3.8 to 11.8% by weight of cementitious materials at a *w/c* ratio of 0.43. They reported that mixtures with 3.8, 7.3, or 9.8% IC water performed well in freeze-thaw testing, while the mixture with 11.8% IC water failed the test (in accordance with ASTM C666-Procedure A).

These observations clearly indicate the continuing need to investigate an upper limit in the quantity of IC water, the effects of *w/cm* ratio, and testing procedures used to the freeze-thaw durability of IC mixtures. This study aims to resolve prior discrepancies by evaluating and comparing the results for concretes with different *w/cm* ratios and freeze-thaw testing procedures to identify the upper limit on the quantity of IC water and determine if such a limit should be based on (1) IC water as a percentage of binder weight or (2) total weight of water per unit volume of concrete. For this purpose, concrete specimens are tested using freeze-thaw testing Procedures A and B of ASTM C666 with different paste and IC water contents to determine differences in performance for the two procedures.

As discussed in Chapter 1, scaling resistance can be influenced depending on the binder composition (cement with or without SCMs), test methods, or deicing salts. Some studies have reported that concretes containing SCMs exhibit more scaling than concrete containing portland cement as the only binder (Bouzoubaâ et al. 2011, Hooton and Vassilev 2012), with more mass loss with increasing SCMs replacements. On the other hand, calcium oxychloride ($CaCl_2 \cdot 3Ca(OH)_2 \cdot 12H_2O$) can form when calcium chloride ($CaCl_2$) from deicing salts reacts with calcium hydroxide ($Ca(OH)_2$), which is produced while portland cement hydrates. The volume of calcium oxychloride exceeds that of calcium hydroxide, resulting in expansion and deterioration of concrete (Qiao et al. 2017). Therefore, scaling can be the result of the formation of calcium oxychloride, as well due to cycles of freezing and thawing. Calcium oxychloride formation depends on the temperature and calcium chloride concentration. Abdul Baki et al. (2020) examined the effects of partial replacement of portland cement with either slag cement or Class C fly ash (0, 20, 35, and 50% by weight of the binder) on concrete durability as affected by scaling and calcium oxychloride formation. They reported that for concrete mixtures with portland cement as the only binder and mixtures with a 20% volume replacement of portland cement with slag cement, $CaCl_2$ caused more scaling damage than NaCl. Research, however, is needed to investigate the effects of different deicing salts on scaling resistance of internally-cured concrete.

Prior studies have found that the freeze-thaw durability of internally-cured mixtures is better correlated with the total internal water or TI water (provided by all aggregates) than with IC water, both as functions of the percentage of total binder weight, or with total values of either in concrete (Lafikes et al. 2020). Thus, in this study also, the effects of total internal water on shrinkage, durability, and ion transport properties of internally-cured mixtures are investigated.

As commonly used by state departments of transportation (DOTs), the ion conductivity of concrete can be measured directly by the rapid chloride permeability test (RCPT) or indirectly by the surface resistivity measurement (SRM) test (Moradllo et al. 2018). As discussed in Chapter 1, while previous researchers have investigated the ionic transport of concrete mixtures incorporating SCMs (cement and slag cement, cement and Class C fly ash, and cement and silica fume) using both RCP and SRM tests (Rupnow and Icenogle 2012, Jenkins 2015), limited studies evaluated mixtures containing both IC and SCMs. Hwang et al. (2013) compared ion permeability of mixtures containing SCMs with and without IC water at *w/cm* ratios of 0.3 and 0.4. They reported that IC mixtures exhibited slightly higher charge passed (maximum 410 Coulomb) in the RCP test than those without IC at both *w/cm* ratios. Lafikes et al. (2020), however, reported that IC water content alone did not have a noticeable effect on the ion transport properties of the mixtures. Instead, the addition of SCMs produced far greater effects, and resulted in greater reduction of charge passed as measured in the RCP test, and higher surface resistivity in the SRM test.

The laboratory portion of this study investigates the effects of IC water in concrete mixtures with different binder compositions, paste contents, and water-to-cementitious material ratios (*w/cm*) on shrinkage, freeze-thaw durability, scaling resistance, and ion transport properties. Internal curing in mixtures was provided using pre-wetted lightweight aggregates. The study evaluates the effects of different quantities of internal curing water ranging from 0 to 13.1% in LWA by total weight of binder (or total internal water ranging from 3.4 to 15.8% by total weight of binder). The mixtures include those with binder compositions consisting of portland cement as the only binder and those containing 30% slag cement and 3% silica fume as partial replacements for portland cement (by total weight of cementitious materials). The paste contents ranged from 23.7 to 33.7% (by volume), with water-to-cementitious material ratios of 0.41 and 0.45. The study consists of three programs.

Program I includes 18 concrete mixtures with IC water contents ranging from 8.2 to 13.1% (by the weight of binder) or 45.2 to 94.8 lb/yd^3 of concrete, containing portland cement as the only binder, with paste contents of 23.7, 26.7, or 33.7%. Nine mixtures had a water-cement (*w/c*) ratio of 0.45 and nine mixtures had a *w/c* ratio of 0.41. These mixtures were evaluated for freeze-thaw durability following ASTM C666-Procedure A and compressive strength in accordance with ASTM C39.

Program II includes 12 concrete mixtures with IC water contents ranging from 8.2 to 13.0% (by the weight of binder) or 45.9 to 101.5 lb/yd^3 of concrete, containing portland cement as the only binder, with paste contents of 23.7, 26.7, or 33.7%. Six mixtures had a *w/c* ratio of 0.45 and 6 mixtures had a *w/c* ratio of 0.41. These mixtures were evaluated for freeze-thaw durability and scaling resistance, as well as compressive strength.

Program III, which evaluates the effects of total internal water (provided by all aggregates) of internally-cured concrete mixtures, includes eight concrete mixtures, two of which include only portland cement and six of which include a ternary binder composition including slag cement and silica fume. For Program III, mixtures were designed to contain nominal quantities of IC water equal to 0, 6, and 9% by weight of binder. The quantity of total internal water for mixtures with portland cement as the only binder is 3.4 or 8.7% (by the weight of binder). The quantities of total internal water for ternary binder composition mixtures ranged from 3.0 to 12.5% (by the weight of binder). These mixtures were evaluated for shrinkage, freeze-thaw durability, scaling resistance, ion conductivity, and compressive strength. The results are presented in Chapter 3.

2.2 MATERIALS

This section describes the properties of the materials used in the mixtures evaluated in the laboratory.

2.2.1 Cement

Type I/II portland cement meeting the requirements of ASTM C150 was used in the concrete mixtures included in this study. Two samples of portland cement were obtained over a period of two years. Sample C1 was obtained from a local producer and was used in Program I. Sample C2 was obtained from the supplier of the IC-LC-HPC project in Kansas in 2019 and was used in Programs II and III. Sample C1 had a specific gravity of 3.13 and a Blaine fineness of 403 m^2/kg. Sample C2 had a specific gravity of 3.15 and a Blaine fineness of 265 m^2/kg. The samples were analyzed by Ash Grove Cement Company Technical Center in Overland Park, KS. The chemical compositions of the cement samples are shown in Table 2.1.

Table 2.1: Cement chemical analysis and physical properties

Sample No.	Percentages by Weight	
	Type I/II Portland Cement	
	C1	C2
Producer	Ash Grove	Ash Grove
Specific Gravity	3.13	3.15
Blaine Fineness, m^2/kg	403	265
XRF Analysis		
SiO_2	20.46	20.36
Al_2O_3	3.77	4.68
Fe_2O_3	3.17	3.06
CaO	63.04	62.38
MgO	1.97	2.01
SO_3	2.63	2.80
Na_2O	0.18	0.25
K_2O	0.48	0.57
TiO_2	0.23	0.29
P_2O_5	0.08	0.08
Mn_2O_3	0.11	0.10
SrO	0.25	0.25
CuO	-[a]	-[a]
ZnO	0.01	0.01
LOI	3.26	3.14
Total	99.64	99.98

[a] Not tested

2.2.2 Supplementary Cementitious Materials (SCMs)

In this study, the supplementary cementitious materials used in Program III were Grade 100 slag cement (S) and silica fume (SF). One sample of each was obtained from the supplier of the IC-LC-HPC project in Kansas in 2019. The slag cement had a specific gravity of 2.87 and a Blaine fineness of 545 m^2/kg. The silica fume had a specific gravity of 2.22 and a Blaine fineness of 563 m^2/kg. The chemical composition of the supplementary cementitious materials is shown in Table 2.2.

Table 2.2: Supplementary cementitious material chemical analysis and physical properties

Sample type	Percentage by weight	
	Slag Cement	**Silica Fume**
Producer	LafargeNewcem	Euclid Chemicals
Specific Gravity	2.87	2.22
Blaine Fineness, m^2/kg	545	563
XRF Analysis		
SiO_2	36.96	92.83
Al_2O_3	7.64	0.15
Fe_2O_3	0.50	0.24
CaO	39.29	0.75
MgO	10.77	0.38
SO_3	2.71	0.44
Na_2O	-[a]	0.35
K_2O	0.57	0.68
TiO_2	0.40	-[a]
P_2O_5	0.01	0.07
Mn_2O_3	0.52	0.03
SrO	0.05	-[a]
CuO	0.19	0.01
ZnO	0.07	0.05
LOI	-[b]	3.94
Total	99.68	99.93

[a] Not detected
[b] Not provided

2.2.3 Coarse Aggregates

Granite and limestone were used as coarse aggregates. Granite was separated into two size fractions, referred to as A and B, with maximum sizes of ¾ and ½ in. (19 and 13 mm), respectively, to improve workability and achieve optimized gradations. Granite A and B were used in Programs I, II, and some mixtures in Program III. Two samples of Granite A and B were obtained from a local producer for this study. Samples of size fraction A had absorptions (oven-dry, OD) of 0.69 and 0.60%, respectively, and a specific gravity (saturated-surface dry, SSD) of 2.60; samples of size fraction B had absorptions (OD) of 0.83 and 0.86%, respectively, and a specific gravity (SSD) of 2.59. A high-absorption limestone with a maximum size of ¾ in. (19 mm) was used in one mixture in Program III. It was obtained from the local producer who provided the granite. The limestone had an absorption (OD) of 2.20% and a specific gravity (SSD) of 2.65. A low-absorption limestone was also used in Program III. It was separated into two size fractions, referred to as A and B, with maximum sizes of ¾ and ½ in. (19 and 13 mm), respectively, and was provided by the supplier of the IC-LC-HPC project in Kansas in 2019. Size fraction A had an absorption (OD) of 0.89% and a specific gravity (SSD) of 2.67; size fraction B had an absorption (OD) of 0.73% and a specific gravity (SSD) of 2.69. The physical properties and the gradations of the coarse aggregates are shown in Table 2.3.

Table 2.3: Physical properties and the gradations of coarse aggregates

Sample No.	**Granite**				**Limestone**		
	Granite A		**Granite B**		**High-absorption limestone**	**Low-absorption limestone**	
						Limestone A	**Limestone B**
	G-68A	G-69A	G-68B	G-68B	LS-3/4	LS-12A	LS-12B
Specific Gravity (SSD)	2.60	2.60	2.59	2.59	2.65	2.67	2.69
Absorption (%)[a]	0.69	0.60	0.83	0.86	2.20	0.89	0.73
Fineness Modulus	7.01	7.00	6.24	6.27	6.62	6.64	6.70
Sieve Size	**Percent Retained on Each Sieve**						
1-1/2-in. (37.5-mm)	0	0	0	0	0	0	0
1-in. (25.4-mm)	0	0	0	0	0	0	0
3/4-in. (19-mm)	0.8	2.7	0	0	0.6	0.4	0
1/2-in. (12.7-mm)	87.5	83.0	3.6	2.6	45.2	40.7	41.3
3/8-in. (9.5-mm)	11.7	12.9	25.8	27.8	20.4	25.2	29.1
No. 4 (4.75-mm)	0	0.9	67.0	67.0	30.6	31.5	29.1
No. 8 (2.38-mm)	0	0.9	1.8	1.7	2.6	1.4	0.2
No. 16 (1.18-mm)	0	0	0	0	0	0	0
No. 30 (0.60-mm)	0	0	0	0	0	0	0
No. 50 (0.30-mm)	0	0	0	0	0	0	0
No. 100 (0.15-mm)	0	0	0	0	0	0	0
No. 200 (0.075-mm)	0	0	0	0	0	0	0
Pan	0	0	1.8	0.9	0.6	0.8	0.3

[a] Oven-dry basis

2.2.4 Fine Aggregates

River sand was used as fine aggregate for the mixtures in this study. Two samples of sand (S-48 and S-50) were obtained from a local producer and used in Programs I and II. Samples S-48 and S-50 had absorptions (OD) of 0.42 and 0.51%, respectively, and a specific gravity (SSD) of 2.61. One sample of sand (MA3) was obtained from the supplier of the IC-LC-HPC project in Kansas in 2019 and used in Program III. The sample had an absorption (OD) of 0.37% and a specific gravity (SSD) of 2.62. The physical properties and the gradations of the fine aggregates are shown in Table 2.4.

Table 2.4: Physical properties and the gradations of fine aggregates

Sample No.	Sand		
	S-49	S-50	MA3
Specific Gravity (SSD)	2.61	2.61	2.62
Absorption (%)[a]	0.42	0.51	0.37
Fineness Modulus	2.93	3.03	3.25
Sieve Size	**Percent Retained on Each Sieve**		
1-1/2-in. (37.5-mm)	0	0	0
1-in. (25.4-mm)	0	0	0
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	0	0	0
3/8-in. (9.5-mm)	0	0	0
No. 4 (4.75-mm)	2.9	2.0	1.2
No. 8 (2.38-mm)	11.0	13.2	14.5
No. 16 (1.18-mm)	20.6	22.3	26.7
No. 30 (0.60-mm)	24.4	25.2	29.2
No. 50 (0.30-mm)	25.8	24.8	22.7
No. 100 (0.15-mm)	13.3	10.2	5.0
No. 200 (0.075-mm)	1.6	1.7	0.5
Pan	0.4	0.6	0.2

[a] Oven-dry basis

2.2.5 Lightweight Aggregates (LWA)

In this study, internal curing was provided by pre-wetted fine lightweight aggregates as a partial replacement of fine aggregates. The fine lightweight aggregates (LWA-MN) used in Programs I and II is an expanded clay sourced from Erwinville, LA. The fine lightweight aggregate (LWA-1/4) used in Program III is an expanded shale sourced from New Market, MO. Prior to batching, the lightweight aggregates were soaked for 72 hours. Following a procedure developed by Miller et al. (2014), the lightweight aggregates were placed into a pre-wetted surface dry condition (PSD) condition using a centrifuge. It has been demonstrated that the use of a centrifuge to obtain LWA in a PSD condition produces more consistent results than the use of paper towels for removing surface moisture, as indicated in ASTM C1761 (Lafikes et al. 2020). As described in Section 2.3.2, a centrifuge was also used to place LWA in a PSD condition when determining the total moisture content of LWA in the field.

The properties and gradations of the pre-wetted LWA are provided in Table 2.5. The actual quantity of IC water was determined by measuring the LWA absorption on the casting day.

Table 2.5: Physical properties and the gradations of LWA

Sample No.	**LWA**	
	LWA-MN	**LWA-1/4**
Specific Gravity (PSD)	1.54	1.76
Nominal Absorption (%)[a]	24.0	13.5
Fineness Modulus	3.60	3.39
Sieve Size	**Percent Retained on Each Sieve**	
1-1/2-in. (37.5-mm)	0	0
1-in. (25.4-mm)	0	0
3/4-in. (19-mm)	0	0
1/2-in. (12.7-mm)	0	0
3/8-in. (9.5-mm)	0	0
No. 4 (4.75-mm)	13.0	0.6
No. 8 (2.38-mm)	25.0	13.7
No. 16 (1.18-mm)	23.0	30.7
No. 30 (0.60-mm)	15.0	36.8
No. 50 (0.30-mm)	8.0	16.7
No. 100 (0.15-mm)	4.0	0.9
No. 200 (0.075-mm)	2.0	0.1
Pan	10.0	0.5

[a] Oven-dry basis

2.2.6 Chemical Admixtures

Air-entraining admixtures (identified here as AEA-1 and AEA-2) were used to obtain desired air contents. AEA-1 is a synthetically manufactured surfactant produced by Sika USA, with a specific gravity of 1.01. AEA-1 was used for mixtures in Programs I and II. AEA-2 is an aqueous solution compound of organic chemicals produced by Euclid Chemicals, with a specific gravity of 1.01. AEA-2 was used for mixtures in Program III.

A high-range-water-reducing admixture (HRWR) was used for some mixtures in Programs I and II to obtain the desired slump. Identified as HRWR-1, it is polycarboxylate produced by Sika USA, with a specific gravity of 1.06. No water-reducing admixtures were used for the mixtures in Program III.

2.3 MATERIAL PREPARATION

This section describes the methods used to prepare the materials and produce the concrete mixtures evaluated in the laboratory.

2.3.1 Mixing Procedure

Coarse aggregates were soaked for at least 24 hours and then placed in the SSD condition in accordance with ASTM C127. With the relatively low absorptions (less than 1%) listed in Table 2.4 for normalweight fine aggregates, sand was prepared with free surface moisture (FSM) determined in accordance with ASTM C70 on the day of batching. Fine lightweight aggregates were prepared in wet conditions. The absorption of LWA is one of the key properties determining its effectiveness as an internal curing agent, the value of which is highly dependent on the pre-wetting method and duration (Barrett et al. 2015). Therefore, the LWA was soaked in water for 72 hours and prepared, as described in detail in Section 2.3.2. The batched mixing water was then adjusted based on the measured FSM values to accommodate excess surface moisture.

A counter-current pan mixer was used for mixing. Prior to mixing, the pan and the blades were dampened. The mixer was first filled with the coarse aggregate and 80% of the mixing water before it started rotating. When used, silica fume was added next. These materials were mixed for 1½ minutes. Portland cement and slag cement (if applicable) were then added and the materials were mixed for another 1½ minutes, followed by the normalweight and lightweight fine aggregates and another 2 minutes of mixing. If used, the water-reducing admixture in 10% of the mixing water was added, followed by one minute of mixing. The air-entraining admixture was then added with the final 10% of the mixing water, followed by four minutes of mixing. The mix was then allowed to rest for 5 minutes. The concrete temperature was measured during this period in accordance with ASTM C1064. Finally, the concrete was mixed for a final three minutes. A summary of the mixing procedure is provided in Table 2.6.

Table 2.6: Mixing procedure (Yuan et al. 2011, Pendergrass and Darwin 2014)

Mixing procedure per minutes	With silica fume	Without silica fume
Coarse Aggregate + 80% Water + Silica Fume	Add all the materials before mixing. Then mix for 01:30*	Add all the materials before mixing
Cement + Slag Cement	01:30-03:00	00.00-01:30
Fine and Lightweight Aggregates	03:00-05:00	01:30-03:30
Water Reducer + 10% Water	05:00-06:00	03:30-04:30
Air Entraining Admixture + 10% Water	06:00-07:00	04:30-05:30
Mixing	07:00-10:00	05:30-08:30
Rest	10:00-15:00	08:30-13:30
Mixing	15:00-18:00	13:30-16:30

*min:sec.

2.3.2 Lightweight Aggregate Preparation

As described in Chapter 1 and expressed in Eq (1.1), the absorption and desorption properties of LWA are used to determine the quantity of pre-wetted fine LWA used in IC mixtures. The LWA absorption is the water holding capacity of LWA as a function of time and desorption is the loss of water from the pores of the LWA during drying as a function of relative humidity at a constant temperature (Castro 2011). For clarification, Eq. (1.1), repeated here, is used to calculate the design weight of LWA (W_{LWA}, lb/yd^3 of concrete) as a function of the total weight of binder, the desired percentage of IC water by weight of binder and the absorption and desorption values for the LWA (Bentz and Snyder 1999).

The W_{LWA}, can be calculated as:

$$W_{LWA} = \frac{C_f \times IC}{\alpha \times \beta} \tag{1.1}$$

where C_f = cementitious materials content (lb/yd^3)

IC = target internal curing water (expressed as a fraction of cementitious materials weight)

α = LWA absorption

β = LWA desorption at specified RH

In accordance with ASTM C1761, the LWA was soaked in water for 72 hours. The excess water on the aggregates was decanted by allowing the LWA to drain for a minimum of 15 minutes. In contrast to ASTM C1761, where paper towels are used to place the aggregates in pre-wetted surface-dry (PSD) condition, a centrifuge (Figure 2.1) was used to place the LWA in the PSD condition to, in turn, determine its total moisture content, following a procedure described by Miller et al. (2014). To do so, 600 ± 5 g was sampled from the pre-wetted LWA and distributed uniformly inside the centrifuge bowl (with a radius of 4.5 in. [114 mm]). A 9.75-in. (248-mm) filter ring was secured between the bowl and the lid of the centrifuge. The bowl was then placed in the centrifuge unit, followed by the upper housing mounted over the unit and secured with clamps. The centrifuge was operated at 2000 rpm for 3 minutes to place the sample in PSD condition. Afterward, the mass of the PSD sample was measured and then transferred to an oven for 24 hours. The 72-hour LWA absorption was then measured to calculate the actual quantity of IC water provided for the mixtures.

For mixtures in Programs I and II, the desorption (β in Eq. (1.1)) was taken to be 1.0 based on the work by Castro (2011) and Khayat (2018), who measured desorption of different types of LWA and reported that as the relative humidity decreased below 90%, the desorption values approached 1.0 rapidly. For mixtures in Program III, however, the desorption was taken as 0.976 per the LWA provider in Eq. (1.1).

Figure 2.1: Centrifuge partitions

2.4 TESTING PROCEDURES

Concrete mixtures were evaluated for free shrinkage, freeze-thaw durability, scaling resistance, and compressive strength. In addition, rapid chloride permeability testing was performed 28 and 56 days after casting on some mixtures. Surface resistivity measurements were obtained 28 days after casting on some mixtures. The procedures for these tests are described in this section.

2.4.1 Free Shrinkage

The length change of specimens prepared from the concrete mixtures in Program III was measured in accordance with a modified version of ASTM C157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* (ASTM C157-2017) that involves beginning measurements shortly after the concrete sets, rather than waiting approximately 24 hours. The modified procedures were employed by Khajehdehi and Darwin (2018) and Feng and Darwin (2020) to measure early-age swelling. By including early-age length changes, Khajehdehi and Darwin (2018) observed that mixtures containing IC, SCMs, or both exhibited more swelling than mixtures without IC or SCMs. They reported that as a result of the additional swelling, the total shrinkage through the drying period was reduced. Similar observations were reported by Feng and Darwin (2020), who observed that incorporating IC water (ranging from 5.3 to 9.7% by the weight of binder) in mixtures containing slag cement and silica fume reduced shrinkage after 365 days of drying, with decreases associated with an increasing the quantity of IC water.

For each batch, three prismatic specimens with dimensions of 3 × 3 × 11¼ in. (75 × 75 × 285 mm) were cast in steel molds. In the modified method, the specimens were demolded, labeled, and the first readings were taken just after final set (5½ ± ½ hours after casting) and two more times on the day of casting, instead of 23½ ± ½ hours after water was added to the mixture, as indicated in ASTM C157 (Khajehdehi and Darwin 2018). The specimens were then submerged in lime-saturated water for 14 days after casting (Lindquist et al. 2008). After the curing period, the specimens were stored for a year in an environmentally-controlled laboratory with a temperature of 73 ± 3 °F (23 ± 2 °C) and relative humidity of 50 ± 4%.

A mechanical dial gauge length comparator with an accuracy of 0.0001 in. (0.0025 mm) was used to measure the length change of the specimens (Figure 2.2). In addition to the three readings taken on the day of casting, specimens were measured daily between the curing period and Day 30 (one month of drying). Readings were subsequently taken every other day between Days 31 and 90, followed by weekly readings through Days 91 and 180 and monthly thereafter.

Figure 2.2: Mechanical dial gauge length comparator

2.4.2 Freeze-Thaw Durability and Fundamental Transverse Frequency

The freeze-thaw durability of concrete mixtures was evaluated in accordance with ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*-Procedures A and B (ASTM C666-15); the fundamental transverse frequency of the specimens was measured in accordance with ASTM C215, *Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens*, using the impact resonance test (ASTM C215-14). Specimens were cast in 3× 4 × 16 in. (75 × 100 × 405 mm) steel molds.

Mixtures in Programs I and III were evaluated for freeze-thaw durability using ASTM C666-Procedure A, with a failure limit of 90% of the initial dynamic modulus of elasticity, while mixtures in Program II were evaluated using both Procedure A and Procedure B. Three specimens were cast for each batch in Programs I and III; six specimens (three for each procedure) were cast for Program II.

Procedure A

The specimens were demolded 23½ ± ½ hours after casting, labeled, and immersed in lime-saturated water for 14 days. After completion of the curing period, the specimens were brought to a temperature of 40 °F (4 °C) in a thermally insulated container. The specimens were dried to a surface-dry condition and weighed. The specimens were then tested for the fundamental transverse frequency (used to calculate the dynamic modulus of elasticity) in accordance with ASTM C215 (Figure 2.3) before exposing the specimens to freeze-thaw cycles. Each specimen was placed into a container at thawed condition; then subjected to freeze-thaw cycles using an automated freeze-thaw machine (Figure 2.4). Following this procedure, the specimens were frozen at 0 ± 3 °F (-18 ± 2 °C) in water and thawed at 40 ± 3 °F (4 ± 2 °C) in water for each freeze-thaw cycle. The specimens were tested for the fundamental transverse frequency at intervals not exceeding 42 freeze-thaw cycles (test cycle). Freeze-thaw testing continued until each specimen completed 300 freeze-thaw cycles or until its dynamic modulus of elasticity dropped below 60% of the initial value.

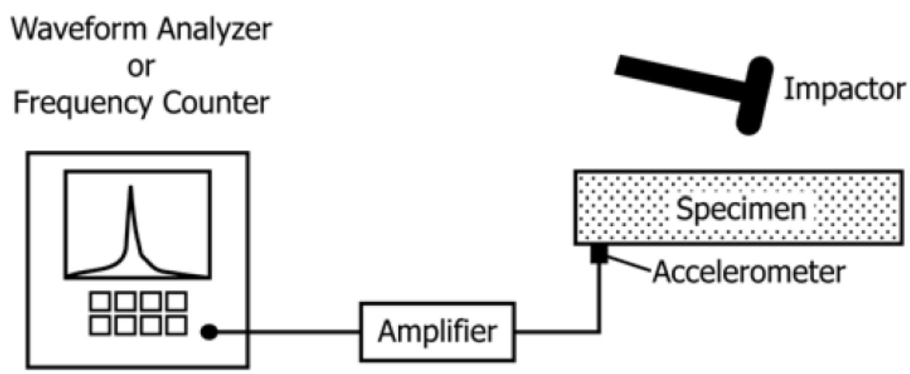


Figure 2.3: Schematic of apparatus for Impact Resonance Test (ASTM C215-14)

Figure 2.4: Freeze-Thaw machine

Procedure B

The specimens tested in accordance with ASTM C666-Procedure B were cured following the regime in Kansas Department of Transportation (KDOT) Test Method KTMR-22, *Resistance of Concrete to Rapid Freezing and Thawing,* with a failure limit of 95% of the initial dynamic modulus of elasticity. The specimens were demolded 23½ ± ½ hours after casting, labeled, and immersed in lime-saturated water for 67 days. The specimens were then stored in an environmentally-controlled room at 73 ± 3 °F (23 ± 2 °C) and a relative humidity of 50 ± 4% for 21 days followed by 24 hours in a tempering tank maintained at 70 °F (21 °C). Finally, the specimens were stored in a thermally insulated container at 40 °F (4 °C) for additional 24 hours. As with Procedure A, the fundamental transverse frequency was measured before exposing the specimens to freeze-thaw cycles in an automated freeze-thaw machine. Following this procedure, the specimens were frozen at 0 ± 3 °F (-18 ± 2 °C) in air and thawed at 40 ± 3 °F (4 ± 2 °C) in water for each freeze-thaw cycle. The fundamental transverse frequency was measured at intervals of not more than 42 freeze-thaw cycles (test cycle). Freeze-thaw testing continued until each specimen completed 660 freeze-thaw cycles or until its dynamic modulus of elasticity dropped below 60% of the initial value.

The dynamic modulus of elasticity (E_{Dyn}) can be calculated as:

$$E_{Dyn} = C \times M \times n^2 \tag{2.1}$$

where E_{Dyn} = Dynamic modulus of elasticity, Pa
C = 1083.6 m^{-1}, a constant based on specimen shape and Poisson's Ratio
M = Mass of the specimen, kg
n = Fundamental transverse frequency, Hz

In addition to the designated failure limit for each procedure, the freeze-thaw performance was also quantified in terms of the Durability Factor (DF), calculated using Eq. (2.2).

$$DF = \frac{P \times N}{M} \tag{2.2}$$

Where DF = Durability Factor of Specimens
P = Percentage of the initial E_{Dyn} at N cycles, %
N = number of cycles at which P reached 60% of E_{Dyn} or the specified number of cycles at which the exposure is to be terminated (300 cycles for Procedure A and 660 for Procedure B) whichever is less.
M = 300 cycles for Procedure A and 660 for Procedure B

2.4.3 Scaling Resistance

Scaling resistance was not evaluated for the mixtures in Program I. The scaling resistance of some mixtures in Program II was evaluated in accordance with Quebec Test BNQ NQ 2621-900 Annex B and ASTM C672-*Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*, with minor modifications. The scaling resistance of the mixtures in Program III was evaluated in accordance with ASTM C672, with some modifications. The testing methods are described next.

Quebec Test BNQ NQ 2621-900

For each batch, three 3 × 9 × 16 in. (75 × 230 × 405 mm) specimens were cast in wooden molds. The specimens were demolded 23½ ± ½ hours after casting, labeled, and immersed in lime-saturated water for 14 days. The specimens were allowed to dry in an environmentally-controlled room at 73 ± 3 °F (23 ± 2 °C) and a relative humidity of 50 ± 4% for 14 days. During this period, a polyurethane sealant was used to attach a polystyrene foam dike to pond brine on top of the upper surface of the specimen, as shown in Figure 2.5. At the end of the 14-day drying period, the top surface of specimens was covered with a ¼-in. (6-mm) deep 3% NaCl solution and stored in the environmentally-controlled room for another 7 days (pre-saturation period). After the pre-saturation period, the specimens were exposed to freeze-thaw cycles consisting of 16 ± 1 hour at 0 ± 5 ºF (-18 ± 3 ºC) followed by 8 ± 1hour thawing period at 73 ± 3 ºF (23 ± 2 ºC). The temperature ranges differed somewhat from those specified by BNQ NQ 2621-900: -0.4 ± 5.4 ºF (-18 ± 3 ºC) and 77 ± 5.4 ºF (25 ± 3 ºC). While no limitation on relative humidity is indicated by BNQ NQ 2621-900, the specimens were thawed in a relative humidity of 50 ± 4% in this study. Mass losses were measured at solution changes after the end of the thawing phase after 7, 21, 35, and 56 freeze-thaw cycles. To measure the mass loss, the surface of the specimens was first flushed using a syringe filled with the salt solution to collect any loose materials that had scaled off during the freeze-thaw cycles; the materials then were wet-sieved over a No. 200 (75 µm) sieve (BNQ NQ 2621-900 specifies an 80-µm sieve). The materials retained on the sieve were dried in an oven for approximately 24 hours at 221°F (105°C) and then weighed. Before returning specimens to testing, a new salt solution was added. Mass loss is expressed lb/ft^2 or kg/m^2. Mixtures with less than 0.1 lb/ft^2 (0.49 kg/m^2) of cumulative mass loss at the end of the test are considered to be scaling resistant by BNQ NQ 2621-900.

Figure 2.5: Scaling specimens with polystyrene foam dikes attached

ASTM C672

For each batch, three 3 × 9 × 16 in. (75 × 230 × 405 mm) specimens were cast using wooden molds. The specimens were demolded 23½ ± ½ hours after casting, labeled, and immersed in lime-saturated water for 14 days. The specimens were then dried in an environmentally-controlled room at 73 ± 3 °F (23 ± 2 °C) and a relative humidity of 50 ± 4% for 14 days. During the 14-day period, a polyurethane sealant was used to attach a polystyrene foam dike to maintain a brine pond on top of the finished surface of the specimen. At the end of the 14-day drying period, the top surface of specimens was covered with a ¼ in. (6 mm) deep layer of 4% $CaCl_2$ solution; the specimens were then exposed immediately to freeze-thaw cycles. The specimens prepared for ASTM C672 testing were tested under a similar temperature range for freezing and thawing phases as with the modified BNQ NQ 2621-900. For ASTM C672, scaling resistance is evaluated after 5, 10, 15, 20, and 50 freeze-thaw cycles, with a solution change at each of these intervals, based on a visual rating between 0 (no scaling) and 5 (severe scaling), to quantify the degree of scaling. In this study, an interval was added after 35 cycles and mass loss was measured, although not specified by ASTM C672.

2.4.4 Compressive Strength

Compressive strength was measured in accordance with ASTM C39-*Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* (ASTM C39-2020) for each batch using three 4 × 8 in. (100 × 205 mm) cylindrical specimens. The specimens were demolded, labeled, and submerged in lime-saturated water 23½ ± ½ hours after casting. The cylinders were tested 28 days after casting.

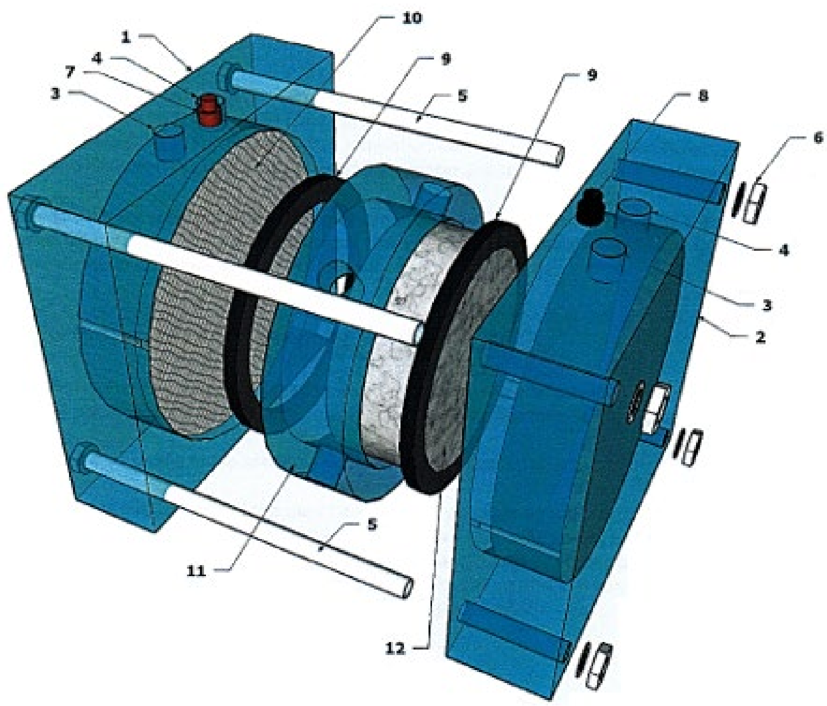
2.4.5 Rapid Chloride Permeability Test

The ion conductivity of the concrete mixtures in Program III was evaluated in accordance with ASTM C1202- *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration* (ASTM C1202-19). For each batch, six 4 × 8 in. (100 × 205 mm) cylindrical specimens were cast. The specimens were demolded 23½ ± ½ hours after casting and cured in a moist-curing room at 73 ± 3 ºF (23 ± 2 ºC) at a relative humidity of 95% or higher in accordance with ASTM C1202. The specimens were tested using the Rapid Chloride Permeability (RCP) test (ASTM C1202), originally developed by Whiting (1981), 28 and 56 days after casting (three specimens at each age).

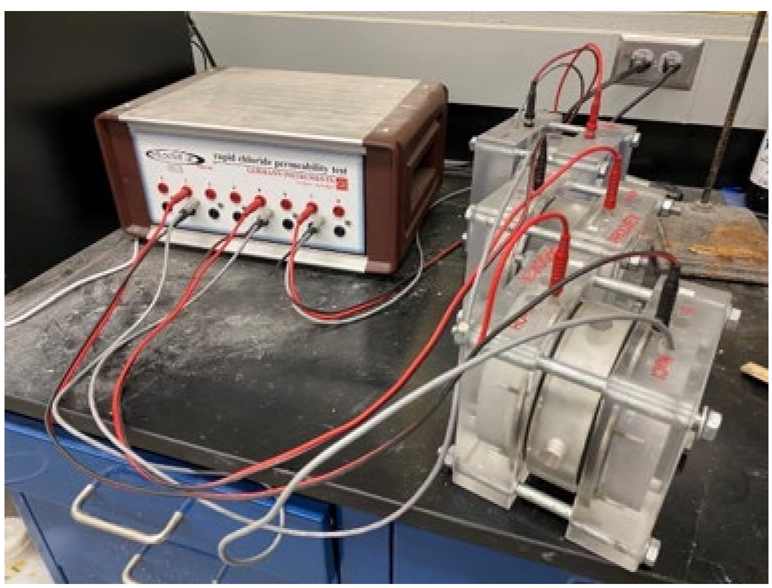
For the RCP test, specimen preparation involves cutting a 2-in. (50 ± 3 mm) thick slice parallel to the top of each of three cylinders, allowing them to surface dry in air for a minimum of one hour, and measuring the diameters and the thicknesses of the slices afterward. The specimens were then placed into a vacuum desiccator with a vacuum pump connected to the desiccator through a vacuum line stopcock. Following ASTM C1202, the specimens were placed in vacuum saturation conditions by providing sufficient de-aerated water through the vacuum line stopcock into the vacuum desiccator. At the end of the preparation period, specimens are kept submerged for 18 ± 2 hours. The test was performed using Germann Instruments, Inc., Proove'it RCP equipment as an alternative to a two-part specimen-test cell indicated in ASTM C1202. A schematic of the cell shown in Figure 2.6(a). On the day of testing, for each test cell, the specimen was inserted through the hollow in within a spacer that had dimensions of 4 × 5.5 × 1⅜ in. (105 × 140 × 35 mm [inner diameter, outer diameter, and thickness, respectively]). A light coat of silicone oil was then applied on both faces of the spacer, where it touched sealing gaskets. The sealing gaskets in the RCP equipment had greater dimensions than that of the ASTM C1202 (with dimensions of 3 × 4 × ¼ in. (75 × 100 × 6 mm [inner diameter, outer diameter, and thickness, respectively]). Two sealing gaskets with dimensions of 4 × 5 × ⅜ in. (99 × 127 × 10 mm [inner diameter, outer diameter, and thickness, respectively]) were then placed over the ends of the specimen, touching the spacer faces, the sealing gaskets and the spacer were squeezed together by tightening the four bolts connecting each half cell reservoir, and the specimen was mounted in the test cell. The test cell included reservoirs that were filled with 0.3N sodium hydroxide (NaOH) solution on one side and 3% sodium chloride (NaCl) solution on the other, connecting to the positive and negative terminals of a power supply capable of maintaining a voltage of 60 ± 0.1 V for 6 hours, respectively. Following the test, the temperature and the total charge passed in coulombs were measured and the chloride ion penetrability class was determined based on Table 2.7. The RCP testing setup is shown in Figure 2.6(b).

Table 2.7: Chloride ion penetrability based on charge passed (ASTM C1202)

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4000	High
2000-4000	Moderate
1000-2000	Low
10-1000	Very Low
< 100	Negligible



(a)



(b)

Figure 2.6: RCP equipment: (a) the schematic of a Proove'it cell: 1. Left cell half, 2. Right cell half, 3. Solution filling inlet, 4. Temperature probe inlet, 5. Steel bolt, 6. Washer and nut, 7. Red banana jack, 8. Black banana jack, 9. Sealing gasket, 10. Wire mesh, 11. Hollow in between Spacer, 12. Concrete specimen (Germann Instruments, INC. 2017); (b) RCP testing setup

2.4.6 Surface Resistivity Measurement

Surface resistivity measurements (SRM) of mixtures in Program III were obtained in accordance with AASHTO TP-95-*Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration* using a Wenner Array Probe with 1½-in. (38.1-mm) spacing 28 days after casting. SRM testing was performed on the three 4 × 8 in. (100 × 205 mm) cylindrical specimens used for the compressive strength test. After removing the specimens from lime-saturated water, excess water was blotted off of the specimens. For each cylinder, the 0, 90, 180, and 270 degree points were marked on the top. Each cylinder was marked with four longitudinal lines spaced 90 degrees apart. A reference point was marked on each line 1.75 in. (44.5 mm) from the top of the cylinder to establish the placement of the first Wenner array probe pin. The specimen was then placed on a sample holder covered with a wet towel. The Wenner array probe pins were kept moist during testing. Readings were taken with the probe aligned on each longitudinal line, as shown in Figure 2.7. After the resistance on each line was measured, the measurements were repeated and the eight surface resistivity measurements obtained for each specimen were averaged.

When the specimens are cured in lime-saturated water instead of a moist room, SRM values must be multiplied by a correction factor of 1.1 (AASHTO TP-95). This is due to the calcium in the lime-saturated water, which makes the specimens more electrically conductive, resulting in a lower SRM than specimens cured in a moist room. The SRM test setup is shown in Figure 2.7.

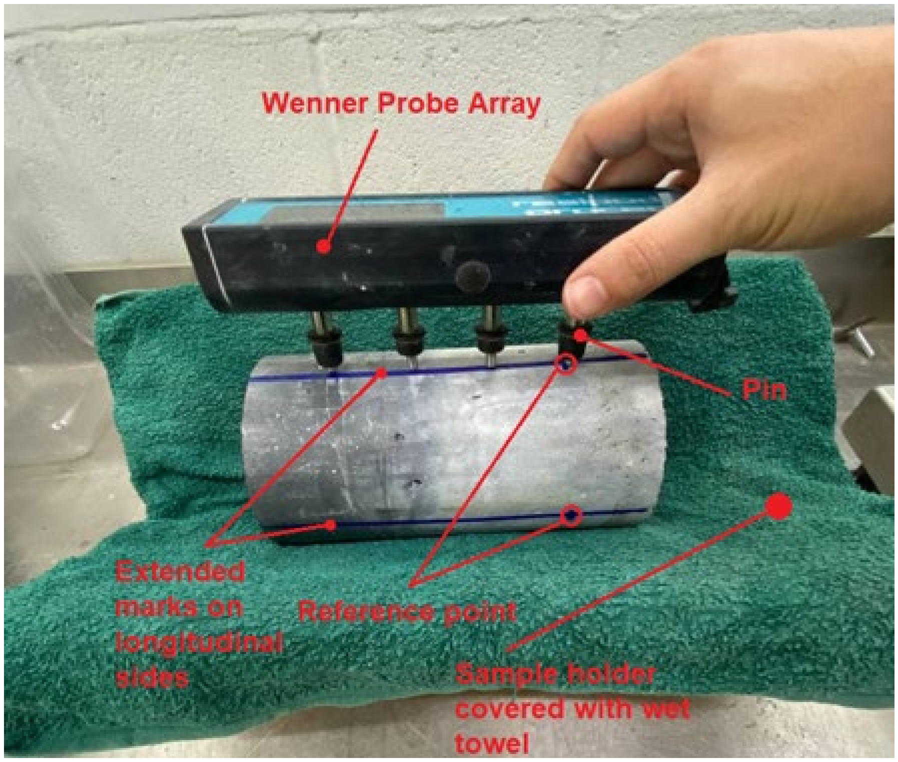


Figure 2.7: SRM testing setup

2.5 CONCRETE MIXTURES

Mixtures in Programs I and II were designed using KU Mix, a mix design program developed at the University of Kansas. KU Mix is available for download from http://www.iri.ku.edu/projects/concrete/phase2.html. Mixtures are identified by the paste content, quantity of IC water, and *w/c* ratio. The naming convention has a form of 'A-B-C.' The indicator A identifies the paste content (23.7, 26.7, or 33.7%); the indicator B represents the quantity of IC water as a percentage of the total weight of the binder; and the indicator C equals the *w/c* ratio, 0.45 or 0.41. For example, 23.7%-8.8-0.45 is a mixture with a paste content of 23.7% that contains 8.8% of IC water by weight of binder with a *w/c* ratio of 0.45. Duplicate mixtures with the same paste, IC water content, and *w/c* ratio have an additional indicator at the end of the mixture ID.

Program III includes mixtures with proportions similar to that used in the construction of an IC-LC-HPC deck in Kansas in 2019. Program III contains eight mixtures with a *w/cm* ratio of 0.45, including six with the slag cement and silica fume used at replacement percentages of 30% and 3%, respectively, based on the total weight of cementitious materials, and two with portland cement as the only binder. Five of the mixtures contain a low-absorption limestone (with absorptions ranging from 0.75 to 1.0% on an OD basis), two contain granite (with absorptions ranging from 0.52 to 0.78% on an OD basis) and one contains a high-absorption limestone (with an absorption of 2.2% on an OD basis) as coarse aggregates. All of the mixtures have a paste content of 24.6%. Mixtures were designed to provide different quantities of internal curing (IC) water provided by pre-wetted lightweight aggregate (LWA) ranging from 0 to 9.0%, or total internal water (TI water) provided by all aggregates ranging from 3.4 to 12.5%, in all cases by the weight of binder. The naming convention has the form of 'D-E-F.' The indicator D identifies the binder composition (T for ternary mixtures with slag cement and silica fume and C for 100% portland cement); the indicator E is the quantity of total internal water or TI water as a percentage of the total weight of binder; and the indicator F represents the type of coarse aggregate (L for low-absorption limestone, H for high-absorption limestone, and G for granite). For example, T-3.4-L is a ternary mixture (a 30% replacement by weight of binder with slag cement and a 3% replacement by weight of binder with silica fume) that contains 3.4% of total internal water by the weight of binder with a low-absorption limestone as the coarse aggregate. Mixtures with total internal water contents of 3.0 or 3.4% contain no LWA (0% IC).

2.5.1 Program I

Eighteen concrete mixtures were cast to help determine if the freeze-thaw durability of IC mixtures is a function of (1) the percentage of IC water as a percentage of binder weight or (2) the total quantity of absorbed water in the lightweight aggregate. The mixture proportions for Program I are listed in Table 2.8. The concrete properties and the total absorbed water in the LWA (lb/yd^3) are shown in Table 2.9. The mixtures had paste contents of 23.7, 26.7, or 33.7%, contained 100% portland cement as the binder, and included nominal IC water contents of either 9 or 13% by the weight of binder. Nine of the mixtures had a *w/c* ratio of 0.45; nine had a *w/c* ratio of 0.41. The actual quantities of IC water ranged from 8.5 to 12.8% by weight of binder for mixtures with a *w/c* ratio of 0.45 ranged and from 8.2 to 13.1% by weight of binder for mixtures with a *w/c* ratio of 0.41. The total absorbed water in the LWA ranged from 44.3 to 94.4 lb/yd^3 for mixtures with a *w/c* ratio of 0.45 and from 45.2 to 94.8 lb/yd^3 for mixtures with a *w/c* ratio of 0.41. Slumps ranged from 1½ to 9 in. (40 to 230 mm) for mixtures with a *w/c* ratio of 0.45, and from 1¼ to 6 in. (30 to 150 mm) for mixtures with a *w/c* ratio of 0.41. The mixtures with a paste content of 33.7% had the highest slumps: either 8¾ or 9 in. (220 or 230 mm) for mixtures with a *w/c* ratio of 0.45 and either 5¼ or 6 in. (135 to 150 mm) for mixtures with a *w/c* ratio of 0.41. Air contents ranged from 6.25 to 9.25% and compressive strengths ranged from 3570 to 5250 psi (24.6 to 36.2 MPa).

Table 2.8: Program I mixture proportions

Mixture ID[a]	Material lb/yd^3 (SSD/PSD)								
	w/c ratio	Cement (Type I/II)	Coarse Agg.		Fine Agg.	Lightweight Agg.	Water	AEA-1[b]	HRWR-1[b]
		C1	G-68A	G-68B	S-49	LWA-MN		fl oz/cwt	fl oz/cwt
23.7%-8.5-0.45	0.45	520	609	1050	955	242	234	0.83	0
23.7%-12.8-0.45		520	629	981	834	350	234	0.89	0
23.7%-12.9-0.45		520	629	981	834	350	234	0.79	0
26.7%-8.5-0.45		585	593	1020	827	272	263	0.84	0
26.7%-8.7-0.45		585	593	1020	827	272	263	0.91	0
26.7%-12.3-0.45		585	614	944	692	393	263	0.77	0
26.7%-12.8-0.45		585	614	944	692	393	263	0.81	0
33.7%-9.0-0.45		740	554	944	509	350	333	0.97	0
33.7%-12.8-0.45		740	581	856	341	497	333	0.83	0
23.7%-8.2-0.41	0.41	549	609	1050	935	255	225	1.31	1.12
23.7%-12.5-0.41		549	629	981	807	369	225	1.31	1.12
26.7%-8.5-0.41		618	593	1020	803	287	253	0.8	0
26.7%-8.6-0.41		618	593	1020	803	287	253	0.8	0
26.7%-12.5-0.41		618	614	944	658	415	253	0.91	0
26.7%-13.1-0.41		618	614	944	658	415	253	0.9	0
33.7%-8.4-0.41		780	554	944	489	363	320	0.66	0
33.7%-12.0-0.41		780	581	856	299	524	320	0.71	0
33.7%-12.2-0.41		780	581	856	299	524	320	0.79	0

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight
C: *w/c* ratio
[b] Admixture designations (HRWR-1=Viscocrete 1000, AEA-1=Sika Air 260)
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Table 2.9: IC and total absorbed water in LWA and concrete properties in Program I

Mixture ID[a]	IC water	Total Absorbed Water in LWA	Slump	Air	Unit Weight	Temperature	28-day Compressive Strength
	(% Binder Weight)	(lb/yd^3)	(in.)	(%)	(lb/ft^3)	(°F)	(psi)
23.7%-8.5-0.45	8.5	44.3	2	6.5	139.3	67	4310
23.7%-12.8-0.45	12.8	66.4	1½	7.50	136.9	61	4480
23.7%-12.9-0.45	12.9	67.2	2½	6.25	137.5	61	4550
26.7%-8.5-0.45	8.5	49.8	3¼	8.00	134.1	67	3960
26.7%-8.7-0.45	8.7	50.8	4½	9.25	135.3	71	3570
26.7%-12.3-0.45	12.3	72.0	2¾	6.75	134.6	69	4130
26.7%-12.8-0.45	12.8	74.8	3¼	7.00	133.8	70	4410
33.7%-9.0-0.45	9.0	66.9	9	6.75	131.7	60	4450
33.7%-12.8-0.45	12.8	94.4	8¾	7.75	129.8	60	4420
23.7%-8.2-0.41	8.2	45.2	1¼	8.50	136.9	75	4800
23.7%-12.5-0.41	12.5	68.4	1¼	7.75	135.4	70	4670
26.7%-8.5-0.41	8.5	52.3	2¾	6.75	138.9	68	5250
26.7%-8.6-0.41	8.6	52.8	2	6.75	137.7	70	4490
26.7%-12.5-0.41	12.5	77.2	2½	7.75	133.8	71	4590
26.7%-13.1-0.41	13.1	81.1	2¼	7.25	134.1	68	4310
33.7%-8.4-0.41	8.4	65.2	6	9.00	132.1	65	4670
33.7%-12.0-0.41	12.0	93.7	5¼	8.50	129.0	71	4520
33.7%-12.2-0.41	12.2	94.8	6	9.00	128.1	69	4240

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight
C: *w/c* ratio

Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.5.2 Program II

Twelve concrete mixtures were cast to evaluate the freeze-thaw durability and scaling resistance of IC mixtures introduced in Program I using different testing procedures. The concrete mixture proportions in Program II are listed in Table 2.10. The concrete properties and the total absorbed water in the LWA (lb/yd^3) are shown in Table 2.11. As in Program I, mixtures had paste contents of 23.7, 26.7, or 33.7%, contained portland cement as the only binder, and included nominal IC water contents of 9 or 13% by the weight of binder. The mixtures had a *w/c* ratio of 0.45 or 0.41. Six mixtures were cast with a *w/c* ratio of 0.45; six mixtures were cast with a *w/c* ratio of 0.41. The actual quantities of IC water ranged from 8.2 to 12.5% for mixtures with a *w/c* ratio of 0.45 and from 8.3 to 13.0% for mixtures with a *w/c* ratio of 0.41. The total absorbed water in the LWA ranged from 45.9 to 92.4 lb/yd^3 for mixtures with a *w/c* ratio of 0.45 and from 49.1 to 101.5 lb/yd^3 for mixtures with a *w/c* ratio of 0.41. Slumps ranged from 2¼ to 8¾ in. (55 to 220 mm) for mixtures with a *w/c* ratio of 0.45 and from 1½ to 6¼ in. (40 to 160 mm) for mixtures with a *w/c* ratio of 0.41. Air contents ranged from 6.25 to 9.25%, and compressive strengths ranged from 4050 to 4720 psi (27.9 to 32.5 MPa).

Table 2.10: Program II mixture proportions

Mixture ID[a]	Material lb/yd^3 (SSD/PSD)								
	w/c ratio	Cement (Type I/II)	Coarse Agg.		Fine Agg.	Lightweight Agg.	Water	AEA-1[b]	HRWR-1[b]
		C2	G-69A	G-69B	S-50	LWA-MN		fl oz/cwt	fl oz/cwt
23.7%-8.8-0.45	0.45	520	609	1050	955	242	234	0.95	0
23.7%-12.2-0.45		520	629	981	834	350	234	0.94	0
26.7%-8.2-0.45		585	593	1020	827	272	263	0.79	0
26.7%-12.1-0.45		585	614	944	692	393	263	0.88	0
33.7%-9.0-0.45-2		740	554	944	509	350	333	0.71	0
33.7%-12.5-0.45		740	581	856	341	497	333	0.82	0
23.7%-9.0-0.41	0.41	549	609	1050	935	255	225	1.22	1.03
23.7%-13.0-0.41		549	629	981	807	369	225	0.95	1.03
26.7%-8.6-0.41-2		618	593	1020	803	287	253	0.83	0
26.7%-12.7-0.41		618	614	944	658	415	253	0.80	0
33.7%-8.3-0.41		780	554	944	489	363	320	0.65	0
33.7%-13.0-0.41		780	581	856	299	524	320	0.65	0

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight
C: *w/c* ratio
[b] Admixture designations (HRWR-1=Viscocrete 1000, AEA-1=Sika Air 260)
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Table 2.11: Program II total absorbed water in LWA and concrete properties

Mixture ID[a]	IC water	Total Absorbed Water in LWA	Slump	Air	Unit Weight	Temperature	28-day Compressive Strength
	(% Binder Weight)	(lb/yd^3)	(in.)	(%)	(lb/ft^3)	(°F)	(psi)
23.7%-8.8-0.45	8.8	45.9	2½	8.75	137.5	74	4490
23.7%-12.2-0.45	12.2	63.3	2¼	8.00	134.1	71	4370
26.7%-8.2-0.45	8.2	47.9	4¾	8.75	134.7	62	4050
26.7%-12.1-0.45	12.1	71.0	4	8.50	131.4	65	4250
33.7%-9.0-0.45-2	9.0	66.8	8¾	6.25	131.4	68	4400
33.7%-12.5-0.45	12.5	92.4	8	6.75	128.7	68	4510
23.7%-9.0-0.41	9.0	49.1	1½	9.00	136.1	70	4700
23.7%-13.0-0.41	13.0	71.3	2	9.25	132.6	71	4360
26.7%-8.6-0.41-2	8.6	52.9	1½	7.75	135.4	70	4720
26.7%-12.7-0.41	12.7	78.5	2	8.25	133.3	69	4420
33.7%-8.3-0.41	8.3	64.8	6¼	7.75	134.7	63	4700
33.7%-13.0-0.41	13.0	101.5	5¼	8.75	127.4	68	4410

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight
C: *w/c* ratio
Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.5.3 Program III

Eight concrete mixtures were cast to evaluate the effects of total internal water (provided by all aggregates) for internally cured concrete mixtures. The primary variables considered in this program include cementitious material compositions (two with only portland cement, and six that include a ternary binder composition consisting of portland cement, slag cement, and silica fume), nominal quantities of internal curing water provided by pre-wetted lightweight aggregate (equal to 6 and 9% by weight of binder), and different coarse aggregates (low absorption limestone, high absorption limestone, and granite). Mixtures with no IC served as control mixtures. The concrete mixture proportions in Program III are listed in Table 2.12. The concrete properties and the total internal water are shown in Table 2.13. All of the mixtures had a paste content of 24.6% by volume and a *w/cm* ratio of 0.45. The quantity of total internal water was 3.4 or 8.7% by the weight of binder for the mixtures with portland cement as the only binder and 3.0 to 12.5% by the weight of binder for the mixtures with ternary binder compositions. Slumps were 1¾ or 3¼ in. (45 to 80 mm) for the mixtures with portland cement as the only binder and ranged from 1¾ to 4½ in. (45 to 115 mm) for the mixtures with the ternary binder compositions. Air contents of 7.25 or 8.25% were measured for the mixtures with portland cement as the only binder and ranged from 7.5 to 9.5% for the mixtures with ternary binder compositions. Compressive strengths ranged from 4640 to 5380 psi (32.0 to 37.1 MPa).

Table 2.12: Program III mixture properties

Mixture ID[a]	Material lb/yd^3 (SSD/PSD)								
	Cement (Type I/II)	Silica Fume	G100 Slag	Coarse Agg.		Fine Agg.	Lightweight Agg.	Water	AEA-2[b]
	C(2)	SF	S	LS-12A	LS-12B	MA3	LWA-1/4		fl oz/cwt
T-3.4-L	355	16	159	1189	284	1598	0	239	1.28
T-9.0-L	355	16	159	1189	284	1144	305	239	1.35
T-12.0-L	355	16	159	1189	284	987	411	239	1.06
C-3.4-L	540	0	0	1189	284	1598	0	243	0.99
C-8.7-L	540	0	0	1189	284	1144	305	243	0.99
				G-68A	**G-68 B**				
T-3.0-G	355	16	159	709	721	1598	0	239	1.11
T-8.7-G	355	16	159	709	721	1144	305	239	1.32
				LS-3/4					
T-12.5-H	355	16	159	1460		1144	305	239	1.06

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone, H=High-absorption limestone, G=Granite)
[b] Admixture designation (AEA-2=AEA 92 S)
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Table 2.13: Total internal water and concrete properties in Program III

Mixture ID[a]	Concrete Properties						
	IC Water	TI Water	Slump	Air	Unit Weight	Temperature	28-day Compressive Strength
	(% Binder Weight)	(% Binder Weight)	(in.)	(%)	(lb/ft^3)	(°F)	(psi)
T-3.4-L	0.0	3.4	1¾	8.00	144.7	70	5290
T- 9.0-L	5.5	9.0	2	8.00	138.1	69	5280
T- 12.0-L	9.0	12.0	2½	7.50	136.7	70	5380
C- 3.4-L	0.0	3.4	1¾	7.25	146.1	71	5090
C-8.7-L	5.9	8.7	3¼	8.25	140.3	71	5110
T-3.0-G	0.0	3.0	4½	9.25	139.4	68	4880
T-8.7-G	6.1	8.7	3¾	9.50	136.3	69	4640
T-12.5-H	5.8	12.5	3¼	8.50	137.5	72	5270

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone, H=High-absorption limestone, G=Granite)
Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

2.5.4 Test Program

Test matrix for the three programs are presented in Tables 2.14 through 2.16. The mixtures were tested for compressive strength in accordance with ASTM C39. The mixtures in Program I were freeze-thaw durability in accordance with ASTM C666-Procedure A. The mixtures in Program II were tested for freeze-thaw durability in accordance with ASTM C666-Procedure A and ASTM C666-Procedure B, the latter following the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22, *Resistance of Concrete to Rapid Freezing and Thawing*. Additionally, some mixtures Program II were evaluated for scaling resistance in accordance with ASTM C672 and Canadian test BNQ NQ 2621-900. Finally, the mixtures in Program III were evaluated for free shrinkage in accordance with the modified version of ASTM C157 described in Section 2.4.1 (readings begin just after final set), scaling resistance in accordance with ASTM C672, freeze-thaw durability in accordance with ASTM C666-Procedure

A, rapid chloride permeability in accordance with ASTM C1202, and surface resistivity in accordance with AASHTO TP-95 and Louisiana Department of Transportation and Development (LA DOTD TR 233-11).

Table 2.14: Tests performed on mixtures in Program I

Mixture ID[a]	**Compressive strength**	**Freeze-Thaw**
	ASTM C39	**ASTM C666-Proc. A**
23.7%-8.5-0.45	×	×
23.7%-12.8-0.45	×	×
23.7%-12.9-0.45	×	×
26.7%-8.5-0.45	×	×
26.7%-8.7-0.45	×	×
26.7%-12.3-0.45	×	×
26.7%-12.8-0.45	×	×
33.7%-9.0-0.45	×	×
33.7%-12.8-0.45	×	×
23.7%-8.2-0.41	×	×
23.7%-12.5-0.41	×	×
26.7%-8.5-0.41	×	×
26.7%-8.6-0.41	×	×
26.7%-12.5-0.41	×	×
26.7%-13.1-0.41	×	×
33.7%-8.4-0.41	×	×
33.7%-12.0-0.41	×	×
33.7%-12.2-0.41	×	×

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight; C: *w/c* ratio

Table 2.15: Tests performed on mixtures in Program II

Mixture ID[a]	Compressive strength	Freeze-Thaw		Scaling	
	ASTM C39	ASTM C666-Proc. A	ASTM C666-Proc. B	ASTM C672	BNQ NQ2621-900
23.7%-8.8-0.45	×	×	×	×	×
23.7%-12.2-0.45	×	×	×	×	×
26.7%-8.2-0.45	×		×		
26.7%-12.1-0.45	×		×		
33.7%-9.0-0.45-2	×	×	×	×	×
33.7%-12.5-0.45	×	×	×	×	×
23.7%-9.0-0.41	×	×	×	×	×
23.7%-13.0-0.41	×	×	×	×	×
26.7%-8.6-0.41-2	×		×		
26.7%-12.7-0.41	×		×		
33.7%-8.3-0.41	×	×	×	×	×
33.7%-13.0-0.41	×	×	×	×	×

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Paste content
B: Internal curing water, % binder weight
C: *w/c* ratio

Table 2.16: Tests performed on mixtures in Program III

Mixture ID[a]	Compressive strength	Free shrinkage	Freeze-Thaw	Scaling	RCP	SRM
	ASTM C39	Modified ASTM C157	ASTM C666-Proc. A	ASTM C672	ASTM C1202	AASHTO TP-95/ LA DOTD TR 233-11
T-3.4-L	×	×	×	×	×	×
T- 9.0-L	×	×	×	×	×	×
T- 12.0-L	×	×	×	×	×	×
C- 3.4-L	×	×	×	×	×	×
C-8.7-L	×	×	×	×	×	×
T-3.0-G	×	×	×	×	×	×
T-8.7-G	×	×	×	×	×	×
T-12.5-H	×	×	×	×	×	×

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Total internal water, % binder weight
F: Type of coarse

CHAPTER 3 – LABORATORY TEST RESULTS

3.1 GENERAL

This chapter presents the test results for the concrete mixtures described in Chapter 2. Chapter 2 includes a detailed description of the materials, mixture proportions, concrete properties, as well as testing procedures for each test program. Laboratory evaluations in this study involve three test programs and aim to evaluate the durability, shrinkage, and transport properties of concrete mixtures incorporating internal curing (IC) water with or without supplementary cementitious materials (SCMs) with further evaluation of the effects of total internal water or TI water (provided by all aggregates) on internally-cured concrete mixtures. The objective of these evaluations is to investigate and compare the results for concretes with different water-to-cementitious material ratios (*w/cm*) and freeze-thaw testing procedures to identify the upper limit on the quantity of IC water and determine if such a limit should be based on (1) IC water as a percentage of binder weight or (2) total weight of water per unit volume of concrete. The freeze-thaw durability of concrete mixtures with *w/cm* ratios typical of those used in bridge deck construction and different paste contents are addressed in test Programs I and II. The effects of total internal water (provided by all aggregates) in internally-cured concrete mixtures are addressed in test Program III.

Unless noted, the results presented in this chapter are the average of three specimens. Data for individual specimens in Programs I and II are presented in Appendix A and for Program III in Appendix B. Detailed information on the procedures of each test is presented in Chapter 2.

3.1.1 Student's *T*-Test

Student's *t*-test is used to determine if the difference between the means of two small data sets, X_1 and X_2, drawn from two normally distributed populations, with unknown means and standard deviations, is due to random variation or represents an actual difference in the populations. The means of two samples are often compared on that basis of the p-value, which indicates the probability that the difference between two means is due to chance at a preselected significance level α when, in fact, they are the same. Thus, the smaller the value of p, the lower the probability that the observed difference is due to chance. A p-value less than a significance level $\alpha = 0.05$, for example, indicates that the probability that the test mistakenly identified the two population means as different is 5% when, in fact, they are not. A p-value greater than the significance level, in this case 0.05, would indicate that that the difference between two means is likely to have been due to chance. Values of $p \leq 0.05$ are usually taken as indicating that the difference between two means is statistically significant.

3.2 PROGRAM I

As described in Chapter 1, the goal of Program I is to establish if the freeze-thaw durability of IC mixtures containing portland cement as the only binder is a function of the IC water as a percentage of the weight of cementitious material or of the total quantity of IC water in a given volume of concrete. The main variables included in this program were paste content (23.7, 26.7, or 33.7%), quantity of internal curing (IC) water provided by pre-wetted lightweight aggregate (8.2 to 13.1%) by the weight of binder, and water-to-cement (*w/c*) ratio (0.45 or 0.41). Nine mixtures each were cast with *w/c* ratios of 0.45 and 0.41. The quantities of IC water for the mixtures with a *w/c* ratio of 0.45 were 8.5 to 9.0% and 12.3 to 12.9% of the binder (cement in this case) content and for the mixtures with a *w/c* ratio of 0.41 were 8.2 to 8.6% and 12.0 to 13.1%. The quantities of absorbed water in LWA for mixtures with the *w/c* ratio of 0.45 ranged from 44.3 to 94.4 lb/yd^3 (26.3 to 56.0 kg/m^3), and for mixtures with the *w/c* ratio of 0.41 ranged from 45.2 to 94.8 lb/yd^3 (26.8 to 56.2 kg/m^3). The air contents and 28-day compressive strengths ranged from

6.25 to 9.25% and 3570 to 5250 psi (24.6 to 36.2 MPa), respectively.

As described in Section 2.5, the naming convention has a form of ‘A-B-C.’ The indicator A identifies the paste content (23.7, 26.7, or 33.7%); the indicator B represents the quantity of IC water as a percentage of the total weight of the binder; and the indicator C equals the *w/c* ratio, 0.45 or 0.41. Duplicate mixtures with the same paste content, IC water content, and *w/c* ratio have an additional indicator at the end of the mixture ID.

Mixtures were evaluated for freeze-thaw durability in accordance with ASTM C666-Procedure A and compressive strength in accordance with ASTM C39. Table 3.1 shows quantities of IC water, absorbed water in LWA, air contents, and compressive strengths of the mixtures included in Program I.

Table 3.1: IC water, absorbed water in LWA, air contents, and compressive strengths of mixtures in Program I

Mixture ID[a]	IC water (% Binder weight)	Absorbed water in LWA (lb/yd^3)	Air content (%)	28-day Compressive strength (psi)
23.7%-8.5-0.45	8.5	44.3	6.50	4310
23.7%-12.8-0.45	12.8	66.4	7.50	4480
23.7%-12.9-0.45	12.9	67.2	6.25	4550
26.7%-8.5-0.45	8.5	49.8	8.00	3960
26.7%-8.7-0.45	8.7	50.8	9.25	3570
26.7%-12.3-0.45	12.3	72.0	6.75	4130
26.7%-12.8-0.45	12.8	74.8	7.00	4410
33.7%-9.0-0.45	9.0	66.9	6.75	4450
33.7%-12.8-0.45	12.8	94.4	7.75	4420
23.7%-8.2-0.41	8.2	45.2	8.50	4800
23.7%-12.5-0.41	12.5	68.4	7.75	4670
26.7%-8.5-0.41	8.5	52.3	6.75	5250
26.7%-8.6-0.41	8.6	52.8	6.75	4490
26.7%-12.5-0.41	12.5	77.2	7.75	4590
26.7%-13.1-0.41	13.1	81.1	7.25	4310
33.7%-8.4-0.41	8.4	65.2	9.00	4670
33.7%-12.0-0.41	12.0	93.7	8.50	4520
33.7%-12.2-0.41	12.2	94.8	9.00	4240

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
Note: 1 psi = 6.89×10^{-3} MPa; 1 lb/yd^3 = 0.593 kg/m^3

3.2.1 Freeze-Thaw Durability

As described in Section 2.5.1, freeze-thaw durability tests were performed in accordance with ASTM C666 Procedure A, with a failure limit corresponding to MnDOT specifications. Per MnDOT IC-LC-HPC specifications, the specimens should maintain at least 90% of the initial dynamic modulus of elasticity values through 300 freeze-thaw cycles to pass the test. The freeze-thaw durability results were also quantified by a Durability Factor (DF) calculated for each mixture using Eq (2.2). In this program, mixtures with DF greater than or equal to 90% through 300 freeze-thaw cycles present satisfactory resistance. Freeze-thaw testing was terminated when the percentage of initial dynamic modulus dropped below 60% of the initial values. Linear interpolation between dynamic moduli and freeze-thaw cycles was used to determine the number of freeze-thaw cycles corresponding to 60 or 90% of the initial dynamic modulus values (if applicable) of the mixtures.

The average percent of initial dynamic moduli of the concrete mixtures with *w/c* ratios of 0.45 and 0.41 are plotted in Figures 3.1 and 3.2 as a function of the number of freezing and thawing cycles, respectively. The dynamic modulus of elasticity for each specimen is provided in Appendix A. The results show that the freeze-thaw durability of concrete mixtures (per ASTM C666-Procedure A) was not satisfactory the requirements in the MnDOT specifications and decreased considerably for IC water contents exceeding 12.0% (by weight of binder), regardless of the paste content or quantity of absorbed water in LWA. Reducing the *w/c* ratio from 0.45 to 0.41 improved the freeze-thaw durability of concrete, as observed earlier by Feng and Darwin (2020) and Lafikes et al. (2020).

As shown in Figure 3.1, the mixtures with IC water contents ranging from 12.3 to 12.9% (by the weight of binder) and *w/c* ratio of 0.45 failed to complete 300 freeze-thaw cycles before their percent of initial dynamic modulus dropped below 90% and would not be considered acceptable under MnDOT specifications. The average percent of initial dynamic modulus of mixture 33.7%-12.8-0.45 decreased to 90% after 161 freeze-thaw cycles, that of mixture 26.7%-12.3-0.45 dropped to 90% after 146 freeze-thaw cycles, that of mixture 26.7%-12.8-0.45 dropped to 90% after 145 freeze-thaw cycles, that of mixture 23.7%-12.8-0.45 dropped to 90% after 146 freeze-thaw cycles, and that of mixture 23.7%-12.9-0.45 reached 90% after 135 freeze-thaw cycles. The average percent of initial dynamic modulus of the mixtures with IC water content ranging from 8.5 to 9.0% (by the weight of binder) dropped below 90% before 300 freeze-thaw cycles, but at a much greater number of cycles than the mixtures with IC water ranging from 12.3 to 12.9%. The average percent of initial dynamic modulus of mixtures 26.7%-8.7-0.45 and 26.7%-8.5-0.45 dropped below 90% after 276 and 267 freeze-thaw cycles, respectively. The average percent of initial dynamic modulus of mixtures 33.7%-9.0-0.45 and 23.7%-8.5(2)-0.45 dropped below 90% after 245 and 240 freeze-thaw cycles, respectively. Table 3.2 presents the number of freeze-thaw cycles corresponding to 90% of the initial dynamic modulus of elasticity and DF values for each mixture with a *w/c* ratio of 0.45. As shown in Table 3.2, the durability factor of the mixtures with IC water contents ranging from 8.5 to 9.0% (by the weight of binder) ranged between 75 and 86%, while that of the mixtures with IC water contents ranging from 12.3 to 12.9% (by the weight of binder) ranged between 38 and 45%, all below the acceptance value of 90%.

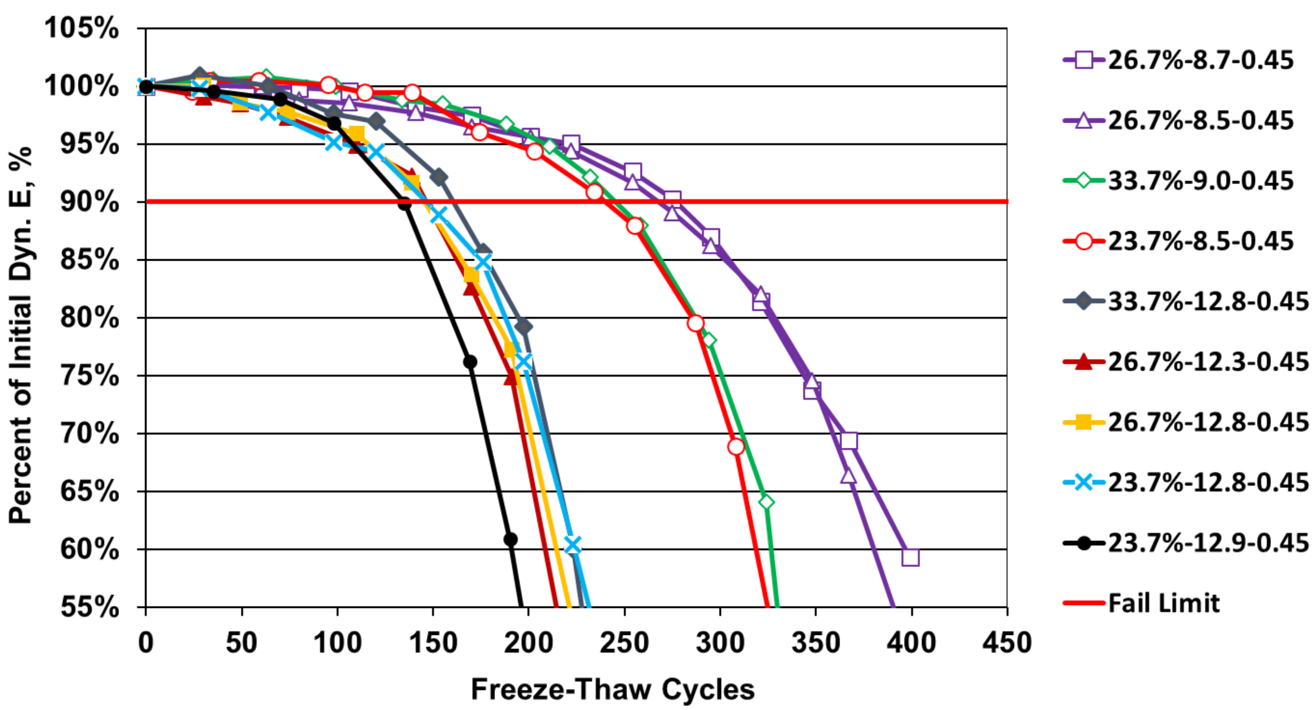


Figure 3.1: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures with a *w/c* ratio of 0.45 tested in accordance with ASTM C666-Procedure A

Table 3.2: Summary of freeze-thaw results in Program I for mixtures with a *w/c* ratio of 0.45 tested in accordance with ASTM C666-Procedure A

Mixture ID[a]	IC water content (%)	Absorbed water in LWA (lb/yd^3)	No. of Cycles to 90% of initial dynamic modulus of elasticity	Durability Factor[b] (%)
23.7%-8.5-0.45	8.5	44.3	240	76
23.7%-12.8-0.45	12.8	66.4	146	45
23.7%-12.9-0.45	12.9	67.2	135	38
26.7%-8.5-0.45	8.5	49.8	267	85
26.7%-8.7-0.45	8.7	50.8	276	86
26.7%-12.3-0.45	12.3	72.0	146	42
26.7%-12.8-0.45	12.8	74.8	145	43
33.7%-9.0-0.45	9.0	66.9	245	75
33.7%-12.8-0.45	12.8	94.4	161	45

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] (DF) = ($P \times N$) / 300 cycles,
where P is the percentage of the initial dynamic modulus remaining at N cycles, N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller)

As with the IC mixtures with a *w/c* ratio of 0.45, the results indicate that mixtures with IC water contents ranging from 8.2 to 8.6% (by the weight of binder) and a *w/c* ratio of 0.41 exhibited better freeze-thaw durability than the mixtures with IC water contents ranging from 12.0 to 13.1%, regardless of the paste content or quantity of absorbed water in LWA. As shown in Figure 3.2, the dynamic modulus of elasticity of all the mixtures, however, dropped below 90% of the initial values by 300 freeze-thaw cycles and would not be considered acceptable under MnDOT specifications. Mixtures with IC water contents ranging from 12.0 to 12.5% failed the test with a similar number of freeze-thaw cycles ranging between 155 and 174 cycles. For mixture 26.7%-13.1-0.41, which contained the highest quantity of IC water (13.1%, by the weight of binder), the dynamic modulus of elasticity dropped below 90% of the initial value after just 134 freeze-thaw cycles, the fewest among this series. Although none of the mixtures with IC water contents ranging from 8.2 to 8.6% and a *w/c* ratio of 0.41 passed the freeze-thaw test, the number of cycles to 90% of the initial dynamic modulus of elasticity was in a close range, between 258 and 280 cycles.

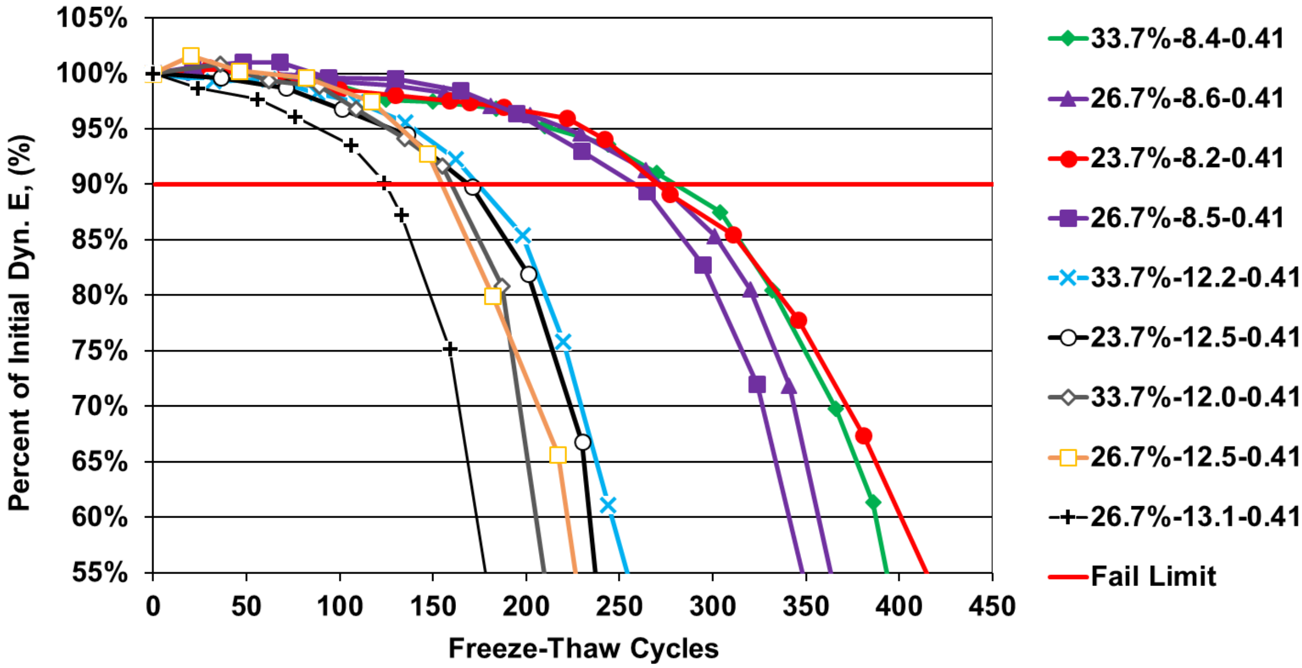


Figure 3.2: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for mixtures with a *w/c* ratio of 0.41 tested in accordance with ASTM C666-Procedure A

Table 3.3 presents the number of freeze-thaw cycles corresponding to 90% of the initial dynamic modulus of elasticity and DF values for each mixture with a *w/c* ratio of 0.41. The durability factor of the mixtures with IC water contents ranging from 8.2 to 8.6% (by the weight of binder) ranged between 81 and 88%, while that of the mixtures with IC water contents ranging from 12.0 to 13.1% (by the weight of binder) ranged between 35 and 49%, again, all below the MnDOT acceptance value of 90%.

Table 3.3: Summary of freeze-thaw results in Program I with a *w/c* ratio of 0.41 tested in accordance with ASTM C666-Procedure A

Mixture ID[a]	IC water content (%)	Absorbed water in LWA (lb/yd^3)	No. of Cycles to 90% of initial dynamic modulus of elasticity	Durability Factor[b] (%)
23.7%-8.2-0.41	8.2	45.2	270	87
23.7%-12.5-0.41	12.5	68.4	166	47
26.7%-8.5-0.41	8.5	52.3	258	81
26.7%-8.6-0.41	8.6	52.8	272	85
26.7%-12.5-0.41	12.5	77.2	155	44
26.7%-13.1-0.41	13.1	81.1	134	35
33.7%-8.4-0.41	8.4	65.2	280	88
33.7%-12.0-0.41	12.0	93.7	160	41
33.7%-12.2-0.41	12.2	94.8	174	49

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] (DF) = ($P \times N$) / 300 cycles,
where P is the percentage of the initial dynamic modulus remaining at N cycles, N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller)

A comparison between the durability factors of the IC mixtures with *w/c* ratios of both 0.45 and 0.41 is illustrated in Figure 3.3. The average durability factor of the mixtures with IC water contents ranging from 12.3 to 12.9%, with a *w/c* ratio of 0.45 was 46%, while that of the mixtures with IC water contents ranging from 12.0 to 13.1%, with a *w/c* ratio of 0.41 was 43%. Similarly, the average durability factor of the mixtures with IC water contents ranging from 8.5 to 9.0%, with a *w/c* ratio of 0.45 was 81%, while that of the mixtures with IC water contents ranging from 8.2 to 8.6%, with a *w/c* ratio of 0.41 was 85%. As shown in Figure 3.3, for the majority of the mixtures, decreasing the *w/c* ratio from 0.45 to 0.41 increased the freeze-thaw durability.

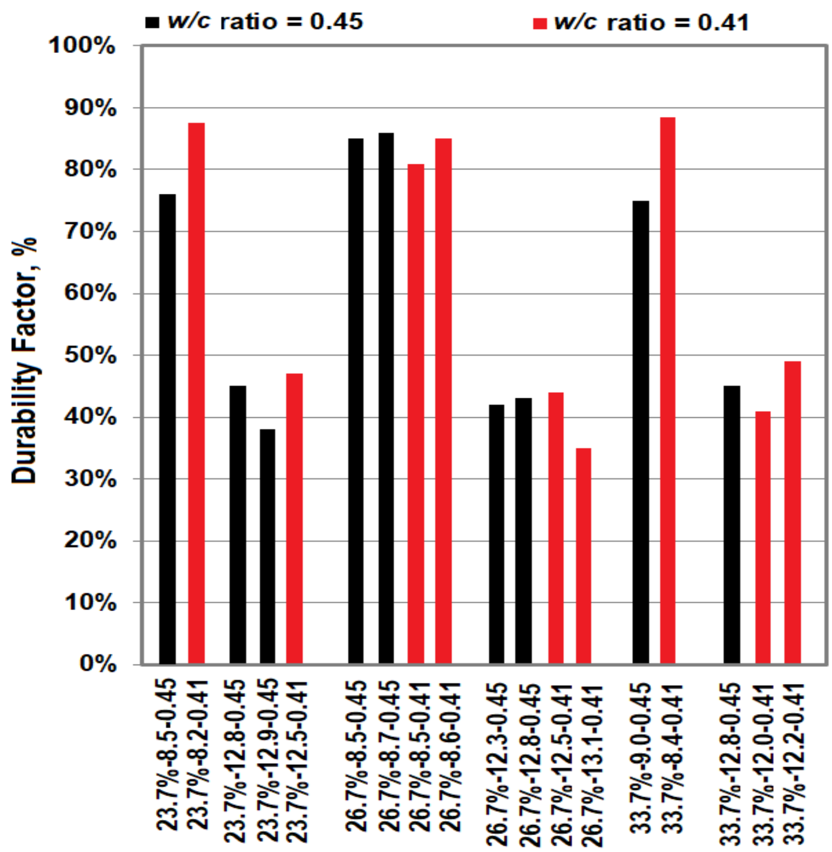
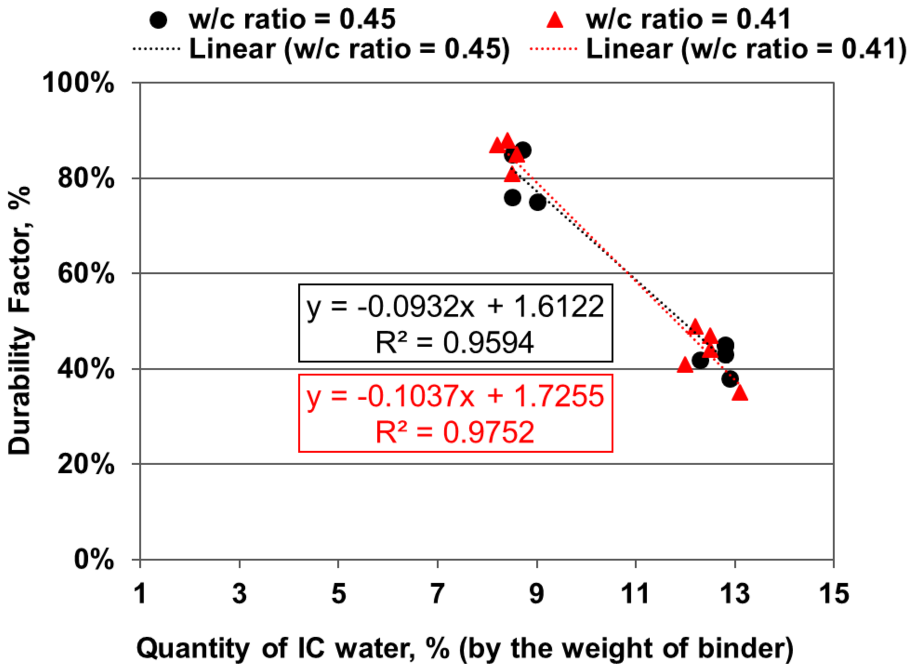
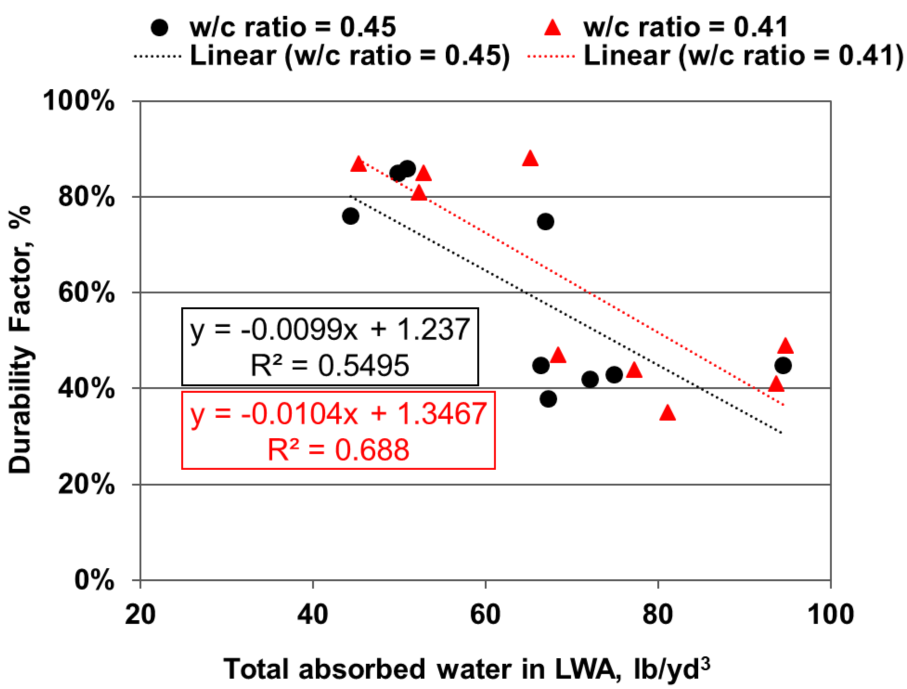


Figure 3.3: Durability factor comparisons between IC mixtures with *w/c* ratios of either 0.45 or 0.41 tested in accordance with ASTM C666-Procedure A

Figure 3.4(a) and Figure 3.4(b) compare the durability factor as a function of the quantity of IC water (by the weight of binder) and absorbed water in LWA, respectively, for mixtures with *w/c* ratios of 0.45 or 0.41. The best fit line, corresponding equations, and R-squared (R^2) values are shown in each figure. The R^2 value indicates how well one variable explains the variance of another; for instance, the R^2 of equal to 0.90 indicates that approximately 90% of the observed variation in the dependent variable (durability factor) can be explained by the independent variable (quantity of IC water [by the weight of binder] or absorbed water in LWA).



(a)



(b)

Figure 3.4: Durability factor as a function of: (a) the quantity of IC water (by the weight of binder); (b) absorbed water in LWA for mixtures with *w/c* ratios of 0.45 or 0.41 tested in accordance with ASTM C666-Procedure A

As shown in Figures 3.4(a) and 3.4(b), the durability factor can be clearly explained by the quantity of IC water as a percentage of binder weight rather than the total weight of IC water per unit volume of concrete (absorbed water in LWA) with R^2 values of 0.96 and 0.98 for *w/c* ratios of 0.45 and 0.41, respectively, compared to that of the 0.55 and 0.69. A linear regression analysis was utilized to further investigate the estimation of relationships between the durability factor and the above-mentioned variables. Considering that the R^2 values for mixtures with *w/c* ratios of either 0.45 or 0.41 were relatively close to each other (0.96 vs. 0.98 and 0.55 vs. 0.69), their data were grouped for the regression analysis. Slope coefficients (β) and *p*-value of the t-statistics of the slope coefficients were obtained for each independent variable. A *p*-value greater than 0.05 indicates that the null hypothesis H_0: β = 0 (that the slope coefficient is equal to zero) is true and, therefore, the variable does not contribute to the model, while a *p*-value less than or equal to 0.05 indicates that the null hypothesis is false and, therefore, the variable contributes to the model. The regression analysis results are shown in Table 3.4. The results show that the durability factor is principally a function of the quantity of IC water by the weight of binder with *p*-value and R^2 of 1.9×10^{-9} (statistically significant) and 0.97, respectively, rather than absorbed water in LWA, with *p*-value and R^2 values of 0.79 (not statistically significant) and 0.59, respectively.

Table 3.4: Regression analysis results

Principle variables	Slope coefficients, β	*p*-values of the t-statistics of the slope coefficients	Coefficient of determination (R^2)[a]
Quantity of IC water by the weight of binder, %	-0.0968	**1.9×10^{-9}**	0.97
Absorbed water in LWA, yd^3	-0.0003	0.79	0.59

[a] For the model having only a single independent variable

3.3 PROGRAM II

As discussed in Chapter 1, prior studies have shown that different methods of testing durability (testing with different curing periods and deicing salts) can lead to inconclusive results regarding freeze-thaw durability and scaling resistance (Abdul Baki et al. 2020). Therefore, Program II examines the freeze-thaw durability and scaling resistance of IC mixtures under different testing procedures to help establish an upper limit on IC water without jeopardizing concrete durability. It is important to note that Programs I and II used granite as the coarse aggregate, and therefore, poor coarse aggregate is not an issue for the mixtures in these programs. As in Program I, the main variables in Program II are paste contents of either 23.7, 26.7, or 33.7% (containing portland cement as the only binder), quantity of internal curing (IC) water provided by pre-wetted lightweight aggregate (8.2 to 13.0%) by the weight of binder, and different water-to-cement material (*w/c*) ratios of 0.45 or 0.41. As described in Section 2.5.4, two different methods of testing durability (freeze-thaw durability and scaling resistance) are used; six mixtures each were cast with *w/c* ratios of 0.45 and 0.41. The quantities of IC water for the mixtures with the *w/c* ratio of 0.45 were 8.2 to 9.0% and 12.1 to 12.5%, and for the mixtures with the *w/c* ratio of 0.41 were 8.3 to 9.0 % and 12.7 to 13.0%. The naming convention is the same as what described for the mixtures in Program I.

Side-by-side durability testing was performed on some mixtures. Eight mixtures were evaluated for freeze-thaw durability in accordance with ASTM C666-Procedure A, and twelve mixtures (including eight paired mixtures and four extra) were evaluated for freeze-thaw durability following the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22, *Resistance of Concrete to Rapid Freezing and Thawing*, exposed to rapid freeze-thaw cycles as specified in ASTM C666-Procedure B. Eight mixtures were evaluated for scaling resistance in accordance with ASTM C672 and Canadian test BNQ NQ 2621-900. All mixtures were evaluated for compressive strength in accordance with ASTM C39. Table 3.5 shows the quantities of IC water, absorbed water in LWA, air contents, and compressive strengths of mixtures in Program II.

As shown in Table 3.5, the quantities of IC water for mixtures with the *w/c* ratio of 0.45 ranged from 8.2 to 12.5%, and for mixtures with the *w/c* ratio of 0.41 from 8.3 to 13.0%. The quantities of absorbed water in LWA for mixtures with the *w/c* ratio of 0.45 ranged from 45.9 to 92.4 lb/yd^3 (27.2 to 54.8 kg/m^3), and for mixtures with the *w/c* ratio of 0.41 from 49.1 to 101.5 lb/yd^3 (29.1 to 60.2 kg/m^3). The air contents and 28-day compressive strengths ranged from 6.25 to 9.25% and 4050 to 4720 psi (27.9 to 32.5 MPa), respectively.

Table 3.5: IC water, absorbed water in LWA, air contents, and compressive strengths of mixtures in Program II

Mixture ID[a]	**IC water**	**Absorbed water in LWA**	**Air**	**28-day Compressive strength**
	(% Binder Weight)	**(lb/yd^3)**	**(%)**	**(psi)**
23.7%-8.8-0.45	8.8	45.9	8.75	4490
23.7%-12.2-0.45	12.2	63.3	8.00	4370
26.7%-8.2-0.45	8.2	47.9	8.75	4050
26.7%-12.1-0.45	12.1	71.0	8.50	4250
33.7%-9.0-0.45-2	9.0	66.8	6.25	4400
33.7%-12.5-0.45	12.5	92.4	6.75	4510
23.7%-9.0-0.41	9.0	49.1	9.00	4700
23.7%-13.0-0.41	13.0	71.3	9.25	4360
26.7%-8.6-0.41-2	8.6	52.9	7.75	4720
26.7%-12.7-0.41	12.7	78.5	8.25	4420
33.7%-8.3-0.41	8.3	64.8	7.75	4700
33.7%-13.0-0.41	13.0	101.5	8.75	4410

[a] Mixture IDs labeled as ‘A-B-C,’ where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
Note: 1 psi = 6.89×10^{-3} MPa; 1 lb/yd^3 = 0.593 kg/m^3

3.3.1 Freeze-Thaw Durability

Eight mixtures were evaluated for freeze-thaw durability in accordance with ASTM C666 Procedure A, with a failure limit corresponding to MnDOT specifications. Per MnDOT IC-LC-HPC specifications, the specimens should maintain at least 90% of the initial dynamic modulus of elasticity values through 300 freeze-thaw cycles to pass the test. The freeze-thaw durability results were also quantified by a Durability Factor (DF) calculated for each mixture using Eq (2.2). For these mixtures, DF greater than or equal to 90% through 300 freeze-thaw cycles presents satisfactory resistance; freeze-thaw testing was terminated when the percent of initial dynamic modulus dropped below 60% of the initial values.

Twelve mixtures (eight paired mixtures and four extra) were evaluated for freeze-thaw durability following the regime specified in KTMR-22. Per KTMR-22, the specimens should maintain at least 95% of the initial dynamic modulus of elasticity values through 660 freeze-thaw cycles to pass the test. For these mixtures, DF greater than or equal to 95% through 660 freeze-thaw cycles presents satisfactory resistance; freeze-thaw testing was terminated when the percent of initial dynamic modulus dropped below 60% of the initial values or after 660 freeze-thaw cycles, whichever occurred first. Linear interpolation between relative dynamic moduli and freeze-thaw cycles was used to determine the number of freeze-thaw cycles corresponding to 60%, 90%, or 95% of the initial dynamic modulus values (if applicable) of the mixtures for the corresponding testing method. The dynamic modulus of elasticity for each specimen is provided in Appendix A.

As in Program I, for mixtures with a *w/c* ratio of 0.45, the freeze-thaw durability of concrete mixtures (per ASTM C666-Procedure A) did not satisfy the MnDOT specifications and decreased considerably for the IC water contents above 12% (by the weight of binder), regardless of the paste content or quantity of absorbed water in LWA. Additionally, the results indicate that reducing the *w/c* ratio from 0.45 to 0.41 improved the freeze-thaw durability of concrete. As expected, the testing procedure has a considerable effect on the freeze-thaw performance of IC mixtures. Compared to the IC mixtures tested in accordance with ASTM C666-Procedure A, where all the specimens failed the test (the dynamic modulus of elasticity of the mixtures dropped below 90% of the initial value in less than 300 cycles), except for mixtures 33.7-9.0-0.45-2 and 33.7%-12.5-0.45, the reminder of the paired mixtures showed better freeze-thaw resistance (DF above 94%) when tested following the regime specified KTMR-22 and ASTM C666-Procedure B. This is not unexpected, as ASTM C666-Procedure A keeps the specimens saturated during both freezing and thawing. Longer curing periods and less intense the testing environment appear to improve freeze-thaw resistance of IC mixtures. Figure 3.5 presents the average percent of initial dynamic moduli of the concrete mixtures with a *w/c* ratio of 0.45 as a function of the number of freeze-thaw cycles for two different durability testing methods.

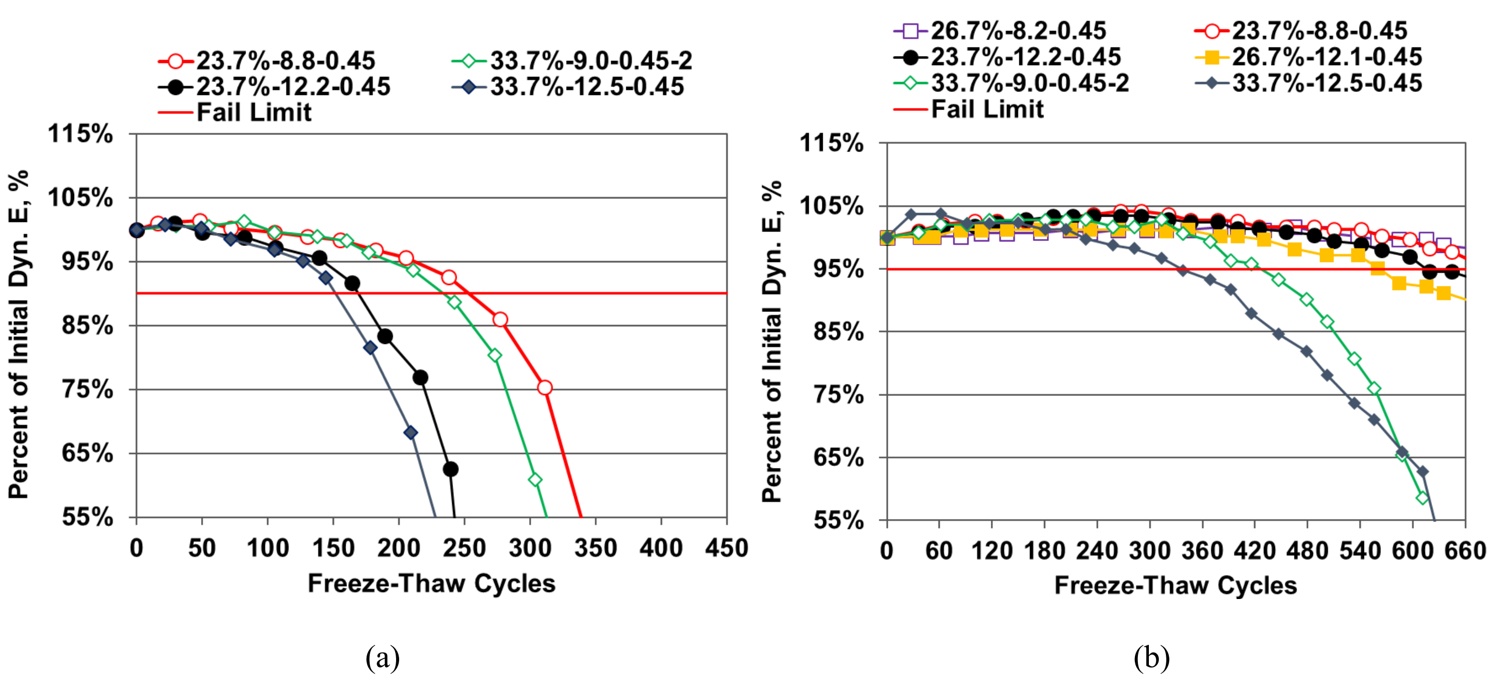


Figure 3.5: Average percent of initial dynamic moduli vs. freeze-thaw cycles for mixtures with a *w/c* ratio of 0.45; (a) tested in accordance with ASTM C666-Procedure A; (b) tested in accordance with KTMR-22 and ASTM C666-Procedure B

As shown in Figure 3.5(a), the dynamic modulus of elasticity of the mixtures tested in accordance with ASTM C666-Procedure A with IC water contents of either 8.8 or 9.0% (by the weight of binder), with a paste content of either 23.7 or 33.7%, respectively, dropped below 90% of the initial values after 253 and 234 cycles, respectively, and failed the test. The dynamic modulus of elasticity of the mixtures tested in accordance with ASTM C666-Procedure A with IC water contents of either 12.2 or 12.5% (by the weight of binder), with a paste content of either 23.7% or 33.7%, dropped below 90% of the initial values in fewer cycles, after 169 and 152 cycles, respectively.

As shown in Figure 3.5(b), except for one mixture (33.7-9.0-0.45-2), the dynamic modulus of elasticity of the mixtures tested in accordance with KTMR-22 and ASTM C666-Procedure B with IC water contents of either 8.2 or 8.8% (by the weight of binder) remained above 95% of the initial value through 660 freeze-thaw cycles and passed the test. All of the mixtures with IC water contents above 12.1% failed the test. The dynamic modulus of elasticity of mixture 33.7-9.0-0.45-2, dropped below 95% of the initial value after 426 cycles. This mixture had an air content of just 6.25%, lower than the lower IC-LC-HPC specification limit of 6.5%. The dynamic modulus of elasticity of the mixtures with IC water contents ranging from 12.1 to 12.5% by the weight of binder and paste contents of either 23.7%, 26.7, or 33.7%, dropped below 95% of the initial value after 615, 562, and 335 cycles, respectively, also failing the test.

To establish an upper limit for the quantity of IC water, the DF values for each mixture with a *w*/*c* ratio of 0.45 from Programs I and II are compared, as shown in Figure 3.6, and summarized in Table 3.6. As shown in the figure, all of the mixtures assessed for freeze-thaw durability in accordance with ASTM C666-Procedure A exhibited durability factors below 90% and failed the test and are not considered acceptable under MnDOT specifications. Two mixtures, with IC water contents (by the weight of binder) of 8.8 (with a paste content of 23.7%) and 8.2% (with a paste content of 26.7%) and tested in accordance with ASTM C666-Procedure B and KTMR-22 exhibited durability factors above 95%, passing the test and are considered acceptable under KDOT specifications. The mixtures with IC water contents of 12.1% and more with paste contents of 23.7 and 26.7% failed the test, as did the mixtures with IC water contents of 9.0, 12.5, and 12.8% with a paste content of 33.7%.

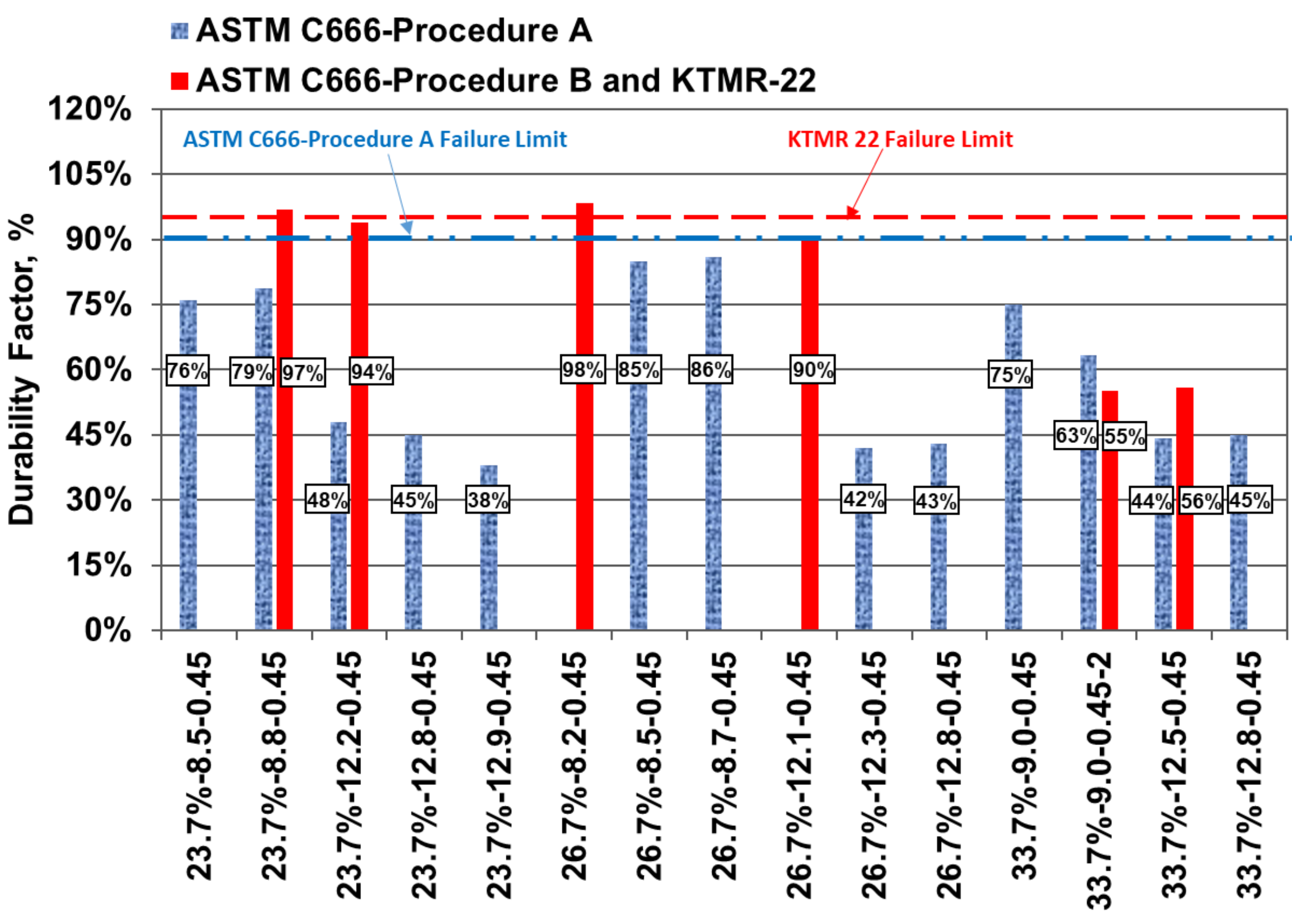


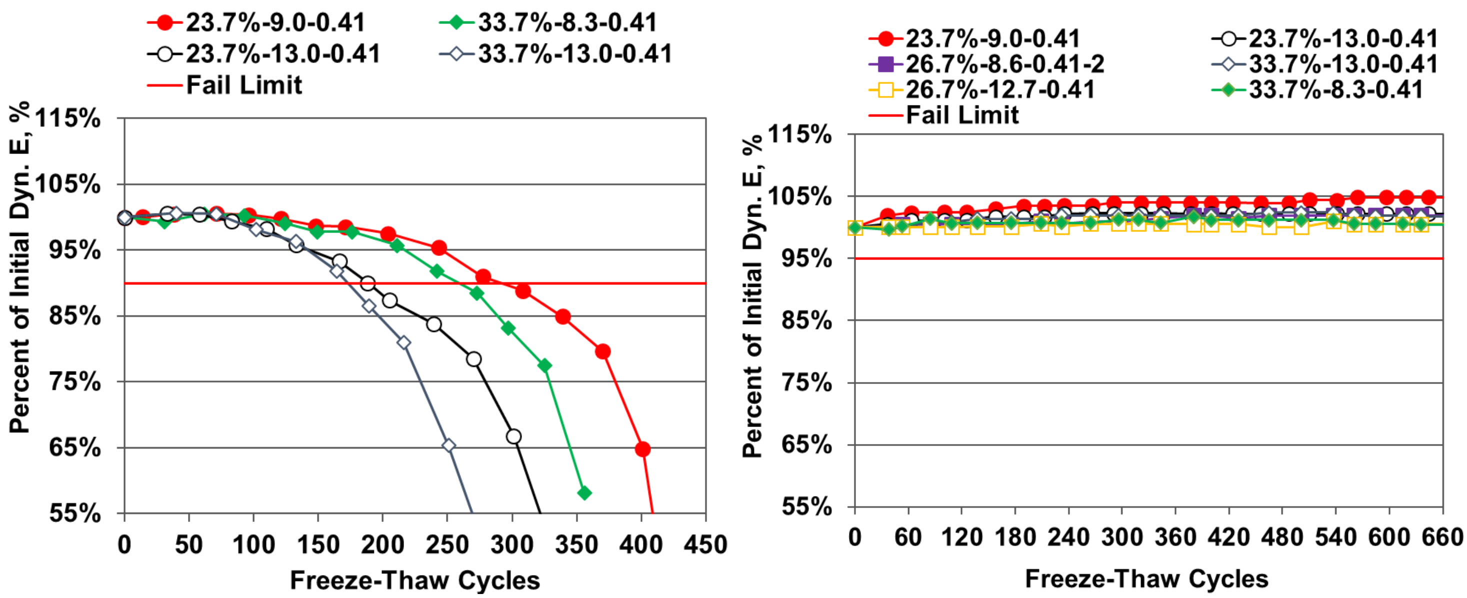
Figure 3.6: Durability factors of mixtures with a *w/c* ratio of 0.45 from Programs I and II

Table 3.6: Summary of freeze-thaw results in Programs I and II with a *w/c* ratio of 0.45 tested in accordance with ASTM C666-Procedure A, and KTMR-22 and ASTM C666-Procedure B

Mixture ID[a]	**IC water content (%)**	**ASTM C666-Procedure A**		**KTMR-22 and ASTM C666-Procedure B**	
		No. of Cycles to 90% of initial dynamic modulus of elasticity	**Durability Factor[b] (%)**	**No. of Cycles to 95% of initial dynamic modulus of elasticity**	**Durability Factor[b] (%)**
23.7%-8.5-0.45	8.5	240	76	-	-
23.7%-8.8-0.45	8.8	253	79	689	97
23.7%-12.2-0.45	12.2	169	48	615	94
23.7%-12.8-0.45	12.8	146	45	-	-
23.7%-12.9-0.45	12.9	135	38	-	-
26.7%-8.2-0.45	8.2	-	-	784	98
26.7%-8.5-0.45	8.5	267	85	-	-
26.7%-8.7-0.45	8.7	276	86	-	-
26.7%-12.1-0.45	12.1	-	-	562	90
26.7%-12.3-0.45	12.3	146	42	-	-
26.7%-12.8-0.45	12.8	145	43	-	-
33.7%-9.0-0.45	9.0	245	75	-	-
33.7%-9.0-0.45-2	9.0	292	63	426	55
33.7%-12.5-0.45	12.5	152	44	335	56
33.7%-12.8-0.45	12.8	161	45	-	-

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] (DF) = ($P \times N$) / 300 (or 660 in accordance with KTMR-22) cycles,
where P is the percentage of the initial dynamic modulus remaining at N cycles, N is either the number of cycles at which P reached 60% or 300 (or 660 in accordance with KTMR-22) cycles (whichever is smaller)
"-" Test not performed

Figure 3.7 presents the average percent of initial dynamic moduli for the concrete mixtures with a *w/c* ratio of 0.41 as a function of the number of freeze-thaw cycles for two different durability testing methods.



(a) (b)

Figure 3.7: Average percent of initial dynamic moduli vs. freeze-thaw cycles for mixtures with a *w/c* ratio of 0.41; (a) tested in accordance with ASTM C666-Procedure A; (b) tested in accordance with KTMR-22 and ASTM C666-Procedure B

As shown in Figure 3.7(a), none of the mixtures with a *w/c* ratio of 0.41 satisfied MnDOT specifications when tested in accordance with ASTM C666-Procedure A, showing the greatest decrease for IC water contents of 13.0%. The dynamic modulus of elasticity of the mixtures with IC water contents of 8.3 and 9.0% by the weight of binder, dropped below 90% of the initial value after 292 and 259 cycles, respectively. The dynamic modulus of elasticity of the mixtures with IC water contents of 13.0% by the weight of binder and paste contents of either 23.7 or 33.7% dropped below 90% of the initial value in fewer cycles, 188 and 173, respectively. Compared with the IC mixtures with a *w/c* ratio of 0.45, reducing the *w/c* ratio from 0.45 to 0.41 improved the freeze-thaw durability. As shown in Figure 3.7(b), the dynamic modulus of elasticity of all mixtures remained above 95% of the initial value through 660 freeze-thaw cycles, and passed the test and would be considered acceptable under KDOT specifications. The extended curing period, less intense the testing environment associated with KTMR-22 and ASTM C666-Procedure B, and decreased *w/c* ratio resulted in better freeze-thaw performance. The DF values for the mixtures with the *w/c* ratio of 0.41 from Programs I and II are compared in Figure 3.8 and summarized in Table 3.7. Further research is needed to study with greater scope how the freeze-thaw resistance of IC mixtures with different binder compositions changes following the regime specified in the KTMR-22 test procedure as a function of paste volume and IC water content.

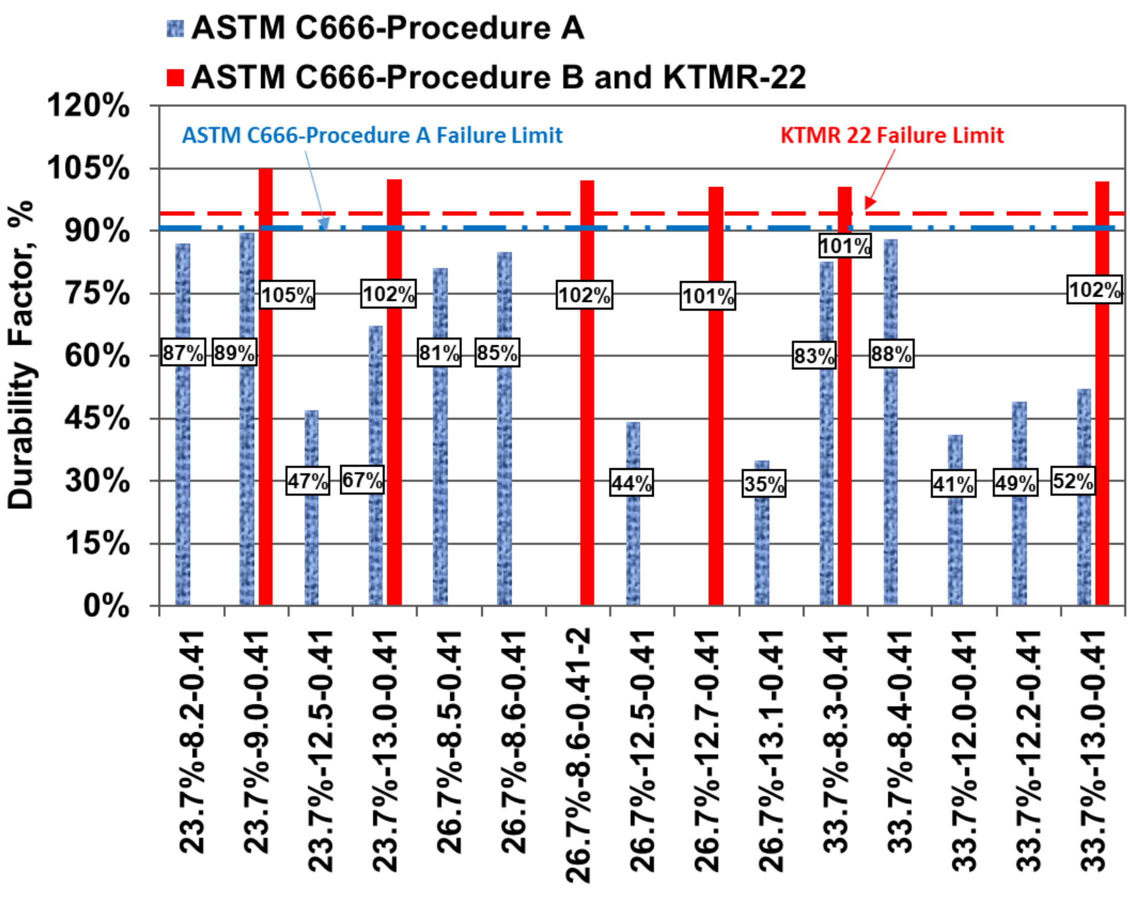


Figure 3.8: Durability factors of mixtures with a *w/c* ratio of 0.41 from Programs I and II

Table 3.7: Summary of freeze-thaw results in Program I and II with a *w/c* ratio of 0.41 tested in accordance with ASTM C666-Procedure A, and KTMR-22 and ASTM C666-Procedure B

Mixture ID[a]	**IC water content (%)**	**ASTM C666-Procedure A**		**KTMR-22 and ASTM C666-Procedure B**	
		No. of Cycles to 90% of initial dynamic modulus of elasticity	**Durability Factor**[b] **(%)**	**No. of Cycles to 95% of initial dynamic modulus of elasticity**	**Durability Factor**[b] **(%)**
23.7%-8.2-0.41	8.2	270	87	-	-
23.7%-9.0-0.41	9.0	292	89	>	105
23.7%-12.5-0.41	12.5	166	47	-	-
23.7%-13.0-0.41	13.0	188	67	>	102
26.7%-8.5-0.41	8.5	258	81	-	-
26.7%-8.6 -0.41	8.6	272	85	-	-
26.7%-8.6-0.41-2	8.6	-	-	>	102
26.7%-12.5-0.41	12.5	155	44	-	-
26.7%-12.7-0.41	12.7	-	-	>	101
26.7%-13.1-0.41	13.1	134	35	-	-
33.7%-8.3-0.41	8.3	259	83	>	101
33.7%-8.4-0.41	8.4	280	88	-	-
33.7%-12.0-0.41	12.0	160	41	-	-
33.7%-12.2-0.41	12.2	174	49	-	-
33.7%-13.0-0.41	13.0	173	52	>	102

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] (DF) = ($P \times N$) / 300 (or 660 in accordance with KTMR-22) cycles,
where P is the percentage of the initial dynamic modulus remaining at N cycles, N is either the number of cycles at which P reached 60% or 300 (or 660 in accordance with KTMR-22) cycles (whichever is smaller)
"-" Test not performed; ">" Relative E_{dyn}. remained above 95%

3.3.2 Scaling Resistance

The scaling test results are presented in Table 3.8 and Figures 3.9 and 3.10. Individual mass loss from each test are included in Appendix A. Table 3.8 shows the average cumulative mass loss at 50 and 56 cycles for the mixtures tested in accordance with ASTM C672 and BNQ NQ2621-900, respectively. Table 3.8 also provides visual ratings corresponding to the mixtures evaluated under ASTM C672. The MnDOT IC-LC-HPC specifications indicate a maximum visual rating of 1 at 50 freeze-thaw cycles for scaling resistance of mixtures in accordance with ASTM C672. To evaluate the effects of the test parameters on scaling, Student's t-test is employed for examining the statistical significance of differences in mass losses as a function of paste content, *w/c* ratio, IC water, and deicing salt type. In this study, the difference between results with a *p*-value less than or equal to 0.05 is considered statistically significant, indicating that the probability that the observed difference in means is due to a meaningful difference in behavior rather than a random variation.

Table 3.8: Average cumulative mass loss for Program II mixtures, lb/ft^2

Mixture ID[a]	ASTM C672		BNQ NQ2621-900
	Visual Rating at 50 Cycles	Mass Loss at 50 Cycles	Mass Loss at 56 Cycles
23.7%-8.8-0.45	1	0.14	0.10
23.7%-12.2-0.45	2	0.23	0.14
33.7%-9.0-0.45-2	3	0.28	0.15
33.7%-12.5-0.45	3	0.30	0.19
23.7%-9.0-0.41	1	0.10	0.07
23.7%-13.0-0.41	2	0.19	0.10[b]
33.7%-8.3-0.41	2	0.16	0.11
33.7%-13.0-0.41	2	0.20	0.11

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] Average of two specimens
Note: 1 lb/ft^2 = 4.88 kg/m^2

The results indicate as the paste content increased from 23.7 to 33.7%, the scaling resistance of the specimens considerably decreased. To clarify, for a given *w/c* ratio (either 0.41 or 0.45) and quantity of IC water, mixtures with a higher paste content had more mass losses than mixtures with a lower paste content. As with results obtained from the freeze-thaw tests, reducing the *w/c* ratio from 0.45 to 0.41 improved the scaling resistance of the concrete mixtures. As a general observation, the mixtures tested in accordance with Canadian test BNQ NQ 2621-900 had lower mass losses than the paired mixtures tested in accordance with ASTM C672. The IC mixtures tested in accordance with ASTM C672 exhibited mass losses ranging from 0.14 to 0.30 lb/ft^2 (0.7 to 1.5 kg/m^2), while the paired mixtures tested in accordance with BNQ NQ 2621-900 exhibited mass losses ranging from 0.07 to 0.19 lb/ft^2 (0.3 to 0.9 kg/m^2).

The scaling results in accordance with ASTM C672 of the concrete mixtures with a 23.7% paste content, *w/c* ratio of 0.45, and IC water contents of either 8.8 or 12.2% by weight of binder showed a visual rating of (1) by the end of 50 freeze-thaw cycles. The paired mixtures exhibited mass losses of 0.1 lb/ft^2 ([0.5 kg/m^2], at the failure limit of 0.1 lb/ft^2 [0.5 kg/m^2]) and 0.14 lb/ft^2 ([0.7 kg/m^2], which failed the test), respectively, by the end of 56 freeze-thaw cycles when tested in accordance with BNQ NQ 2621-900. The scaling results in accordance with ASTM C672 of the concrete mixtures with a 23.7% paste content, *w/c* ratio of 0.41, and IC water contents of either 9.0 or 13.0% by weight of binder showed visual ratings of (1) and (2), respectively, by the end of 50 freeze-thaw cycles. The paired mixtures exhibited mass losses of 0.07 and 0.10 lb/ft^2 (0.3 and 0.5 kg/m^2), respectively, by the end of 56 freeze-thaw cycles, respectively, when tested in accordance with BNQ NQ 2621-900.

The scaling results in accordance with ASTM C672 of the concrete mixtures with a 33.7% paste content, *w/c* ratio of 0.45, and IC water contents of either 9.0 or 12.5% by weight of binder showed a visual rating of (3) by the end of 50 freeze-thaw cycles. The paired mixtures exhibited mass losses of 0.15 and 0.19 lb/ft^2 (0.7 and 0.9 kg/m^2), respectively, by the end of 56 freeze-thaw cycles when tested in accordance with BNQ NQ 2621-900 and failed the test. The scaling results in accordance with ASTM C672 of the concrete mixtures with a 33.7% paste content, *w/c* ratio of

0.41, and IC water contents of either 8.3 or 13.0% by weight of binder showed a visual rating of (2) by the end of 50 freeze-thaw cycles. The paired mixtures exhibited mass losses of 0.11 lb/ft^2 (0.5 kg/m^2) each by the end of 56 freeze-thaw cycles when tested in accordance with Canadian test BNQ NQ 2621-900.

Figure 3.10 shows the average cumulative mass loss of scaling specimens exposed to $CaCl_2$ in accordance with ASTM C672. The results of Student's t-test are shown in Table 3.9.

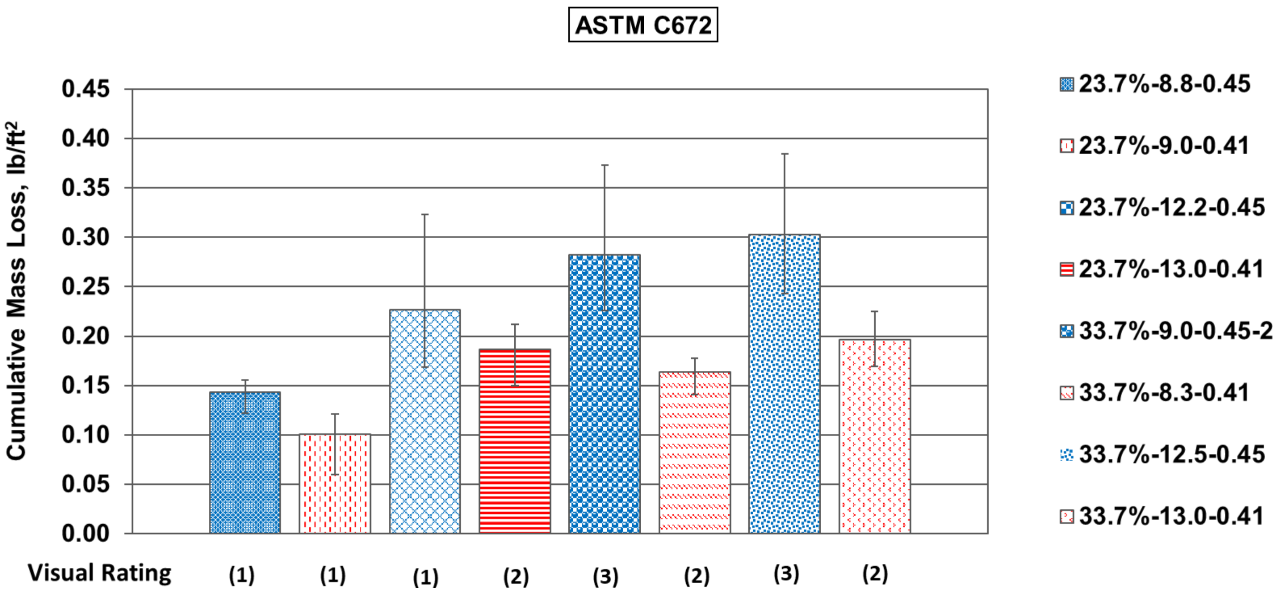


Figure 3.9: Average cumulative mass loss of IC mixtures with *w/c* ratios of 0.45 and 0.41 and exposed to $CaCl_2$ (ASTM C672)

As shown in Figure 3.9, as the paste content increased from 23.7 to 33.7%, mass loss increased in mixtures with a similar quantity of IC water or *w/c* ratio. A mixture with a 33.7% paste content, *w/c* ratio of 0.45, and IC water content of 9.0% (by weight of binder) had higher mass losses than a mixture with a 23.7% paste content, the same *w/c* ratio, and a similar quantity of IC water (0.28 vs. 0.14 lb/ft^2 [1.4 vs. 0.7 kg/m^2]), with differences that are statistically significant (*p*-value of 0.04). As discussed in Chapter 1, scaling tests such as ASTM C672 that use $CaCl_2$ as a deicing salt, test both scaling and calcium oxychloride resistance. Consequently, the scaling tests performed in accordance with ASTM C672 appear to exhibit increased damage due to both scaling and formation of calcium oxychloride. The increased quantity of calcium hydroxide available to react with calcium chloride in mixtures with higher paste contents (specifically higher cement content) increases the likelihood of calcium oxychloride formation, resulting in more damage.

The results also show that increasing the quantity of IC water did not positively improve the scaling resistance of the concrete specimens when exposed to $CaCl_2$, with differences that are not statistically significant. Although reducing the *w/c* ratio from 0.45 to 0.41 resulted in a notable decrease in mass loss, the differences between paired mixtures are not statistically significant.

Table 3.9: *p* values obtained from Student's t-test for the differences in cumulative scaling mass in accordance with ASTM C672

Mixtures ID[a]	**Average mass loss at 50 cycles (lb/ft^2)**	**23.7%-8.8-0.45**	**23.7%-9.0-0.41**	**23.7%-12.2-0.45**	**23.7%-13.0-0.41**	**33.7%-9.0-0.45-2**	**33.7%-8.3-0.41**	**33.7%-12.5-0.45**	**33.7%-13.0-0.41**
		(0.14)	(0.10)	(0.23)	(0.19)	(0.28)	(0.16)	(0.30)	(0.20)
23.7%-8.8-0.45	(0.14)		0.14	0.17	0.12	**0.04**	0.27	**0.02**	**0.05**
23.7%-9.0-0.41	(0.10)			0.08	**0.04**	**0.02**	0.05	**0.01**	**0.02**
23.7%-12.2-0.45	(0.23)				0.49	0.45	0.28	0.30	0.59
23.7%-13.0-0.41	(0.19)					0.12	0.37	0.07	0.71
33.7%-9.0-0.45-2	(0.28)						0.07	0.76	0.15
33.7%-8.3-0.41	(0.16)							**0.03**	0.17
33.7%-12.5-0.45	(0.30)								0.08

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
Note: *p* values ≤ 0.05 are shown in bold

Figure 3.10 shows the average cumulative mass loss of scaling specimens exposed to NaCl in accordance with BNQ NQ 2621-900. The results of Student's t-test are shown in Table 3.10.

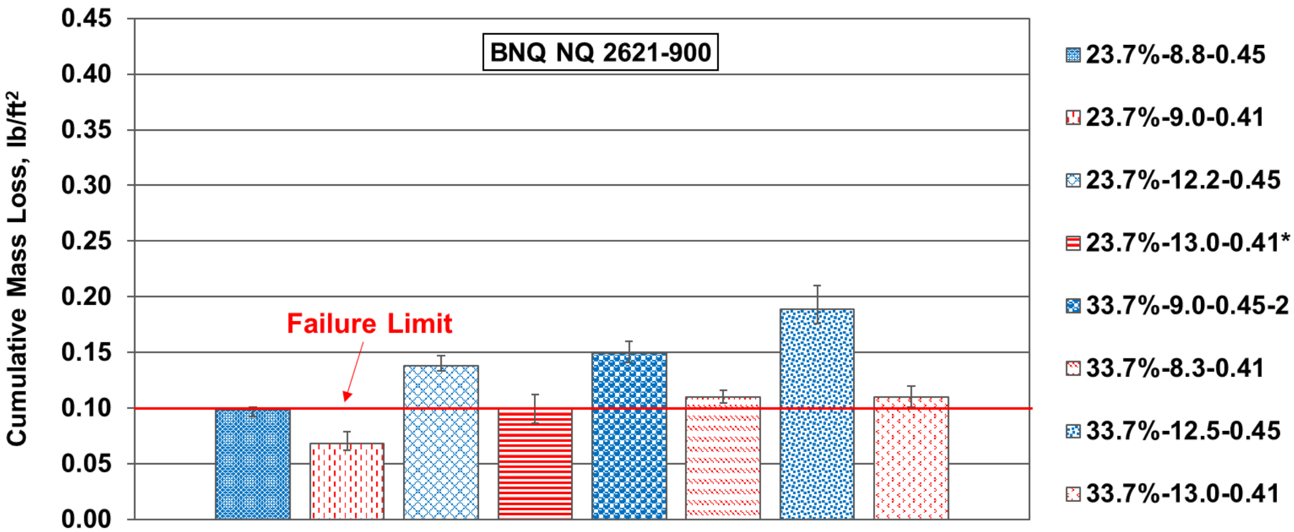


Figure 3.10: Average cumulative mass loss of IC mixtures with *w/c* ratios of 0.45 and 0.41 and exposed to NaCl (BNQ NQ 2621-900); *: average of two specimens

As with mixtures exposed to $CaCl_2$, as the paste content increased from 23.7 to 33.7%, mass loss increased for similar mixtures. These differences are, in most cases, statistically significant, with *p* values ranging from 1.1×10^{-3} to 0.01. Similar to mixtures exposed to $CaCl_2$ with expectation, as the *w/c* decreased from 0.45 to 0.41%, mass loss decreased for similar mixtures. These differences are statistically significant, with *p* values ranging from 1.5×10^{-3} to 0.04. This observation is in agreement with previous studies that found that reducing the *w/cm* ratio increases the scaling resistance of concrete (Hooton and Vassilev 2012, Abdul Baki et al. 2020).

As shown in Figure 3.10, the results indicate that increasing the quantity of IC water in mixtures with a *w/c* ratio of 0.45 decreases the scaling resistance of concrete mixtures, regardless of the paste content. These differences are statistically significant, with *p* values ranging from 1.1×10^{-3} to 0.01. Increasing the quantity of IC water in mixtures with a *w/c* ratio of 0.41, however, did not significantly decrease the scaling resistance of similar concrete mixtures, with *p* values ranging from 0.08 to 0.17, indicating the dominant role of the *w/c* ratio compared to quantities of IC water. None of the mixtures with IC water contents greater than 12.2% by weight of binder and a *w/c* ratio of 0.45 passed the scaling test in accordance with BNQ NQ 2621-900. On the other hand, mixtures with a paste content of 33.7%, IC water contents lower than 8.3%, and a *w/c* ratio of 0.41, would likely be able to pass the test since the mass losses of mixtures with IC water contents of either 8.3 or 13.0% were at or near to the failure limit (0.10 and 0.11 lb/ft^2 [0.5 and 0.53 kg/m^2]).

The results shown in Figures 3.9 and 3.10 indicate that exposure to $CaCl_2$ causes 32% to 47% more mass loss than exposure to NaCl. This finding is in line with observations by Hooton and Vassilev (2012) and Abdul Baki et al. (2020) who reported that mixtures containing portland cement as the only binder exhibited a higher mass loss when tested according to ASTM C672 than when tested per the modified BNQ NQ 2621-900.

Table 3.10: *p* values obtained from Student's t-test for the differences in cumulative scaling mass in accordance with BNQ NQ 2621-900

Mixtures ID[a]	**Average mass loss at 56 cycles (lb/ft^2)**	**23.7%-8.8-0.45**	**23.7%-9.0-0.41**	**23.7%-12.2-0.45**	**23.7%-13.0-0.41**	**33.7%-9.0-0.45-2**	**33.7%-8.3-0.41**	**33.7%-12.5-0.45**	**33.7%-13.0-0.41**
		(0.10)	(0.07)	(0.14)	(0.10)	(0.15)	(0.11)	(0.19)	(0.11)
23.7%-8.8-0.45	(0.10)		**6.9×10^{-3}**	**1.6×10^{-3}**	0.92	**1.1×10^{-3}**	0.89	**1.1×10^{-3}**	0.13
23.7%-9.0-0.41	(0.07)			**5.4×10^{-4}**	0.08	**4.3×10^{-4}**	**7.9×10^{-3}**	**5.1×10^{-4}**	**5.3×10^{-3}**
23.7%-12.2-0.45	(0.14)				**0.04**	0.19	**2.3×10^{-3}**	**0.01**	**0.02**
23.7%-13.0-0.41[b]	(0.10)					**0.03**	0.97	**0.01**	0.45
33.7%-9.0-0.45-2	(0.15)						**1.5×10^{-3}**	**0.03**	**7×10^{-3}**
33.7%-8.3-0.41	(0.11)							**1.2×10^{-3}**	0.17
33.7%-12.5-0.45	(0.19)								**2.6×10^{-3}**

[a] Mixture IDs labeled as 'A-B-C,' where:
A: Amount of Paste content
B: Quantity of Internal curing water, % binder weight
C: *w/c* ratio
[b] Average of two specimens
Note: *p* values ≤ 0.05 are shown in bold.

In summary, scaling results indicate that at the *w/c* ratio of 0.45, mixtures with IC water content of 8.8% (not greater) with a paste content of 23.7% are acceptable. Further research is needed to study the scaling resistance of concrete with lower quantities of IC water and paste contents between 23.7 and 33.7%. Similarly, results show that at the *w/c* ratio of 0.41, mixtures with IC water contents less than or equal to 13% with a paste content of 23.7% are acceptable. In contrast with freeze-thaw results, increased paste contents significantly reduced scaling resistance even with a *w/c* ratio and IC water contents as low as 0.41 and 8.3%, respectively. Except for two mixtures with IC water contents of either 8.8 or 9.0% with a *w/c* ratio of 0.45 and 0.41, respectively, the remainder of the mixtures exhibited a visual rating of (2) or (3) and failed the test in accordance with the MnDOT IC-LC-HPC specifications.

3.4 PROGRAM III

This program examines the effects of total internal water or TI water (provided by all aggregates) in internally-cured concrete mixtures. The main variables included in this program are cementitious material compositions (two include only portland cement, and six include a ternary binder composition including slag cement and silica fume), weight of internal curing (IC) water provided by pre-wetted lightweight aggregate (0 to 9.0%) by the weight of binder, and different coarse aggregates (low absorption limestone [with absorptions of 0.73 and 0.89%], high absorption limestone [with an absorption of 2.2%], and granite [with absorptions between 0.6 and 0.86%]). All the mixtures had a 24.6% paste content and a *w/cm* ratio of 0.45. The quantity of total internal water for mixtures with portland cement as the only binder was either 3.4 or 8.7% by the weight of binder. The quantities of total internal water for ternary binder composition mixtures ranged from 3.0 to 12.5% by the weight of binder. Mixtures with TI water content equal to either 3.0 or 3.4%, had no LWA (no IC water). As described in Section 2.5, the naming convention has the form of 'D-E-F.' The indicator D identifies the binder composition (T for ternary mixtures with slag cement and silica fume and C for 100% portland cement); the indicator E is the quantity of total internal water or TI water as a percentage of the total weight of binder; and the indicator F represents the type of coarse aggregate (L for low-absorption limestone, H for high-absorption limestone, and G for granite). Table 3.11 shows quantities of IC water, absorbed water in LWA, air contents, and compressive strengths of the mixtures included in Program III.

Mixtures were evaluated for free shrinkage following a modified version of ASTM C157, freeze-thaw durability in accordance with ASTM C666-Procedure A, and scaling resistance per ASTM C672. Rapid chloride permeability (RCP) and surface resistivity measurement (SRM) were obtained in accordance with ASTM C1202 and AASHTO TP-95 and Kansas Test Method KT-79, respectively. As a general observation, for a given binder composition, mixtures with no IC water exhibited greater shrinkage and lower scaling resistance than mixtures with IC water. All of the mixtures without IC water exhibited satisfactory freeze-thaw resistance. Additionally, a comparison between mixtures with similar TI water but different IC water, or more specifically mixtures with low and high absorption limestone, respectively, indicates that mixture with low absorption limestone, T-12.0-L, exhibited better performance than the mixture with high absorption limestone, T-12.5-H, with lower shrinkage, higher freeze-thaw and scaling resistance, lower RCP and higher SRM values, with differences that are statistically significant.

Table 3.11: IC water, TI water, air contents, and compressive strengths of the mixtures included in Program III

Mixture ID[a]	IC water (% binder weight)	TI water (% binder weight)	Air content (%)	28-day Compressive strength (psi)
T-3.4-L	0.0	3.4	8.00	5290
T- 9.0-L	5.5	9.0	8.00	5280
T- 12.0-L	9.0	12.0	7.50	5380
C- 3.4-L	0.0	3.4	7.25	5090
C-8.7-L	5.9	8.7	8.25	5110
T-3.0-G	0.0	3.0	9.25	4880
T-8.7-G	6.1	8.7	9.50	4640
T-12.5-H	5.8	12.5	8.50	5270

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of absorbed water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: 1 in. = 25.4 mm; 1 lb/ft^3 = 16 kg/m^3; °C = (°F-32)×5/9 ; 1 psi = 6.89×10^{-3} MPa

3.4.1 Free Shrinkage

This section evaluates results in terms of strain (in microstrain) at different points in time, including during the 14-day curing period, and 30-day and 365-day drying periods. Drying shrinkage is also evaluated separately for the first 30 days and between 30 to 365 days of drying, with respect to the length of a specimen at the beginning of the drying period (absolute value, abs.); it does not account for any swelling that occurred during the curing period. Unless noted, the results discussed in this section are the average of three specimens. Data taken from individual specimens is included in Appendix B. Positive strain values indicate swelling while negative values indicate shrinkage.

3.4.1.1 Strain

Figure 3.11 shows the average strain of three specimens from each mixture in this program as a function of time up to 379 days after casting (365 days of drying). The mixtures in Figure 3.11 are presented based on different types of binder systems, the quantity of TI water, and types of coarse aggregate, with the orders in the legend that matched the order of each curve.

As shown in Figure 3.11, all mixtures containing slag cement and silica fume as partial replacements for portland cement exhibited lower shrinkage (negative strain) compared to mixtures containing portland cement as the only cementitious material for similar quantities of TI water. Results also indicate that as the total internal water increases, shrinkage of concrete decreases for a given binder composition. Also, the rate of strain reduced gradually over time, with the highest reduction at the end of the 14-day curing period and with the relatively lowest after 180 days of drying for most of the mixtures.

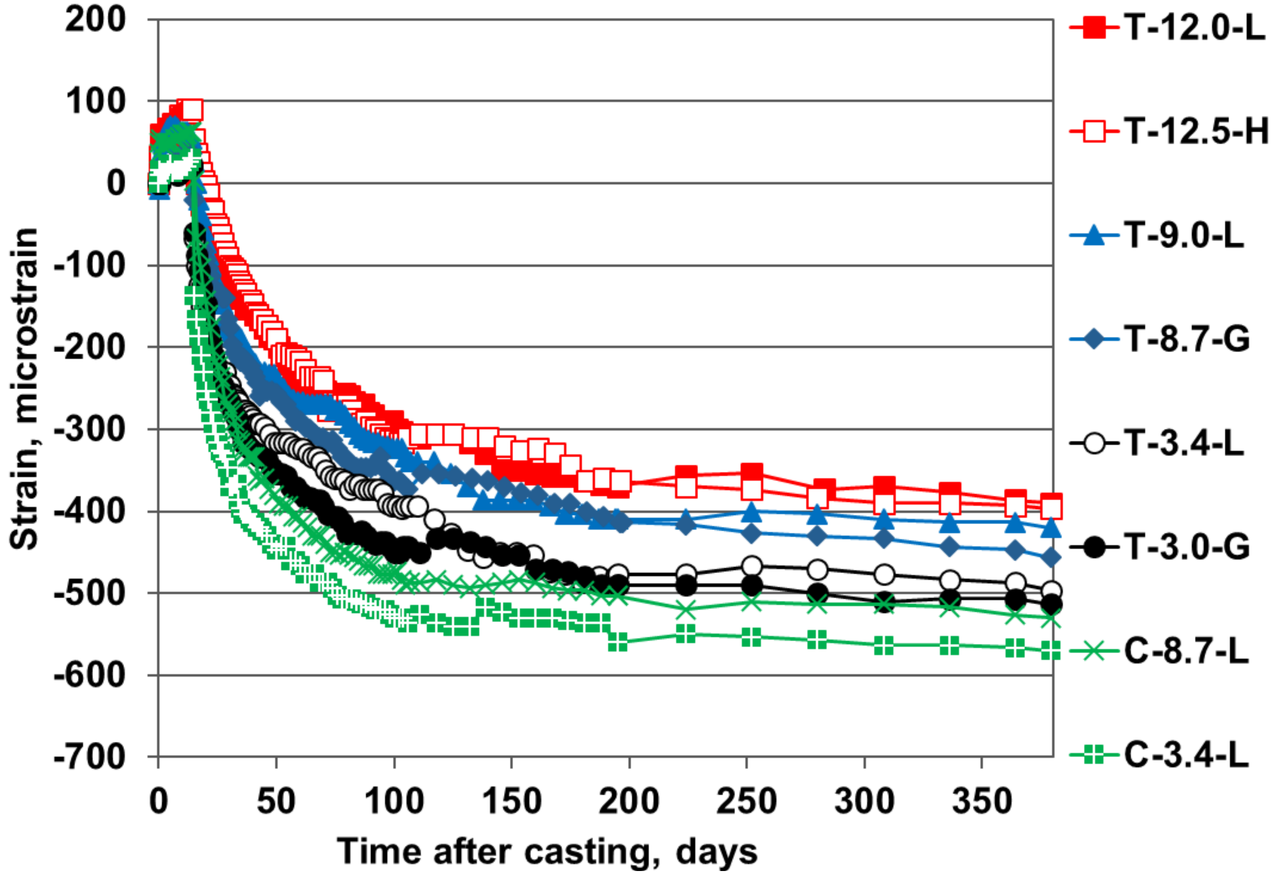


Figure 3.11: Average strain during curing and drying periods for the mixtures included in Program III

Table 3.12 summarizes the average strain for the mixtures at the end of the 14-day curing period, 30-day, and 365-day drying periods; the quantity of IC water for each mixture is also provided. Tables 3.13 to 3.15 provide the *p* values obtained in Student's t-test between the average strains for the mixtures at the end of the 14-day curing period, at 30 days of drying, and at 365 days of drying, respectively.

As shown in Table 3.12, all specimens expanded during the 14-day curing period, as indicated by the positive strain ranging from 20 to 90 microstrain, regardless of binder compositions or quantity of IC water. Mixtures T-3.4-L (with no IC) and T-12.5-H (with 5.8% IC water) exhibited, respectively, the lowest and the greatest expansions at the end of the curing period. Mixture T-12.0-L (with 9% IC water) exhibited the lowest shrinkage of 390 microstrain, and mixture C-3.4-L (with no IC water) exhibited the greatest shrinkage of 570 microstrain through 379 days after casting.

Table 3.12: Strain at different points in time (microstrain) for the mixtures included in Program III[a]

Mixture ID[b]	IC water content (%)	Strain		
		End of 14-day curing	30 days of drying	365 days of drying
T-3.4-L	0	20	-297	-497
T-9.0-L	5.5	53	-230	-420
T-12.0-L	9.0	37	-177	-390
C-3.4-L	0	30	-423	-570
C-8.7-L	5.9	63	-360	-530
T-3.0-G	0	23	-333	-513
T-8.7-G	6.1	37	-253	-457
T-12.5-H	5.8	90	-167	-397

[a] Shrinkage is negative; swelling is positive
[b] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])

In comparison with mixtures with IC water, mixtures with no IC water (3.0 and 3.4% TI water) exhibited lower strains at the end of the curing period, ranging from 20 to 30 microstrain (vs. 37 to 90 microstrain). Additionally, the differences in strains exhibited by any two IC mixtures, regardless of the total internal water content, are not statistically significant. Further, the differences in strains exhibited by any two mixtures with no IC water, regardless of the binder compositions, are not statistically significant, indicating that the use of SCMs did not influence the magnitude of expansion beyond that resulting from the use of only portland cement, in the absence of IC water.

Table 3.13: *p* values obtained in Student's t-test for the differences in strains at the end of curing for the mixtures included in Program III[a]

Mixture ID[b]	Strain (microstrain)	T-3.4-L	T-9.0-L	T-12.0-L	C-3.4-L	C-8.7-L	T-3.0-G	T-8.7-G	T-12.5-H
		(20)	(53)	(37)	(30)	(63)	(23)	(37)	(90)
T-3.4-L	(20)		0.39	0.44	0.55	**0.03**	0.77	0.24	**0.04**
T-9.0-L	(53)			0.68	0.54	0.79	0.42	0.65	0.40
T-12.0-L	(37)				0.76	0.23	0.48	1.00	0.12
C-3.4-L	(30)					0.08	0.61	0.64	0.07
C-8.7-L	(63)						**0.01**	0.07	0.30
T-3.0-G	(23)							0.15	**0.03**
T-8.7-G	(37)								0.07

[a] Shrinkage is negative; swelling is positive
[b] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: *p* values ≤ 0.05 are shown in bold

At 30 days of drying, all mixtures showed negative strains (shrinkage), with maximum and minimum strain values of -423 and -167 microstrain, corresponding to mixtures C-3.4-L and T-12.5-H, respectively. The ternary mixtures exhibited lower shrinkage strains (ranging from -167 to -333 microstrain) than the 100% portland cement mixtures (either -360 or -423 microstrain) for similar quantities of TI water, with differences that are statistically significant (*p* values ranging from 3.5×10^{-3} to 0.02). As shown in Table 3.14, the ternary mixtures with 3.0, 3.4, 8.7, 9.0, 12, and 12.5% of total internal water by the weight of binder exhibited shrinkage strains of -333, -297, -253, -230, -177, and -167 microstrain, respectively, and the 100% portland cement mixtures with 3.4 and 8.7% of TI water exhibited shrinkage strains of -423 and -360 microstrain, respectively, with shrinkage decreasing with increasing TI water content for each binder type. Ternary mixtures containing similar IC water contents (5.5 to 6.1%) but different TI water contents (8.7 to 12.5%) exhibited similar shrinkage strains, with differences that are not statistically significant. For the two ternary mixtures with different coarse aggregates and no IC water, the difference in shrinkage strains (T-3.0-G and T-3.4-L with -333 and -297 microstrain, respectively) is not statistically significant, with a *p*-value of 0.17 Although mixtures T-12.0-L and T-12.5-H had different IC water contents (9.0 and 5.8%, respectively), possibly due to having a similar TI water content (12.0 and 12.5%), they exhibited similar shrinkage strains after 30 days of drying, with a difference that is not statistically significant (*p*-value of 0.73).

Table 3.14: *p* values obtained in Student's t-test for the differences in strains at 30 days of drying for the mixtures included in Program III[a]

Mixture ID[b]	**Strain (microstrain)**	**T-3.4-L**	**T-9.0-L**	**T-12.0-L**	**C-3.4-L**	**C-8.7-L**	**T-3.0-G**	**T-8.7-G**	**T-12.5-H**
		(-297)	(-230)	(-177)	(-423)	(-360)	(-333)	(-253)	(-167)
T-3.4-L	(-297)		0.15	**0.9×10^{-3}**	**3.5×10^{-3}**	**0.01**	0.17	0.17	**0.01**
T-9.0-L	(-230)			0.21	**0.01**	**0.02**	0.06	0.61	0.22
T-12.0-L	(-177)				**1.6×10^{-4}**	**0.3×10^{-4}**	**1.4×10^{-3}**	**0.03**	0.73
C-3.4-L	(-423)					**0.02**	**0.02**	**4.1×10^{-3}**	**1.1×10^{-3}**
C-8.7-L	(-360)						0.24	**0.01**	**1.9×10^{-3}**
T-3.0-G	(-333)							0.06	**0.01**
T-8.7-G	(-253)								0.07

[a] Shrinkage is negative; swelling is positive
[b] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: *p* values ≤ 0.05 are shown in bold

As observed for mixtures after 30 days of drying, the ternary mixtures with or without IC exhibited lower shrinkage strains (ranging from -390 to -513 microstrain) at 365 days of drying than the 100% portland cement mixtures (either -530 or -570 microstrain), with differences that are statistically significant in some but not all cases. Overall, however, these observations indicate that increased TI water results in reduced strain, and that binder composition can have effect on both early-age and long-term strain.

As shown in Table 3.15, the ternary mixtures with 3.0, 3.4, 8.7, 9.0, 12.0, and 12.5% of TI water by the weight of binder exhibited shrinkage strains of -513, -497, -457, -420, -390, and -397 microstrain, respectively, and the 100% portland cement mixtures with 3.4 and 8.7% of TI water exhibited shrinkage strains of -570 and -530 microstrain, respectively, with shrinkage decreasing with increasing TI water content for each binder type, as observed after 30 days of shrinkage. The ternary mixtures containing similar IC water contents (5.5 to 6.1%) but different TI water contents (8.7 to 12.5%, T-12.5-H vs. T-9.0-L and T-8.7-G) exhibited shrinkage strains of -397, -420, and -457 microstrain, respectively, with differences that are not statistically significant. For the ternary mixtures with no IC water but different coarse aggregates, the difference in shrinkage strains (T-3.0-G and T-3.4-L with -513 and -497 microstrain, respectively) is not statistically significant, with a *p*-value of 0.72. It is also observed that the difference in the shrinkage strains for the ternary mixtures with similar quantities of TI water, but different IC water contents is small and not statistically significant (T-12.0-L vs. T-12.5-H [-390 and -397 microstrain, respectively]) with a *p* value equal to 0.56).

Table 3.15: *p* values obtained in Student's t-test for the differences in strains at 365 days of drying for the mixtures included in Program III[a]

Mixture ID[b]	Strain (microstrain)	T-3.4-L	T-9.0-L	T-12.0-L	C-3.4-L	C-8.7-L	T-3.0-G	T-8.7-G	T-12.5-H
		(-497)	(-420)	(-390)	(-570)	(-530)	(-513)	(-457)	(-397)
T-3.4-L	(-497)		0.23	**0.05**	0.16	0.44	0.72	0.45	0.06
T-9.0-L	(-420)			0.48	**0.02**	**0.04**	0.09	0.49	0.58
T-12.0-L	(-390)				**0.6×10^{-3}**	**0.1×10^{-3}**	**3.2×10^{-3}**	0.09	0.56
C-3.4-L	(-570)					0.09	0.09	**0.03**	**0.9×10^{-3}**
C-8.7-L	(-530)						0.44	0.07	**0.2×10^{-3}**
T-3.0-G	(-513)							0.18	**4.7×10^{-3}**
T-8.7-G	(-457)								0.12

[a] Shrinkage is negative; swelling is positive
[b] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: *p* values ≤ 0.05 are shown in bold

3.4.1.2 Drying Shrinkage

Table 3.16 summarizes the drying shrinkage (based on length change after of the drying begins) for the first 30 days and for 30 to 365 days. Tables 3.17 and 3.18 provide the *p* values obtained from Student's t-test between the average drying shrinkage for the mixtures at the end of the 14-day curing period, at 30 days of drying, and at 365 days of drying, respectively.

Table 3.16: Drying shrinkage at different points in time (microstrain) for the mixtures included in Program III[a]

Mixture ID[a]	IC water content (%)	Drying shrinkage (abs.)	
		After 30 days of drying	Between 30 and 365 days of drying
T-3.4-L	0	317	517
T-9.0-L	5.5	283	473
T-12.0-L	9.0	213	427
C-3.4-L	0	453	600
C-8.7-L	5.9	423	593
T-3.0-G	0	357	537
T-8.7-G	6.1	290	493
T-12.5-H	5.8	257	487

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])

At early age as shown in Table 3.17, for a given binder composition, as the total internal water increases, the shrinkage of concrete decreases. Mixture T-3.0-G (no IC water) exhibited the greatest drying shrinkage with 357 microstrain, and mixture T-12.0-L (with 9% IC water) exhibited the lowest drying shrinkage with 213 microstrain among the ternary mixtures, a difference that is statistically significant (p-value of 3.3×10^{-3}). Similarly, mixture C-3.4-L (no IC water) exhibited the greatest drying shrinkage with 453 microstrain, and mixture C-8.7-L (with 6.1% IC water) exhibited the lowest drying shrinkage with 423 microstrain among the 100% portland cement mixtures, a difference that is not statistically significant (p-value of 0.37). Ternary mixtures exhibited lower drying shrinkage than mixtures containing 100% portland cement as the binder for similar quantities of TI water. For example, mixtures with ternary binder compositions with 9.0 and 8.7% TI water (5.5 and 6.1% IC water) exhibited lower shrinkage, with 283 and 290 microstrain through 30 days of drying, than the mixture with 100% portland cement as the binder and 8.7% TI water (5.9% IC water) with 423 microstrain of shrinkage during the same period, differences that are statistically significant (*p* values equal to either 0.4×10^{-3} or 3.2×10^{-3}, respectively).

Table 3.17: *p* values obtained in Student's t-test for the differences in drying shrinkage at 30 days of drying for the mixtures included in Program III[a]

Mixture ID[a]	**Shrinkage (microstrain)**	**T-3.4-L**	**T-9.0-L**	**T-12.0-L**	**C-3.4-L**	**C-8.7-L**	**T-3.0-G**	**T-8.7-G**	**T-12.5-H**
		(317)	(283)	(213)	(453)	(423)	(357)	(290)	(257)
T-3.4-L	(317)		0.07	**0.01**	**0.01**	**4×10^{-3}**	0.14	0.29	**0.02**
T-9.0-L	(283)			**0.01**	**3.5×10^{-3}**	**0.4×10^{-3}**	**0.02**	0.72	**0.02**
T-12.0-L	(213)				**1.5×10^{-3}**	**0.4×10^{-3}**	**3.3×10^{-3}**	**0.03**	**0.05**
C-3.4-L	(453)					0.37	**0.04**	**0.01**	**2.2×10^{-3}**
C-8.7-L	(423)						**0.04**	**3.2×10^{-3}**	**0.3×10^{-3}**
T-3.0-G	(357)							**0.05**	**0.01**
T-8.7-G	(290)								0.15

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: *p* values ≤ 0.05 are shown in bold

As shown in Table 3.18, for a given binder composition, mixtures with no IC water exhibited greater shrinkage than mixtures with IC water. Results between 30 to 365 days of drying show that the ternary mixtures with similar quantities of IC water but different TI water contents exhibited similar drying shrinkage with differences that are not statistically significant (*p* values of 0.82 and 0.52). Ternary mixtures with similar quantities of TI water but different IC water contents (T-12.0-L and T-12.5-H) exhibited drying shrinkage of 427 and 487 microstrain, respectively, with a difference that is statistically significant (*p*-value of 0.05); Because the number of specimens with similar TI water but different IC water was small and the difference in drying shrinkage between these mixtures is statistically significant (p = 0.05), further study is recommended to investigate the effects of TI water on drying shrinkage of concrete. These observations, however, are quite different when comparing mixtures with different binder compositions but similar TI water or IC water contents. For example, mixtures with ternary binder compositions with 9.0 and 8.7% TI water (5.5 and 6.1% IC water) exhibited similar drying shrinkage of 473 and 493 microstrain between 30 and 365 days of drying, respectively, but the mixture with 100% portland cement as the binder and 8.7% TI water (5.9% IC water) exhibited drying shrinkage of 593 microstrain during the same period, differences that are statistically significant (p values equal to either 4.3×10^{-3} or 0.02, respectively). The differences in drying shrinkage between mixtures without IC water (TI water equal to 3.0 or 3.4%), however, are not statistically significant, with p values ranging between 0.13 and 0.66.

Table 3.18: p values obtained in Student's t-test for the differences in drying shrinkage between 30 to 365 days of drying for the mixtures included in Program III[a]

Mixture ID[a]	**Shrinkage (microstrain)**	**T-3.4-L**	**T-9.0-L**	**T-12.0-L**	**C-3.4-L**	**C-8.7-L**	**T-3.0-G**	**T-8.7-G**	**T-12.5-H**
		(517)	(473)	(427)	(600)	(593)	(537)	(493)	(487)
T-3.4-L	(517)		0.34	0.10	0.15	0.13	0.66	0.63	0.49
T-9.0-L	(473)			0.11	**0.02**	**4.3×10^{-3}**	**0.05**	0.52	0.52
T-12.0-L	(427)				**0.01**	**1.9×10^{-3}**	**0.01**	0.09	**0.05**
C-3.4-L	(600)					0.85	0.13	**0.05**	**0.02**
C-8.7-L	(593)						0.07	**0.02**	**4.8×10^{-3}**
T-3.0-G	(537)							0.22	0.08
T-8.7-G	(493)								0.82

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: p values ≤ 0.05 are shown in bold

3.4.2 Freeze-Thaw Durability

In this section, the effects of binder composition and total internal water (TI water) are assessed on freeze-thaw resistance. As described in Section 2.5.3, the freeze-thaw durability tests in Program III were performed in accordance with ASTM C666 Procedure A with a failure limit corresponding to MnDOT IC-LC-HPC specifications. Per MnDOT IC-LC-HPC specifications, the specimens should maintain at least 90% of their initial dynamic modulus of elasticity values after 300 freeze-thaw cycles to pass the test. Freeze-thaw durability results are also quantified by a

Durability Factor (DF) calculated for each mixture using Eq (2.2). In this program, mixtures with DF greater than or equal to 90% through 300 freeze-thaw cycles present satisfactory resistance. Freeze-thaw testing was terminated when the percent of initial dynamic modulus dropped below 60% of the initial values. Linear interpolation between dynamic moduli and freeze-thaw cycles was used to determine the number of freeze-thaw cycles corresponding to 60 or 90% of the initial dynamic modulus values (if applicable) of the mixtures.

The average percent of initial dynamic moduli of the concrete mixtures in the freeze-thaw test are plotted in Figure 3.12 as a function of the number of freeze-thaw cycles. The dynamic modulus elasticity of the specimens from each specimen is provided in Appendix B. As shown in the figure, three mixtures (T-12.5-H, T-12.0-L, and T-9.0-L) failed to complete 300 freeze-thaw cycles before their percent of initial dynamic modulus dropped below 60%. The average percent of initial dynamic modulus of mixture T-12.5-H decreased to 58% after 174 freeze-thaw cycles, that of mixture T-12.0-L dropped to 63% after 306 freeze-thaw cycles, and that of mixture T-9.0-L reached 61% after 363 freeze-thaw cycles. The remainder of the mixtures completed 300 freeze-thaw cycles with a percent of initial dynamic modulus of elasticity above 90%.

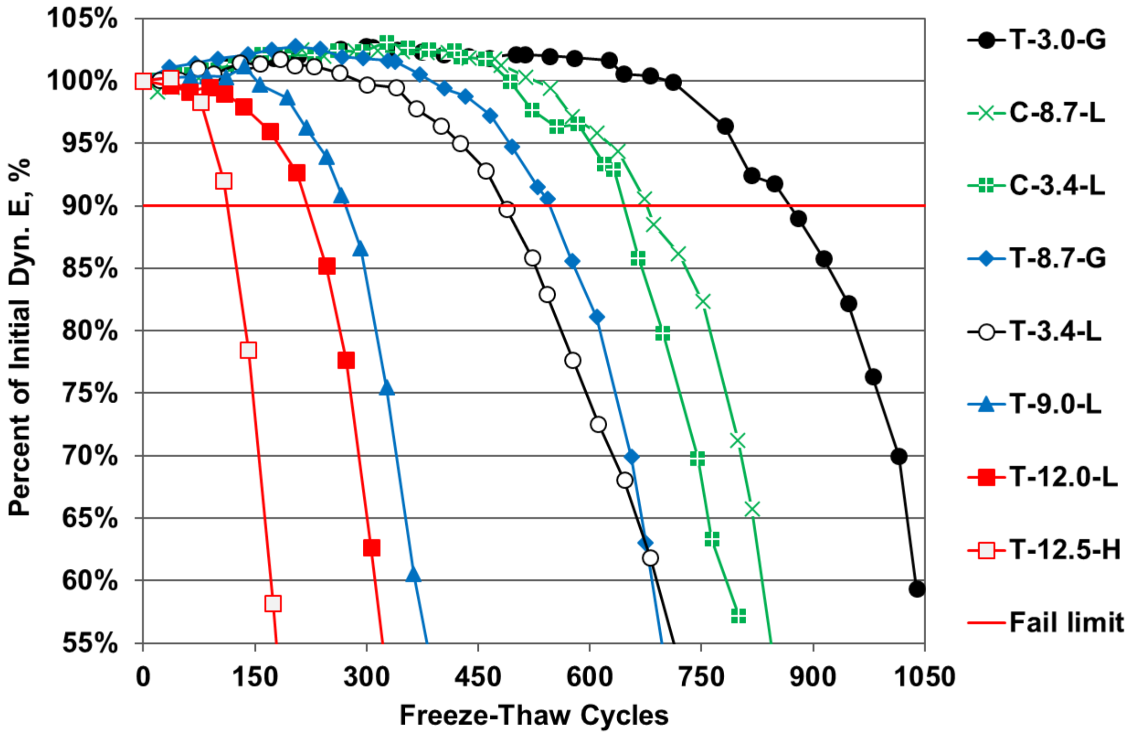


Figure 3.12: Average percent of initial dynamic modulus of elasticity versus freeze-thaw cycles tested in accordance with ASTM C666 Procedure A

Table 3.19 presents the number of freeze-thaw cycles corresponding to 90% of the initial dynamic modulus of elasticity and DF values for each mixture; the quantity of IC water, as well as air content for each mixture, are also provided. The mixtures had air content values ranging from 7.25 to 9.25%.

Table 3.19: Summary of freeze-thaw results in Program III

Mixture ID[a]	IC water content (%)	Internal water content in normalweight aggregates (%)	Air content (%)	No. of Cycles to 90% of initial dynamic modulus of elasticity	Durability Factor[b] (%)
T-3.4-L	0	3.4	8	486	100
T-9.0-L	5.5	3.5	8	271	73
T-12.0-L	9.0	3.0	7.5	220	62
C-3.4-L	0	3.4	7.25	646	102
C-8.7-L	5.9	2.8	8.25	677	102
T-3.0-G	0	3.0	9.25	902	103
T-8.7-G	6.1	2.6	9.5	546	102
T-12.5-H	5.8	6.7	8.5	171	34

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
[b] (DF) = ($P \times N$) / 300 cycles,
where P is the percentage of the initial dynamic modulus remaining at N cycles, N is either the number of cycles at which P reached 60% or 300 cycles (whichever is smaller)

The results indicate that the freeze-thaw resistance of the mixtures decreased markedly for the two mixtures with total internal water contents (provided by all aggregates) of 12.0 and 12.5% (by the weight of binder). Similar results were observed by Lafikes et al. (2020), who evaluated the durability of 64 concrete mixtures with different binder composition systems (100% portland cement, binary [cement and slag], and ternary [cement, fly ash, and silica fume]). Lafikes et al. (2020) concluded that concrete mixtures with total internal water contents greater than 12% exhibit failures in fewer freeze-thaw cycles than mixtures with total internal water below 12% by weight of binder. In this study, the dynamic modulus of elasticity of the mixtures with 9.0% or more TI water (by the weight of binder), dropped below 90% of the initial value in less than 271 cycles and failed the test. The durability factors of these mixtures (T-9.0-L, T-12.0-L, and T-12.5-H) were much below 90%, the minimum acceptable value, with values ranging from 34 to 73%.

It should be noted that, in this study, except for one mixture with high-absorption limestone, the normalweight aggregates in the other mixtures (granite or low-absorption limestone with fine aggregates) only provide a small portion of the TI water (between 2.6 and 3.5% by the weight of binder), while the lightweight sand provides most of TI water (between 5.5 and 9.0% by the weight of binder), and therefore, except for mixture T-12.5-H (with 5.8% IC water and 6.7% internal water from normalweight aggregates) the TI water content is mainly comprised of IC water. The results reveal that as the TI water content in the mixtures increased, mainly driven by an increase in IC water, the freeze thaw resistance decreased. As an example, for the ternary mixtures with low-absorption limestone (T-3.4-L, T-9.0-L, and T-12.0-L), as the TI water increased from 3.4 to 12.0%, primarily due to an increase in IC water from 0 to 9.0% by the weight of binder, freeze-thaw resistance decreased. Similarly, for the ternary mixtures with granite (T-3.0-G and T-8.7-G), as the TI water increased from 3.0 to 8.7%, primarily due to an increase in IC water from 0 to 6.1% by the weight of binder, freeze-thaw resistance also decreased. Similar freeze-thaw performance, however, was not observed for mixtures with portland cement as the only binder with 3.4 and 8.7% TI water (C-3.4-L and C-8.7-L; with 0 and 5.9% IC water, respectively).

The ternary mixtures with granite as the coarse aggregate (T-3.0-G and T-8.7-G) exhibited better freeze-thaw resistance than similar ternary mixtures with low-absorption limestone (T-3.4-L and T-9.0-L) through 300 freeze-thaw cycles, with durability factors of either 103 or 102%, respectively (versus 100 and 73%, respectively). The single mixture with high-absorption limestone as the coarse aggregate (T-12.5-H), with 5.8% IC water (by the weight of binder), exhibited lower freeze-thaw resistance (with DF of 34) than the mixtures with similar quantities of IC water (T-9.0-L and T-8.7-G with DF = 73 and 102, respectively) that had much lower quantities of internal water in the normalweight aggregates (6.7% for T-12.5-H vs. 3.5 and 2.6% for T-9.0-L and T-8.7-G, respectively, by the weight of binder).

The results also show that in mixtures with TI water equal to either 3.4% or 8.7% (by the weight of binder), the mixtures that had portland cement as the only binder had considerably higher freeze-thaw resistance than the paired ternary mixtures. All mixtures with portland cement as the only binder as well as ternary mixtures with less than 9.0% TI water maintained at least 90% of the initial dynamic modulus of elasticity value after 300 freeze-thaw cycles and passed the test (durability factors ranged from 100 to 103%).

3.4.3 Scaling Resistance

The average cumulative scaling mass loss for specimens tested in accordance with ASTM C672 is plotted in Figure 3.13 as a function of the number of freeze-thaw cycles. Individual mass loss from each test is included in Appendix B. Table 3.20 lists the quantity of IC water, air content, and visual rating, and mass loss at 50 cycles for each mixture. The results of Student's t-test are shown in Table 3. 21.

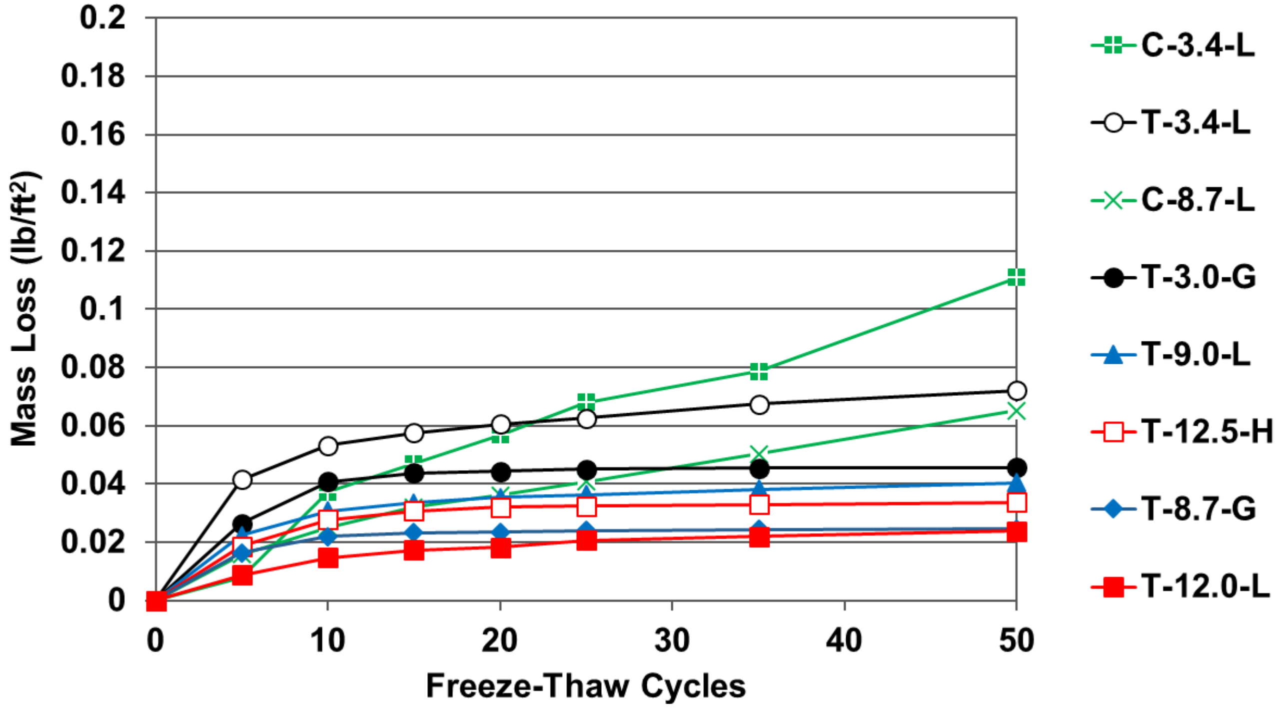


Figure 3.13: Average cumulative mass loss vs. freeze-thaw cycles for mixtures in Program III, specimens tested in accordance with ASTM C672

In contrast to the freeze-thaw test, total internal water did not negatively affect the scaling resistance. At the same time, the type of coarse aggregate did impact on the scaling resistance of the mixtures. The ternary mixtures with granite as the coarse aggregate, with either 3.0 or 8.7% of TI water (0 or 5.9% of TI water), had lower mass losses than the ternary mixtures with low-absorption limestone and similar quantities of TI water, with the differences that are statistically significant (a *p*-value equal to either 0.01 or 1.9×10^{-3}). A possible explanation for the better performance of the granite mixtures could be having higher air contents than the paired limestone mixtures. Mixtures T-3.0-G and T-8.7-G had 9.25 and 9.5% air contents, respectively, while mixtures T-3.4-L and T-9.0-L had air contents of 8%. As discussed in Chapter 1, the use of air entrainment is an effective way to increase the durability of concrete in the presence of water and deicing salts. Hooton and Vassilev (2012) reported that a higher air content in the concrete mixtures reduces scaling mass loss, with a recommended air content range between 7 and 9%. The mixtures T-3.0-G and T-8.7-G exhibited mass losses of 0.05 and 0.02 lb/ft^2 (0.2 and 0.1 kg/m^2) and a visual rating of (0), while the mixtures T-3.4-L and T-9.0-L exhibited mass losses of 0.07 and 0.04 lb/ft^2 (0.3 and 0.2 kg/m^2) and a visual rating of (1) after 50 freeze-thaw cycles.

Table 3.20: Mixture properties and visual rating and mass loss results at 50 freeze-thaw cycle, specimens tested in accordance with ASTM C672

Mixture ID[a]	**IC water content (%)**	**Air content (%)**	**Visual Rating at 50 cycles**	**Average mass loss at 50 cycles (lb/ft^2)**
T-3.4-L	0	8	1	0.07
T-9.0-L	5.5	8	1	0.04
T-12.0-L	9.0	7.5	0	0.02
C-3.4-L	0	7.25	1	0.11
C-8.7-L	5.9	8.25	1	0.07
T-3.0-G	0	9.25	0	0.05
T-8.7-G	6.1	9.5	0	0.02
T-12.5-H	5.8	8.5	1	0.03

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: 1 lb/ft^2 = 4.88 kg/m^2

The binder compositions also influenced the scaling resistance of the mixtures. The mixtures with 100% portland cement, with either 3.4 or 8.7% of TI water (0 or 5.9% of IC water), had higher mass losses than mixtures with ternary binder compositions with similar quantities of TI water, although the differences are not statistically significant (p values of either 5.3×10^{-3} or 0.26). Mixtures with 100% portland cement composition exhibited a visual rating of (1) at the end of 50 freeze-thaw cycles. The mass loss of mixtures with no IC water in 100% portland cement (C-3.4-L) and ternary mixtures (T-3.4-L and T-3.0-G) were 0.11, 0.07, and 0.05 lb/ft^2 (0.5, 0.3, and 0.2 kg/m^2), respectively, after 50 freeze-thaw cycles. The mass loss of the 100% portland cement mixture with 8.7% TI water (5.9% IC water) and the ternary mixtures with 8.7 and 9% TI water (6.1 and 5.5% IC water) were 0.07, 0.02, and 0.04 lb/ft^2 (0.3, 0.1, and 0.2 kg/m^2), respectively, after 50 freeze-thaw cycles. As discussed in Chapter 1, one likely cause of the better performance of the ternary mixtures is the effect of supplementary cementitious materials in reducing calcium hydroxide, which leads to the formation of calcium oxychloride, which forms when hydrated cement comes in contact with calcium chloride, as used in these tests, at low temperatures. Calcium oxychloride does not form when scaling tests are performed using sodium chloride. Thus, scaling tests that use calcium chloride are really testing both scaling and calcium oxychloride resistance.

The ternary mixtures with TI water equal to or greater than 12.0%, T-12.0-L and T-12.5-H, exhibited similar mass losses of 0.02 and 0.03 lb/ft^2 (0.1 and 0.14 kg/m^2), respectively, although statistically significant (a p-value equal to 0.04), with a visual rating of either (0) or (1).

Table 3.21: p values obtained in Student's t-test for the differences in cumulative scaling mass losses, specimens tested in accordance with ASTM C672

Mixture ID[a]	**Average mass loss at 50 cycles (lb/ft^2)**	**T-3.4-L** (0.07)	**T-9.0-L** (0.04)	**T-12.0-L** (0.02)	**C-3.4-L** (0.11)	**C-8.7-L** (0.07)	**T-3.0-G** (0.05)	**T-8.7-G** (0.02)	**T-12.5-H** (0.03)
T-3.4-L	(0.07)		**0.02**	**2.2×10^{-3}**	0.20	0.74	**0.01**	**1.9×10^{-3}**	**3.6×10^{-3}**
T-9.0-L	(0.04)			0.06	5.3×10^{-2}	0.26	0.43	0.06	0.31
T-12.0-L	(0.02)				**0.02**	0.09	**3.2×10^{-3}**	0.87	**0.04**
C-3.4-L	(0.11)					0.21	**0.05**	**0.02**	**0.03**
C-8.7-L	(0.07)						0.34	0.09	0.16
T-3.0-G	(0.05)							**1.4×10^{-3}**	**3.5×10^{-3}**
T-8.7-G	(0.02)								**0.02**

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
Note: 1 lb/ft^2 = 4.88 kg/m^2 | p values ≤ 0.05 are shown in bold

3.4.5 Rapid Chloride Permeability and Surface Resistivity

Tables 3.20 present the results for the rapid chloride permeability test (RCP) and the surface resistivity measurement (SRM). As explained in Chapter 2, as part of the test procedure, due to the specimen being cured in lime-saturated water instead of a moist room, SRM values were multiplied by 1.1 as a correction factor in accordance with AASHTO TP-95. Table 3.22 shows the corrected values. Individual results from RCP and SRM tests are included in Appendix B.

Kansas Department of Transportation (KDOT) IC-LC-HPC specifications for RCP tests require a maximum charge passed less than 2500 and 1500 coulombs at 28 and 56 days, respectively; the specifications also require a minimum surface resistivity measurement of 19 kΩ-cm at 28 days. As shown in Table 3.22, all mixtures except for those with portland cement as the only binder passed the requirements.

As shown in Table 3.22, small changes in mixture proportions tended to result in large changes in the SRM values between groups. These observations are in line with Spragg et al. (2013), who reported that factors such as specimen geometry, specimen temperature, and sample storage and conditioning could result in significant changes in SRM values. Similar observations were noticed when comparing RCP Student's t-test results, as provided in Appendix B.

Large changes in SRM values are reflected in Appendix B, where the majority of p values obtained from Student's t-test using SRM values were below 0.05. However, as shown in Table 3.22, the range of SRM values in test mixtures was between 25.9 and 35.2 kΩ-cm, indicating that while there were observable differences between test groups, the magnitude of these differences was limited. Additionally, some non-linear trends were observed in the effect of total internal water on SRM values. Congruent to prior research, it is possible that minor changes in lab conditions, such as differing lab temperature at the time of mixing, influenced SRM values. Thus, despite the significant p values in Table 3.22, limited conclusions can be drawn on the effect of total internal water on SRM values.

As an overall observation, the results obtained in this study show that the mixtures containing a ternary binder composition improved the transport properties of concrete compared to the respective mixtures with 100% portland cement as the binder. The average charge passed in the RCP test at 28 and 56 days for mixtures with 100% portland cement were 3520 and 2980 coulombs, respectively, well above the maximum limits stated in the KDOT specifications, while the values for the mixtures with ternary binder compositions were 980 and 690 coulombs, respectively. The differences between RCP results at 28 and 56 days for mixtures with 100% portland cement and mixtures with ternary binder compositions are statistically significant, with *p* values ranging from 2.2×10^{-4} to 1.2×10^{-3} and 1.1×10^{-4} to 4.2×10^{-4}, respectively. As a general observation, incremental increases in the amount of TI water in all the mixtures with the same binder composition, except for T-12.5-H, did not significantly affect the RCP values, especially at 28 days with *p* values ranging from 0.17 to 0.8. Furthermore, while the majority of *p* values were below 0.05 at 56 days, the difference in RCP values for ternary mixtures was small (between 560 and 790), preventing a conclusive conclusion. Nevertheless, mixtures with TI water equal to or greater than 12% (by the weight of binder) exhibited greater charge passed than mixtures with equal to or less than 9% in the 56-day RCP test. In mixtures with portland cement as the only binder, as the TI water increased, the increase in charge passed did not result in statistically significant RCP values at 28 and 56 days (*p* values of 0.08 and 0.16, respectively).

The ternary mixtures, on average, showed higher SRM values than the mixtures with 100% portland cement. Similar to the RCP results, incremental increases in the amount of TI water in the mixtures did not affect the SRM values. Lafikes et al. (2020) made similar observations and reported no clear trends when comparing SRM values between mixtures with and without IC water. The surface resistivity measurements for the mixtures containing slag cement and silica fume as partial replacements for portland cement ranged from 25.9 to 35.2 kΩ-cm at 28 days; the surface resistivity measurements for mixtures containing portland cement as the only binder were either 9.3 or 10.8 2 kΩ-cm at 28 days.

Table 3.22: Average RCP and SRM results for mixtures in Program III

Mixture ID[a]	**28-Day RCP (Coulombs)**	**56-Day RCP (Coulombs)**	**28-Day SRM[b] (kΩ-cm)**
T-3.4-L	890	700	31.6
T-9.0-L	820	620	30.3
T-12.0-L	960	750	32.0
C-3.4-L	3040	2750	10.8
C-8.7-L	3990	3210	9.3
T-3.0-G	1170	700	27.6
T-8.7-G	860	560	35.2
T-12.5-H	1170	790	25.9

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder composition (T=30% slag cement by weight, 3% silica fume by weight, C=100% cement
E: Amount of total internal water, % binder weight
F: Type of coarse aggregate (L: Low-absorption limestone [with absorptions of 0.73 and 0.89%], H=High-absorption limestone [with an absorption of 2.2%], G=Granite [with absorptions between 0.6 and 0.86%])
[b] Multiplied by 1.1, a correction factor for specimens cured in lime-saturated water rather than in a moist room

3.5 SUMMARY AND CONCLUSIONS

Through three programs, a number of concrete mixtures with different quantities of internal curing water, binder compositions, paste contents, water-to-cementitious material (*w/cm*) ratios, and different coarse aggregates (low absorption limestone, high absorption limestone, and granite) were cast and tested.

Program I had 18 concrete mixtures with paste contents of 23.7, 26.7, or 33.7%, containing portland cement as the only binder, *w/c* ratios of 0.45 and 0.41, and IC water contents ranging from 8.2 or 13.1% by the weight of binder and were evaluated for freeze-thaw durability following ASTM C666-Procedure A. Program II, which had 12 concrete mixtures, also included paste contents of 23.7, 26.7, or 33.7%, had portland cement as the only binder, *w/c* ratios of 0.45 and 0.41, and IC water contents between approximately 8 and 9 percent and between 12 and 13% by the weight of binder, were evaluated for both freeze-thaw durability and scaling resistance. The freeze-thaw performance of the mixtures was investigated following both ASTM C666-Procedure A and the regime specified in KDOT Test Method KTMR-22, including the use of ASTM C666-Procedure B. Scaling resistance was evaluated for eight of the mixtures in accordance with ASTM C672 and a modification of Canadian test BNQ NQ 2621-900.

Program III had eight concrete mixtures (six IC and two control mixtures) and investigated concrete shrinkage, freeze-thaw durability, scaling resistance, and permeability. The primary variables considered in this program included cementitious material compositions (two include only portland cement and six included a ternary binder composition including slag cement and silica fume), quantities of total internal water provided by all aggregates of 3.0 to 3.4%, 8.7 to 9.0%, and 12.0 to 12.5% by the weight of binder (or IC water provided by pre-wetted lightweight aggregate ranging from 0 to 9% by the weight of binder).

Based on the results and analysis described in this study, the following conclusions can be made:

1. **Results from mixtures in Program I** demonstrate that freeze-thaw durability of internally-cured concrete mixtures is a function of the percentage of IC water by the weight of binder, rather than the absorbed water in the lightweight aggregate per unit volume of concrete.
2. Reducing the *w/c* ratio from 0.45 to 0.41 for all the mixtures with a paste content of 23.7%, and for some mixtures with paste contents of either 26.7 or 33.7% improved the freeze-thaw durability of the concrete.
3. **Results from mixtures in Program I and II** show that, all the mixtures assessed for freeze-thaw durability in accordance with ASTM C666-Procedure A exhibited durability

factors below 90% and failed the freeze-thaw test and would not be considered acceptable under MnDOT specifications.

4. At a *w/c* ratio of 0.45, mixtures with IC water contents (by the weight of binder) of 8.2 (with a paste content of 23.7%) and 8.8% (with a paste content of 26.7%) and tested in accordance with ASTM C666-Procedure B and KTMR-22 exhibited durability factors above 95%, passing the test and are considered acceptable under KDOT specifications.
5. At a *w/c* ratio of 0.41, all mixtures tested (IC water contents ranging from 8.6 to 13.0 and paste contents ranging from 23.7 to 33.7%) satisfied the requirements of ASTM C666-Procedure B and KTMR-22 and are considered acceptable under KDOT specifications.
6. As the paste content increased from 23.7 to 33.7%, scaling resistance decreased.
7. As observed in the freeze-thaw tests, reducing the *w/c* ratio from 0.45 to 0.41 improved scaling resistance. Mixtures tested in accordance with BNQ NQ 2621-900 (exposed to NaCl) had lower mass losses (by 32 to 47%) than the paired mixtures tested in accordance with ASTM C672 (exposed to $CaCl_2$). The reaction between calcium hydroxide ($Ca(OH)_2$) produced during the hydration of portland cement and calcium chloride can result in the formation of calcium oxychloride, which is expansive and causes tensile stresses and deterioration in concrete. The scaling tests performed in accordance with ASTM C672 result in increased damage.
8. When tested in accordance BNQ NQ 2621-900 (exposed to NaCl), for a given *w/c* and paste content, as the quantity of IC water increased, the scaling damage increased. At a *w/c* ratio of 0.45 and a paste content of 23.7%, mixtures with an IC water content of 8.8% passed the test, while those with an IC water content above 12.0% did not; at a *w/c* ratio of 0.41 and a paste content of 23.7%, mixtures with IC water contents of less than or equal to

13% passed the test. None of the mixtures with *w/c* ratios of 0.45 and 0.41 and a paste content of 33.7% passed the test.

9. Except for two mixtures with IC water contents of 8.8 or 9.0% and *w/c* ratios of 0.45 and 0.41, respectively, mixtures tested in accordance with ASTM C672 exhibited a visual rating of (2) or (3). MN-IC-LC-HPC specifications limit visual rating of concrete specimens to (0) or (1), representing minimal damage, when tested in accordance with ASTM C672.
10. **Results from mixtures in Program III** demonstrate that mixtures containing slag cement and silica fume as partial replacements for portland cement exhibited lower shrinkage than mixtures containing portland cement as the only cementitious material for similar quantities of total internal water. Furthermore, as the total internal water increased, shrinkage of concrete decreased for a given binder composition.
11. All specimens expanded (swelling) during the 14-day curing period, regardless of binder compositions or quantity of IC water. Mixtures with IC water (8.7 to 12.5% TI water) exhibited somewhat greater expansion at the end of the curing period than mixtures with no IC water (3.0 and 3.4% TI water) with values for mixtures without IC water ranging from 20 to 30 microstrain compared to mixtures with IC water that exhibited expansions ranging from 37 to 90 microstrain.
12. For a given binder composition, mixtures with no IC water exhibited greater shrinkage and lower scaling resistance than mixtures with IC water. All of the mixtures with no IC water exhibited satisfactory freeze-thaw resistance while three mixtures with IC water (T-9.0-L, T-12.0-L, and T-12.5-H) failed the freeze-thaw test in accordance with ASTM C666-Procedure A.

13. The freeze-thaw resistance of the mixtures decreased markedly when the total internal water (provided by all aggregates) exceeded 12.0% by the weight of binder.
14. The ternary mixtures (consisting of 30% slag cement and 3% silica fume as partial replacements for portland cement [by total weight of cementitious materials]) with granite as the coarse aggregate exhibited better freeze-thaw resistance than the paired ternary mixtures with low-absorption limestone. Additionally, the mixtures containing portland cement as the only binder with total internal water contents equal to either 3.4 or 8.7% (by the weight of binder) exhibited considerably higher freeze-thaw resistance than the ternary mixtures with the same TI water content.
15. In contrast to findings in the freeze-thaw test, increased TI water did not negatively affect scaling resistance. At the same time, the type of coarse aggregate did. The ternary mixtures with granite as the coarse aggregate, with either 3.0 or 8.7% of TI water (0 or 5.9% of IC water), had lower mass losses than the ternary mixtures with low-absorption limestone and similar quantities of TI water.
16. Increases in TI water in mixtures did not affect rapid chloride permeability (RCP) or the surface resistivity measurement (SRM). The effect of binder compositions, however, was more pronounced, with the ternary mixtures, on average, showing higher and lower SRM and RCP values, respectively, than mixtures with 100% portland cement.
17. A comparison between mixtures with similar TI water content but different IC water contents, or more specifically mixtures with low and high absorption limestone, respectively, indicates that mixture with the low absorption limestone, T-12.0-L, exhibited better performance than the mixture with high absorption limestone, T-12.5-H, with lower

shrinkage, higher freeze-thaw and scaling resistance, lower RCP and higher SRM values, with differences that are statistically significant.

CHAPTER 4 – CONSTRUCTION OF INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) AND CONTROL BRIDGE DECKS IN MINNESOTA AND KANSAS

4.1 GENERAL

This chapter describes the construction of twelve bridge decks in Minnesota and Kansas that incorporate Minnesota and Kansas Department of Transportations (MnDOT and KDOT, respectively) Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) specifications. Of the twelve decks, nine (identified as MN-IC-LC-HPC-1 through 9) were constructed in Minnesota between 2016 and 2020 and are described in Sections 4.2 through 4.4, and three (identified as KS-IC-LC-HPC-1 through 3) were constructed in Kansas between 2019 and 2021 and are described in Sections 4.5 through 4.7. The differences between the MnDOT and KDOT IC-LC-HPC specifications are also discussed. In the cases where the bridge decks were constructed in multiple placements, the placement number (P#) is added to the end of the bridge ID. The construction of two additional decks that followed provisions for High-Performance Concrete (HPC) in Minnesota is also documented and designated as MN-Control-1 and MN-Control-2. The MN-Control-1 and-2 decks are paired with MN-IC-LC-HPC-1 and-2, respectively, constructed by the same concrete suppliers and contractors, with similar geometries to assess the effectiveness of IC. For each state, the IC-LC-HPC decks are numbered in the order they were constructed, except for MN-IC-LC-HPC-3, which was constructed before MN-IC-LC-HPC-2 to keep the MN-IC-LC-HPC and MN-Control pairs sequential. An additional deck that was bid under the MnDOT IC-LC-HPC specifications, but not constructed following those specifications, is described as well. The failed IC-LC-HPC deck placement is located near Hinckley and will be discussed in Section 4.4.12.

4.2 MNDOT IC-LC-HPC SPECIFICATIONS

The IC decks constructed in Minnesota followed the requirements of MnDOT specifications 2461 “Structural Concrete” and 2401 “Concrete Bridge Construction,” supplemented by a special provision for Section 2401.2 A, “Concrete,” for designing internally-cured concrete mixtures that reduce cracking by incorporating pre-wetted fine lightweight aggregate (LWA). The special provision provides materials, mixture designs, concrete properties, and construction requirements. The most recent version of MnDOT IC-LC-HPC specifications are provided in Appendix C.

4.2.1 Aggregates

The special provisions cover the requirements for fine lightweight aggregate based on a replacement of total aggregate volume with up to 10% pre-wetted LWA with a maximum size aggregate of ⅜ in. (9.5 mm). The LWA is required to be to have achieved acceptable absorption and moisture content at the time of batching. The specifications also cover requirements pertaining to handling and stockpiling LWA, including protection from contamination, segregation, and non-uniform grading and moisture distribution.

In addition to the MnDOT special provisions, several recommendations and procedures dealing with handling, stockpiling, and pre-wetting LWA were made by KU researchers. The recommendations were based on previous studies involving a series of internally-cured bridge decks in Indiana (Barrett et al. 2015). The procedures included pre-wetting the LWA stockpile using sprinklers for a minimum of 48 to 72 hours and allowing it to drain for 12 to 15 hours prior to batching. In addition, it was recommended that the LWA stockpile height to be limited to 5 ft (1.5 m) and that it be turned at least twice a day to provide a uniform moisture content. It was also recommended not to use the bottom 4 to 6 in. (100 to 150 mm) of the LWA stockpile because the moisture content is significantly higher than that of the top sections, resulting in non-uniform moisture contents of the LWA when batched.

The LWA absorption and specific gravity should be measured during and after pre-wetting to ensure that constant values are achieved. A centrifuge was recommended to be used to place the LWA in a pre-wetted surface-dry (PSD) condition prior to these tests. Miller et al. (2014) and Lafikes et al. (2020) demonstrated that the use of a centrifuge to place LWA in the PSD condition produces more consistent results than the use of paper towels (as indicated in ASTM C1761) for removing surface moisture. The mixture proportions were revised based on the measured LWA absorption and specific gravity values to achieve the design quantity of internal curing (IC) water (7 or 8% by the weight of binder). It was also recommended by KU researchers that the free-surface moisture content of the LWA be measured within one hour of batching. The procedure used by KU researchers to measure LWA absorption, specific gravity, and free-surface moisture is described in Section 2.3.2.

The special provisions require that the composite gradation of the aggregates comply with requirements specified in accordance with Table HPC-6, as provided in Appendix C, Section 2.A.7. The specified percentages in Table HPC-6 provide an allowable range for the difference between the actual gradation of the materials during construction and the original gradations submitted with mixture proportions to MnDOT. Additionally, according to the MnDOT IC-LC-HPC specifications, the volume of lightweight aggregate shall not exceed 10 percent of the total volume of aggregates. With the approval of MnDOT, the adjustments in the quantity of LWA (to obtain the desired quantity of IC water), caused the LWA to exceed 10 percent of the total aggregate volume in some cases, but not by more than 0.9%.

4.2.2 Concrete

Table 4.1 summarizes the concrete requirements in the specifications for the MnDOT IC-LC-HPC decks. The specifications require a water-to-cementitious material (*w/cm*) ratio between 0.43 and 0.45, with a maximum paste content of 27% by concrete volume. The specifications also limit the mass replacement of portland cement by slag cement or silica fume to 28 or 2%, respectively, by the weight of binder. If both are used, total replacement may not exceed 30 percent. No silica fume was used in MnDOT IC-LC-HPC mixtures. The design air content range for 2016 decks ranged from 6.5 to 9.5%, while the maximum limit increased slightly to 10% for subsequent years. The design concrete slump range changed substantially, with the maximum limit increasing from 3½ to 5½ in. (90 to 140 mm) between 2016 and 2019, and decreasing to 5 in. (125 mm) in 2020.

According to the specifications, all mixing water is required to be added at the plant, with no water allowed to be added at the job site. As discussed in Section 4.4, however, in most cases, water was added at the job site to increase pumpability and workability. The addition of set retarding admixtures is allowed in accordance with MnDOT IC-LC-HPC specifications.

Table 4.1: Requirements for concrete in MnDOT IC-LC-HPC decks

<table>
<tr><th>Construction year</th><th>w/cm ratio</th><th>Paste content (%)</th><th>Maximum SCM (fly ash/Slag cement/Silica Fume/Ternary [%])</th><th>Air content (%)</th><th>Slump (in.)</th></tr>
<tr><td>2016</td><td rowspan="5">0.43-0.45</td><td rowspan="5">27</td><td rowspan="5">0/28/2/30</td><td>6.5-9.5</td><td>1-3½</td></tr>
<tr><td>2017</td><td rowspan="4">6.5-10</td><td>1½-4</td></tr>
<tr><td>2018</td><td rowspan="2">1½-5½</td></tr>
<tr><td>2019</td></tr>
<tr><td>2020</td><td>1½-5</td></tr>
</table>

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa.

The specifications also provide requirements for hardened concrete properties, such as 28-day compressive strength, rapid chloride permeability, freeze-thaw durability, free shrinkage, and scaling resistance, as shown in Table HPC-5 in Appendix C.

The specifications limit both the maximum and the minimum of 28-day compressive strengths (ASTM C 31) to 5500 and 4000 psi (37.9 and 27.6 MPa), respectively; for the rapid chloride permeability (RCP) test, the maximum charge passed must be less than 2500 and 1500 coulombs at 28 and 56 days, respectively. In addition, the upper limit for shrinkage is 400 microstrain at 28 days. It also specified requirements for the freeze-thaw resistance of concrete in accordance with ASTM C666-procedure A, with a failure limit of 90% of the initial dynamic modulus of elasticity at 300 cycles. The specifications also have a maximum visual rating of 1 by the end of 50 freezing and thawing cycles for specimens tested in accordance with ASTM C672 for scaling resistance.

4.2.3 Construction

To demonstrate that the concrete supplier and the contractor can properly produce, pump, and place IC-LC-HPC, a trial placement containing a minimum of two 10-yd^3 (7.6-m^3) loads is required at least 14 calendar days before the actual deck placement. Contractors are required to employ the same concrete supplier, ready-mix plant, materials, equipment, and methods used on both the trial and the deck placements. Contractors must also provide deck placement and curing plans such as concrete delivery rates, estimated start and finish time, number of work bridges, and curing methods. According to the specifications, sections of bridge footings, abutments, end diaphragms, and other construction near the project can be used for the trial placements.

During construction period, MnDOT IC-LC-HPC specifications specify a maximum evaporation rate of 0.2 lb/ft^2/hr (1.0 kg/m^2/hr). The specifications require contractors to provide a weather forecast confirmation three hours prior to placement to show a low chance of rain during construction, as well as preparation to maintain the evaporation rate below the allowable limit.

According to the specifications, the use of finishing aids or evaporation retarders for use in finishing is prohibited.

MnDOT IC-LC-HPC specifications require that full-depth decks be bullfloated before carpet dragging with a 10 ft (3 m) bullfloat, regardless of the specified texturing plan for the final surface. The final surface and curing methods are based on the deck type. Table 4.2 summarizes the deck types and required curing methods in accordance with the specifications.

Table 4.2: Required curing method based on final deck surface (Minnesota Department of Transportation 2018)

Bridge deck type	Final bridge deck surface	Required curing method[a]
Bridge structural slab curing	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks	Bridge Deck Planing	Conventional wet curing after carpet drag.
	Tined Texturing[b]	Conventional wet curing after tine texturing AMS curing Compound after wet cure period
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)[b]	Conventional wet curing after applying transverse broom finish AMS curing Compound after wet cure period

[a] Apply conventional wet curing to bridge slabs following the finishing machine or air screed.
[b] Prevent marring of broomed finish or tined textured surface by careful placement of wet curing.

The specifications indicate covering the entire deck with pre-soaked burlap (for at least 12 hours) with no visible openings on the deck within 20 minutes after the final strikeoff, followed by white plastic sheeting. The concrete surface is required to remain continuously wet for at least 7 calendar days. Where there are concerns regarding the marring of broomed or tined surface, the specifications allow applying a Poly-Alpha Methylstyrene (AMS) membrane curing compound within 30 minutes of concrete placement followed by conventional wet curing. Conventional wet curing is required to be applied when walking on the surface resulting in no imprints deeper than $^{1}/_{16}$ in (1.6 mm).

4.3 DECK CONSTRUCTION-MINNESOTA

Table 4.3 summarizes the general information of the decks included in this study. The MnDOT IC-LC-HPC decks were constructed between 2016 and 2020. MN-IC-LC-HPC decks are numbered in the order they were constructed, except for MN-IC-LC-HPC-3, which was constructed before MN-IC-LC-HPC-2 to keep the MN-IC-LC-HPC and MN-Control pairs sequential. In the cases where the bridge decks were constructed in multiple placements, the placement number (P#) is added at the end of the bridge ID. The decks are located in the Twin Cities area, Winona, Pine City, or between Rochester and St. Paul. All decks are supported by prestressed concrete girders. Three of the twelve placements (MN-IC-LC-HPC-1, 5, and MN-Control-1) are pedestrian decks, while the other decks carry vehicular traffic with or without sidewalks.

Half of the IC placements were constructed between May and August, cured in warm ambient temperatures with a longer time for the IC water to be consumed/evaporated prior to exposure to freezing temperatures. The other placements were constructed in September. Three placements received a 2-in. (50-mm) overlay (MN-IC-LC-HPC-2, MN-IC-LC-HPC-3, and MN-Control-2). Overlays were placed in two days, each day covering half the deck width. Except for MN-IC-LC-HPC-7, the remainder of the monolithic decks were placed in one placement. Table 4.4 lists the bridge dimension information, concrete suppliers, and construction contractors for the decks constructed in Minnesota.

Table 4.3: MnDOT IC-LC-HPC and MN-Control deck information

Bridge ID	Bridge No.	Location	Structure type	Subdeck placement date	Overlay placement dates[a]
MN-IC-LC-HPC-1	62892	Mackubin St. over I-94, St. Paul	Prestressed concrete girders	9/22/2016	-
MN-IC-LC-HPC-2	25036	S.B. T.H. 52 near Cannon Falls,		7/6/2017	9/7/2017, 9/9/2017
MN-IC-LC-HPC-3	25037	T.H. 58 over T.H. 52, Zumbrota		6/29/2017	7/21/2017, 7/24/2017
MN-IC-LC-HPC-4	9619	38th St. over I-35W, Minneapolis		5/15/2018	-
MN-IC-LC-HPC-5	27700	40th St. over I-35W, Minneapolis		7/23/2019	-
MN-IC-LC-HPC-6	58826	C.S.A.H. 7 over I-35W near Pine City		9/19/2019	-
MN-IC-LC-HPC-7-P1[b]	62735	Dale St. over I-35, St. Paul		6/24/2020	-
MN-IC-LC-HPC-7-P2				9/22/2020	-
MN-IC-LC-HPC-8	85862	C.S.A.H. 12 over I-90, Winona		8/20/2020	-
MN-IC-LC-HPC-9	85863	I-90 over Dakota Valley, Winona		9/4/2020	-
MN-Control-1	62800	Grotto St. over I-94, St. Paul		9/28/2016	-
MN-Control-2	25032	N.B. T.H. 52 near Cannon Falls		9/15/2017	9/28/2017, 9/30/2017

[a] Subdeck is topped by a 2-in overlay, in two days, each day covering half the deck width.
[b] P stands for placement.

The IC bridge decks have between one and four spans with skews between 0° and 16º 2' 30". The lengths of the bridges range from 153.6 to 237.0 ft (46.8 to 72.2 m), and the widths range from 14.3 to 56.7 ft (4.4 to 17.2 m).

Table 4.4: MnDOT IC-LC-HPC and MN-Control deck geometry, project supplier, and contractor

Bridge ID	Skew (deg.)	No. of spans	Length (ft)	Width (ft)	Concrete supplier	Contractor
MN-IC-LC-HPC-1	0	2	182.5	14.3	Cemstone Products Co.	Kraemer North America
MN-IC-LC-HPC-2	0	1	153.6	45.3	Ready-Mix Concrete Company L.L.C.	Lunda Construction Co.
MN-IC-LC-HPC-3	0	2	212.0	48.9	Ready-Mix Concrete Company L.L.C.	Lunda Construction Co.
MN-IC-LC-HPC-4	0	4	209.0	56.0	Aggregate Industries U.S.	Lunda Construction Co.
MN-IC-LC-HPC-5	0	2	191.5	16.8	Aggregate Industries U.S.	Lunda Construction Co.
MN-IC-LC-HPC-6	16º 2’ 30”	2	188.0	59.8	Cemstone Products Co.	Ames Construction
MN-IC-LC-HPC-7-P1[a]	2º 24’38”	2	179.9	56.7	Cemstone Products Co.	Redstone Construction
MN-IC-LC-HPC-7-P2				56.7		
MN-IC-LC-HPC-8	4º 6’ 7”	2	229.1	39.0	Modern Ready-Mix Inc.	Icon Constructors
MN-IC-LC-HPC-9	13º 45’ 24”	3	143.1	43.0	Modern Ready-Mix Inc.	Icon Constructors
MN-Control-1	0	2	237.0	14.3	Cemstone Products Co.	Kraemer North America
MN-Control-2	0	1	153.6	45.3	Ready-Mix Concrete Company L.L.C.	Lunda Construction Co.

[a] P stands for placement.

4.3.1 Concrete Mixture Proportions

The cementitious material percentages and aggregate proportions for each deck are given in Table 4.5. The mixtures for MnDOT IC-LC-HPC decks contained a binary cementitious system, with mass replacement of portland cement (between 27 and 30%) with slag cement. The MnDOT Control decks contained a design binary composition system, with mass replacement of portland cement (25%) with Class F fly ash. The overlay concrete included portland cement as the only binder. Table 4.6 shows the LWA properties obtained by KU personnel as well as the designed values given by the concrete suppliers.

Table 4.5: Cementitious material percentages and aggregate proportions (SSD/PSD basis)[a]

Bridge ID	Cementitious material percentages[c] (lb/yd^3)	Coarse Agg. (lb/yd^3)		Fine Agg. (lb/yd^3)		LWA Agg. (lb/yd^3)	
		Design	Actual	Design	Actual	Design	Actual
MN-IC-LC-HPC-1	70% C, 30% S	1655	1650	1106	1102	194	191
MN-IC-LC-HPC-2	70% C, 27% S	1411	1415	1141	1144	238	245
MN-IC-LC-HPC-3	70% C, 27% S	1411	1415	1141	1144	238	247
MN-IC-LC-HPC-4	70% C, 28% S	1701	1708	970	973	201	201
MN-IC-LC-HPC-5	70% C, 28% S	1701	1697	948	949	216	215
MN-IC-LC-HPC-6	70% C, 30% S	1641	1631	1092	1084	164	122
MN-IC-LC-HPC-7-P1[d]	70% C, 30% S	1643	1637	1098	1095	159	163
MN-IC-LC-HPC-7-P2		1643	1637	1105	1103	156	156
MN-IC-LC-HPC-8	70% C, 30% S	1583	1579	1074	1071	192	193
MN-IC-LC-HPC-9	70% C, 30% S	1583	1579	1113	1108	169	170
MN-Control-1	75% C, 25% F-FA	1719	1716	1318	1315	-	
MN-Control-2	75% C, 25% F-FA	1736	1740	1243	1244	-	
Overlays[b]	100% C	1411		1373		-	

[a] Actual values are based on the average of trip tickets.
[b] Overlay construction records only indicate the design amounts of materials used.
[c] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; F-FA = Class F fly ash.
[d] P stands for placement.
Note: 1 lb/yd^3 = 0.593 kg/m^3.

Table 4.6: LWA properties, design, and actual values obtained by KU researchers

Bridge ID	Absorption (%, OD basis)		Specific gravity (OD basis)	
	Design	KU measurements	Design	KU measurements
MN-IC-LC-HPC-1	30.0	23.1	1.29	1.35
MN-IC-LC-HPC-2	23.5	24.5	1.35	1.33
MN-IC-LC-HPC-3	23.5	24.9	1.35	1.33
MN-IC-LC-HPC-4	23.6	30.3	1.33	1.26
MN-IC-LC-HPC-5	30.2	27.6	1.27	1.30
MN-IC-LC-HPC-6	27.2	32.9	1.23	1.21
MN-IC-LC-HPC-7-P1[a]	32.9	34.0	1.21	1.20
MN-IC-LC-HPC-7-P2		35.1		1.20
MN-IC-LC-HPC-8	30.0	31.1	1.40	1.27
MN-IC-LC-HPC-9	31.1	30.8	1.27	1.28

[a] P stands for placement.

Table 4.7 provides the design and actual values of the total weight of cementitious materials, water content, water-to-cementitious material (*w/cm*) ratio, paste content, and IC water content (if applicable) for each deck. The actual values are based on averages obtained from trip tickets. As will be discussed, the main reason for the differences between the design and actual values, specifically for water content, *w/cm* ratio, and paste content, is that the concrete suppliers, in most cases, withhold a portion of mixing water from the majority of truckloads. For example, MN-IC-LC-HPC-9 had a design *w/cm* ratio of 0.43 but an actual *w/cm* ratio of 0.37, the lowest in this study. The design *w/cm* ratio for the MnDOT IC-LC-HPC decks was either 0.43 or 0.45, with actual *w/cm* ratios ranging from 0.40 to 0.43. Subsequently, the actual paste content was reduced in concrete mixtures with lower actual water contents. The design paste contents ranged from 25.4 to 26%, with actual paste contents ranging from 24 to 25.7%. The design IC water content was either 7 or 8%, with actual values ranging from 5.2 to 8.7%. The quantity of IC water was based on the amount of absorbed water and the quantity of LWA in the mixture. The variation in LWA absorption observed in this study resulted in a considerable difference between the design value and the actual quantity of IC water for some decks, as illustrated in Table 4.7. Failure to measure LWA properties correctly can also result in incorrect amounts of mixing water being batched or withheld during batching, affecting actual *w/cm* ratios and paste contents. Data from individual trip tickets are shown in Appendix D.

The mixture proportions of the overlays included portland cement as the only binder, with a paste content and *w/c* ratio of 34.3% and 0.37, respectively, in accordance with MnDOT 3U17A "Low Slump Concrete" specifications. The trip tickets for the overlays placed on MN-IC-LC-HPC-2, MN-IC-LC-HPC-3, and MN-Control-2 are unavailable.

Table 4.7: Cementitious material content, water content, *w/cm* ratio, paste, and IC water contents for MnDOT IC-LC-HPC and MN-Control decks[a]

Bridge ID	Cementitious material content (lb/yd^3)		Water content (lb/yd^3)		*w/cm* ratio		Paste content (%)		IC water (% of binder weight)	
	Design	Actual	Design	Actual	Design	Actual	Design	Actual	Design	Actual
MN-IC-LC-HPC-1	550	551	248	239	0.45	0.43	25.4	24.9	8	6.5
MN-IC-LC-HPC-2	564	565	254	244	0.45	0.43	26.0	25.4	8	8.5
MN-IC-LC-HPC-3	564	568	254	240	0.45	0.42	26.0	25.2	8	8.7
MN-IC-LC-HPC-4	582	581	250	245	0.43	0.42	26.0	25.7	8	8
MN-IC-LC-HPC-5	582	581	250	240	0.43	0.41	26.0	25.3	8	8
MN-IC-LC-HPC-6	580	580	248	232	0.43	0.40	26.0	25.0	7	5.2
MN-IC-LC-HPC-7-P1[c]	580	579	248	239	0.43	0.41	25.9	25.4	7	7.1
MN-IC-LC-HPC-7-P2		579		237		0.41		25.3	7	7
MN-IC-LC-HPC-8	570	571	245	239	0.43	0.42	25.6	25.3	8	8
MN-IC-LC-HPC-9	570	571	245	219	0.43	0.37	25.6	24.0	7	7
MN-Control-1	595	594	250	222	0.42	0.37	26.9	25.3	-	
MN-Control-2	580	582	245	230	0.42	0.40	26.7	25.8	-	
Overlays[b]	836		312		0.37		34.3		-	

[a] Actual values are based on the average of trip tickets.
[b] Overlay construction records only indicate the design amounts of materials used.
[c] P stands for placement.
Note: 1 lb/yd^3 = 0.593 kg/m^3.

4.4 BRIDGE DECKS

Table 4.8 summarizes concrete properties, including the average slumps, air contents, concrete temperatures, and 28-day compressive strengths for the MnDOT decks. Construction of each deck is discussed in detail in Sections 4.4.1 through 4.4.11. The average slump ranged from 3¼ to 4¾ in. (80 to 120 mm), with the maximum value corresponding to MN-IC-LC-HPC-4. As discussed in Section 4.2.2, MnDOT allowed an increase in the maximum slump limit over the years from 3½ to 5½ in. (90 to 140 mm), primarily due to the good performance of similar IC decks constructed in Indiana (Lafikes et al. 2020). The average slump for MN-Control-1 and -2 were 4 or 3¼ in. (100 or 80 mm), respectively, well above the specifications range of ½ to 1 in. (15 to 25 mm). Air contents were within the specification limits, ranging from 7.5 to 9.1% for MN-IC-LC-HPC decks and either 6.1 or 6.3% for MN-Control decks. Concrete temperatures were also within the specification limits (50 to 90 °F [10 to 32 °C]), ranging from 64 to 78 °F (18 to 26 °C) for MN-IC-LC-HPC decks and either 66 or 73 °F (19 or 23°C) for MN-Control decks; the 28-day compressive strengths for most of the IC decks, however, exceeded the maximum specifications limit of 5500 psi (37.9 MPa), ranging from 4560 to 7090 psi (31.4 to 48.8 MPa). The 28-day compressive strengths of MN-Control decks were well above 4000 psi (27.6 MPa), the requirement for high-performance concrete mixtures. Based on the work of Khajehdehi and Darwin (2018), higher strength concrete is no longer thought to be an issue in bridge deck cracking.

Table 4.8: Average MnDOT IC-LC-HPC and MN-Control concrete properties

Bridge ID	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength
MN-IC-LC-HPC-1	3¼	7.5	67	7090
MN-IC-LC-HPC-2	3½	9.1	78	4560
MN-IC-LC-HPC-3	3½	8.2	75	5140
MN-IC-LC-HPC-4	4¾	8.9	64	5540
MN-IC-LC-HPC-5	3¾	7.3	77	5320
MN-IC-LC-HPC-6	3½	7.9	71	6490
MN-IC-LC-HPC-7-P1	4½	8.9	73	6630
MN-IC-LC-HPC-7-P2[a]	3½	8.2	73	5830
MN-IC-LC-HPC-8[a]	4½	7.9	71	6500
MN-IC-LC-HPC-9[a]	4½	7.9	72	6320
MN-Control-1	4	6.1	66	6630
MN-Control-2	3¼	6.3	73	5410

[a] Values measured before pumping; cylinders were filled from truck discharge
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

4.4.1 MN-IC-LC-HPC-1

MN-IC-LC-HPC-1 is a pedestrian bridge deck located at Mackubin St. over I-94 in St. Paul. The deck was constructed in one placement on September 22, 2016. The concrete supplier and the contractor were Cemstone Products Co. and Kraemer North America, respectively. The bridge has two spans with lengths of 92 ft (28.0 m) and 90 ft-6 in (27.6 m), for a total length of 182 ft-6 in. (55.6 m). The deck has a 12 ft (3.7 m) wide walkway and a 1 ft-2 in. (0.4 m) wide barrier on each side, for a total deck width of 14 ft-4 in. (4.4 m). The nominal deck thickness is 7 in. (178 mm); the deck is supported by prestressed concrete girders with no skew.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-1 was an expanded clay stored in an open area at the ready-mix plant. A lawn sprinkler was used to pre-wet the LWA on top of the aggregate stockpile. The stockpile was approximately 4 ft (1.2 m) high, less than the recommended 5-ft (1.5-m) limit. To allow the material to drain properly, the sprinkler was turned off on the morning of deck placement at 7:00 am. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

The average absorption (OD basis) and specific gravity of the LWA obtained by KU researchers were 23.1% and 1.35, which differed significantly from the value indicated in the original mixture proportions (30% and 1.29, respectively). Having a lower absorption than used for determining batch weights can lead to a lower than the intended quantity of internal curing water. No adjustments, however, were made to the mixture proportions, resulting in an IC water content of 6.5%, lower than the design value of 8% by weight of binder. Representatives from KU were not in attendance during the trial placement for this deck. According to MnDOT personnel, the IC mixture design was approved while emphasizing using the same pump size for the deck construction.

The design and actual (based on the average of trip tickets) mixture proportions are provided in Table 4.9. MN-IC-LC-HPC-1 had a design *w/cm* ratio of 0.45, a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement, and a design paste content of 25.4%. The design quantity of internal curing water was 8% (by the weight of binder). Based on the trip tickets, either 8 or 17 lb/yd^3 (5 or 10 kg/m^3) of water was withheld from truckloads, reducing the actual *w/cm* ratio to an average of 0.43. Prior to casting, KU researchers measured a total moisture content (absorbed and free) of 28.1% (of the LWA), which was used for batching by the ready-mix plant personnel. Crushed granite and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, individual paste contents ranged from 24.6 to 25.0%, with an average of 24.9% and the actual quantities of IC water ranged from 6.4 to 6.6%, with an average of 6.5% by total weight of binder. The dosages of the air-entraining, mid-range water-reducing, and viscosity modifying admixtures were held constant throughout batching at 0.58, 5, and 3 oz/cwt (0.4, 3.3, and 1.9 mL/kg), respectively.

Table 4.9: MN-IC-LC-HPC-1 mixture proportions (SSD/PSD basis)

Material		Mixture proportions (lb/yd^3)	
		Design	Actual[a]
Cement (Type I/II)		385	387
Grade 100 slag cement		165	164
Water		248	239
Fine lightweight aggregate		194	191
Coarse aggregate		1655	1650
Fine aggregate		1106	1102
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Design**	**Actual[a]**
Air AE 90	Air-Entraining	0.1-10	0.58
Polyheed 1020	Mid-range Water-Reducing	1-12	5
Matrix VMA 358	Viscosity Modifying	0-6	3

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are provided in Table 4.10. Only the first truckload was rejected during the construction. The concrete in the first truck was tested for air content and slump after pumping. The air content was 8.4% within the specified range, but the initial test for the slump showed a 6-in. slump (150-mm), well above 3½ in. (90 mm), the maximum limit of the specifications. A second test was performed and showed a slump of 5½ in. (140 mm), again above the specifications limit, and thus the truckload was rejected. Slumps ranged from 2½ to 4 in. (65 to 100 mm), with an average of 3¼ in. (85 mm); air contents ranged from 7.0 to 8.1%, with an average of 7.5%; concrete temperatures were measured in two tests with the values of 65 and 68 °F (18 and 20 °C), with an average of 67 °F (19 °C), all within the specifications. The 28-day compressive strengths ranged from 6990 to 7200 psi (78.2 to 49.6 MPa), with an average of 7090 psi (48.9 MPa).

Table 4.10: Concrete test results-MN-IC-LC-HPC-1

MN-IC-LC-HPC-1	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	2½	7.0	65	6990
Maximum	3½	8.1	68	7200
Average	3¼	7.5	67	7090

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The bridge was located about 10 minutes away from the ready-mix plant. Placement started on September 22, 2016 at 10:30 pm, at the north end of the deck, continued to the south end, and was completed in the early morning of September 23, 2016 at 2:36 am. The concrete was placed using a pump (located below the bridge), consolidated using a single spud vibrator, and finished using a vibrating screed. The concrete was then bullfloated, finished with a broom, and finally covered with wet burlap. The time between batching and discharge ranged from 21 to 34 minutes, with an average of 29 minutes.

During the construction, environmental conditions were recorded, with wind speed ranging from 4.6 to 8.1 mph (7.4 to 13 km/hr), relative humidity ranging from 82 to 86%, and ambient air temperature ranging from 60 to 63 °F (16 to 17 °C), resulting in low evaporation rates, ranging from 0.03 to 0.05 lb/ft^2/hr (0.15 to 0.24 kg/m^2/hr), well below 0.2 lb/ft^2/hr (1 kg/m^2/hr), the maximum specifications limit. No significant issues arose during concrete pumping, placement, or finishing. A 20-minute delay occurred, however, at the beginning of the construction (approximately 15 ft [4.3 m] from the north end) due to imperfections left on the surface after the first screed pass. At this location, a 2×4-in. (50×100-mm) manual wooden screed was used to refinish the concrete surface. The time between placement and strikeoff ranged from 6 to 52 minutes, with an average of 25 minutes.

The concrete in the last truck was wetter than the concrete in the previous trucks, and a high amount of bleed water was observed on the last 20 ft (6.1 m) of the deck. The contractor chose to delay placing the wet burlap by 60 to 77 minutes under the mistaken assumption that doing so would damage the deck surface (experience in Kansas show that it would not). The time between strikeoff and curing ranged from 13 to 77 minutes. Some scaling damage was observed on the deck (Section 5.3.1.1).

4.4.2 MN-Control-1

The associated control deck for MN-IC-LC-HPC-1, MN-Control-1, is a pedestrian bridge deck located at Grotto St. over I-94 in St. Paul. The deck substructure was constructed in one placement on September 28, 2016. As with MN-IC-LC-HPC-1, the concrete supplier and the contractor were Cemstone Products Co. and Kraemer North America, respectively. The bridge has two equal span lengths of 118 ft-6 in. (36.1 m), for a total length of 237 ft (72.2 m). The deck has a 12 ft (3.7 m) wide walkway, a 1 ft-2 in. (0.4 m) wide barrier on each side, for a total deck width of 14 ft-4 in. (4.4 m). The nominal deck thickness is 7 in. (178 mm); the deck is supported by prestressed concrete girders with no skew.

Representatives from KU were not present during the construction of MN-Control-1. The design and actual (based on the average of trip tickets) mixture proportions are provided in Table 4.11. MN-Control-1 had a design *w/cm* ratio of 0.42 and a 28% replacement of cement (by total weight of binder) with Class F fly ash, with a design paste content of 26.9%. Based on the trip tickets, between 23 and 33 lb/yd^3 (14 or 20 kg/m^3) of water was withheld during batching, reducing the actual *w/cm* ratio to an average of 0.37. Crushed granite and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, individual paste contents ranged from 24.8 to 25.6%, with an average of 25.3%. The dosages of the air-entraining, mid-range water-reducing, and viscosity modifying admixtures were held constant throughout batching at 0.43, 1, and 3 oz/cwt (0.3, 0.7, and 1.9 mL/kg), respectively.

Table 4.11: MN-Control-1 mixture proportions (SSD/PSD basis)

Material		Mixture proportions (lb/yd^3)	
		Design	Actual[a]
Cement (Type I/II)		446	445
Class F fly ash		149	149
Water		250	222
Coarse aggregate		1719	1716
Fine aggregate		1318	1315
Chemical Admixture (oz/cwt)			
BASF	Type	Design	Actual[a]
Air AE 90	Air-Entraining	0.1-10	0.43
Polyheed 1020	Mid-range Water-Reducing	1-12	1
Matrix VMA 358	Viscosity Modifying	0-6	3

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are provided in Table 4.12. Slumps ranged from 3¾ to 4 in. (95 to 100 mm), with an average of 4 in. (100 mm); air contents ranged from 5.6 to 6.8%, with an average of 6.1%; concrete temperatures were measured in two tests with the values of either 62 and 70 °F (16 or 21 °C), with an average of 66 °F (19 °C), all within the MnDOT specifications. The 28-day compressive strengths ranged from 6360 to 6820 psi (43.9 to 47.0 MPa), with an average of 6630 psi (45.7 MPa).

Table 4.12: Concrete test results-MN-Control-1

MN-Control-1	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3¾	5.6	62	6360
Maximum	4	6.8	70	6820
Average	4	6.1	66	6630

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

4.4.3 MN-IC-LC-HPC-2

MN-IC-LC-HPC-2 is a two-lane bridge that carries southbound traffic on T.H. 52 over the Little Cannon River, near Cannon Falls. The concrete supplier and the contractor were Ready-Mix Concrete Company L.L.C. and Lunda Construction Co., respectively. The bridge has one span with a length of 153 ft-7 in. (46.8 m). The deck has a 42 ft (12.8 m) wide roadway with a 1 ft-8 in. (0.5 m) wide barrier on each side, for a total deck width of 45 ft-4 in. (13.8 m). The deck thickness includes a 7-in. (178-mm) subdeck and a 2-in. (51-mm) thick overlay, for a total thickness of 9 in. (229 mm). The overlay placed on the deck later did not incorporate IC; the deck is supported by prestressed concrete girders with no skew.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-2 was an expanded clay stored in an open area at the ready-mix plant. A lawn sprinkler was used to pre-wet the LWA located on top of a partition wall near the aggregate stockpile. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit, as shown in Figure 4.1. The sprinklers were turned off the night before deck placement, letting the material drain for about 14 hours. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

Figure 4.1: Lightweight aggregate stockpile for MN-IC-LC-HPC-2

One of the MN-IC-LC-HPC-2 abutments was used as a trial placement. Although KU researchers were not in attendance during the trial placement, they were informed that concrete properties met the specifications with no problems observed during pumping.

The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 24.5% and 1.33, respectively, which differed slightly from the values indicated in the original mixture proportions (23.5% and 1.35, respectively). No adjustments, however, were made to the mixture proportions based on the differences in the LWA properties between those obtained by KU and those indicated in the original design. Prior to casting, KU researchers measured a total moisture content of 31% (of the LWA), which was used by the ready-mix plant personnel.

The design and actual (based on the average of trip tickets) mixture proportions of the subdeck are provided in Table 4.13. MN-IC-LC-HPC-2 had a design *w/cm* ratio of 0.45 and a 27.3% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 26%. The design quantity of internal curing water was 8% (by the weight of binder). Based on the trip tickets, 17 lb/yd^3 (20 kg/m^3) of water was withheld during batching, resulting in stiff concrete with a *w/cm* ratio as low as 0.42. A portion of the withheld water ranging from 5 to 10 lb/yd^3 [3 to 6 kg/m^3] was added back at the jobsite, increasing the *w/cm* ratio to an average of 0.43. Crushed granite and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, paste contents ranged from 24.6 to 25.7%, with an average of 25.4% and the actual quantity of IC water ranged from 8.4 to 8.6%, with an average of 8.5% by total weight of binder. The dosages of the air-entraining, mid-range water-reducing, and viscosity modifying admixtures were held constant throughout batching at 0.9, 3, and 2 oz/cwt (0.6, 1.9, and 1.3 mL/kg), respectively. A set-retarding admixture was added to all truckloads at a dosage of 2 oz/cwt (1.3 mL/kg).

Table 4.13: MN-IC-LC-HPC-2 subdeck mixture proportions (SSD/PSD basis)

Material		**Mixture proportions (lb/yd^3)**	
		Design	**Actual[a]**
Cement (Type I/II)		410	411
Grade 100 slag cement		154	154
Water		254	244
Fine lightweight aggregate		238	245
Coarse aggregate		1411	1415
Fine aggregate		1141	1144
Chemical Admixture (oz/cwt)			
GRT	**Type**	**Design**	**Actual[a]**
Polyheed SA50	Air-Entraining	As needed	0.9
KB 1200	Mid-range Water-Reducing	3-12	3
Polychem VMA	Viscosity Modifying	2-5	2
Polychem Renu	Set-Retarding	3-6	2

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.14. Slump tests showed the same value of 3½ in. (90 mm); air contents ranged from 9.0 to 9.3%, with an average of 9.1%; concrete temperatures ranged from 76 to 81 °F (24 or 27 °C), with an average of 78 °F

(26 °C), all within the specifications. The 28-day compressive strengths ranged from 4370 to 4670 psi (30.1 to 32.2 MPa), with an average of 4560 psi (31.4 MPa).

Table 4.14: Concrete test results-MN-IC-LC-HPC-2 subdeck

MN-IC-LC-HPC-2 subdeck	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3½	9.0	76	4370
Maximum	3½	9.3	81	4670
Average	3½	9.1	78	4560

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

MN-IC-LC-HPC-2 was located about 25 minutes away from the ready-mix plant. Construction of the subdeck started on July 6, 2017 at 7:00 am, at the south end of the deck, continued to the north end, and was completed at 9:45 am. The concrete was placed using two pumps positioned at opposite ends of the deck, consolidated using a single spud vibrator, and finished using two vibrating screeds (one 17 ft [5.2 m] long and the other 24 ft [7.3 mm] long) each with a carpet drag, as shown in Figure 4.2. There was a gap about 2 ft (0.6 m) wide between the two screeds, as well as two gaps about 1 ft (0.3 m) wide between the end of the screeds and the barrier reinforcement. Concrete in these gaps was consolidated by the spud vibrator and finished by bullfloating. Bullfloating was performed mostly in the transverse direction, with some in the longitudinal direction (near the centerline).

Figure 4.2: Finishing equipment for MN-IC-LC-HPC-2 subdeck

During construction, environmental conditions were recorded, with wind speed ranging from 0 to 1.7 mph (0 to 2.7 km/hr), relative humidity ranging from 65 to 75%, and ambient air temperature ranging from 74 to 84 °F (23 to 29 °C), resulting in low evaporation rates, ranging from 0.01 to 0.03 lb/ft^2/hr (0.05 to 0.15 kg/m^2/hr), well below 0.2 lb/ft^2/hr (1 kg/m^2/hr), the maximum specification limit. No significant issues arose during concrete pumping, placement, or finishing. The time between batching and discharge ranged from 37 to 48 minutes, with an average of 42 minutes. The deck was finished efficiently with an average time of 2 minutes after placement.

One work bridge was used to place wet burlap on the deck. A layer of burlap was placed on with an average time of 15 minutes after strikeoff. On some occasions, it was observed that water dripped onto the deck from rolls of burlap stacked on the work bridge, leaving ponds of water on the east side of the deck near the barrier, as shown in Figure 4.3.

Figure 4.3: Water from burlap dripping onto the deck

MN-IC-LC-HPC-2 received a 2-in. (25-mm) wearing course (overlay) on July 21 and July 24, 2017, for the right lane and shoulder, and left lane and shoulder, respectively. The procedures for placing overlay were similar for both placements. KU researchers were in attendance only during the left lane and shoulder overlay placement on July 24. A paving mix was designated for the overlay with no internal curing.

The mixture had a *w/c* ratio of 0.32 with a paste content of 31.8%. The concrete for overlay was provided using a mobile mixer at the job site. Immediately before overlay placement, the subdeck was cleaned and sandblasted, followed by brooms to remove debris from the surface. A layer of bonding grout (sand, water, and portland cement) was then applied to the surface. The concrete was transported using buggies and deposited on the subdeck. A pavement finishing machine was used to finish the concrete surface, followed by bullfloats and trowels. The surface was then tined with an artificial grass-type carpet drag followed by transverse tining. Curing compound was applied to the surface within 22 minutes of finishing (within 12 minutes of tining) followed about 2 hours later by wet burlap, followed by plastic sheeting. The single cylinder made from the right lane and shoulder overlay concrete had a 28-day compressive strength of 7060 psi (48.7 MPa); the two cylinders made at different locations from the left lane and shoulder overlay concrete had 28-day compressive strengths of 7130 and 8450 psi (49.2 and 58.3 MPa).

4.4.4 MN-Control-2

The associated control deck for MN-IC-LC-HPC-2, MN-Control-2, is a two-lane bridge that carries northbound traffic on T.H. 52 over the Little Cannon River, near Cannon Falls. As with MN-IC-LC-HPC-2, the concrete supplier and the contractor were Ready-Mix Concrete Company L.L.C. and Lunda Construction Co., respectively. The bridge has the same geometry, deck, and girder type as MN-IC-LC-HPC-2 with a 7-in. (178-mm) subdeck and a 2-in. (51-mm) thick overlay, for a total thickness of 9 in. (229 mm).

Representatives from KU were not present during the construction of the MN-Control-2 subdeck and overlay. Based on the trip tickets, placement of the subdeck started on September 15, 2017 at 11:15 am and finished at 2:26 pm. The design and actual (based on the average of trip tickets) mixture proportions of the subdeck are provided in Table 4.15. MN-Control-2 subdeck had a design *w/cm* ratio of 0.42 and a 35% replacement of cement (by total weight of binder) with Class F fly ash, with a design paste content of 26.7%. The mixture proportions also included macrofibers at a dosage of 4 lb/yd^3 (2.4 kg/m^3). The MN-Control-2 wearing course (overlay) did not incorporate fibers.

Based on the trip tickets, approximately 25 lb/yd^3 (15 kg/m^3) of water was withheld during batching, resulting in a *w/cm* ratio as low as 0.38. Therefore, a portion of the withheld water, ranging from 3 to 15 lb/yd^3 [2 to 9 kg/m^3], was added back to some truckloads, increasing the *w/cm* ratio to an average of 0.40. Crushed granite and river sand were used as the coarse and fine aggregates, respectively. Based on the trip tickets, the paste content ranged from 25.4 to 26.3%, with an average of 25.8%. The dosages of the mid-range water-reducing admixture and superplasticizer were held constant throughout batching at 3 and 2 oz/cwt (1.9 and 1.2 mL/kg), respectively. A set-retarding admixture was added to all truckloads at a dosage of 3 oz/cwt (1.9 mL/kg).

Table 4.15: MN-Control-2 subdeck mixture proportions (SSD/PSD basis)

Material		Mixture proportions (lb/yd^3)	
		Design	**Actual[a]**
Cement (Type I/II)		377	379
Class F fly ash		203	203
Water		245	230
Macrofibers[b]		4	4
Coarse aggregate		1736	1740
Fine aggregate		1243	1244
Chemical Admixture (oz/cwt)			
GRT	**Type**	**Design**	**Actual[a]**
Polyheed SA50	Air-Entraining	As needed	0.4-0.5
KB 1200	Mid-range Water-Reducing	3-12	3
Polychem SPC	Superplasticizer	2-20	2
Polychem Renu	Set-Retarding	3-6	3

[a] Actual values based on average of trip tickets
[b] GRT Advantage Macrosynthetic Fibers
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are provided in Table 4.16. Slumps ranged from 3 to 3½ in. (75 to 95 mm), with an average of 3¼ in. (85 mm); air contents ranged from 5.5 to 7.2%, with an average of 6.3%; concrete temperatures ranged from71 to 73 °F (21.5 to 23 °C), with an average of 72 °F (22 °C), all of which were within the specifications. The 28-day compressive strengths ranged from 4520 to 5580 psi (31.2 to 38.5 MPa), with an average of 5140 psi (35.4 MPa).

Table 4.16: Concrete test results-MN-Control-2 subdeck

MN-Control-2 subdeck	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3	5.5	72	4520
Maximum	3½	7.2	75	5580
Average	3¼	6.3	73	5410

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

MN-Control-2 received a 2-in. (25-mm) wearing course (overlay) on September 28 and September 30, 2017, for the right lane and shoulder and the left lane and shoulder, respectively. The procedures for placing the overlay were similar to that described in Section 4.4.3. The mixture had a *w/c* ratio of 0.32 with a paste content of 31.8%. Two cylinders were made from the right lane and shoulder overlay with 28-day compressive strengths of 8870 and 9480 psi (61.2 and 65.4 MPa); two cylinders were made from the left lane and shoulder overlay with 28-day compressive strengths of 7760 and 8650 psi (53.5 and 59.6 MPa).

4.4.5 MN-IC-LC-HPC-3

MN-IC-LC-HPC-3 is a two-way bridge that carries traffic on T.H. 58 over T.H. 52 in Zumbrota. The subdeck was constructed in one placement on June 29, 2017. Even though MN-IC-LC-HPC-3 was placed a week before MN-IC-LC-HPC-2, the numbering was assigned so that the MN-IC-LC-HPC and corresponding MN-Control decks could be paired sequentially. As with MN-IC-LC-HPC-2, the concrete supplier and the contractor were Ready-Mix Concrete Company L.L.C. and Lunda Construction Co., respectively, and the concrete supplier used the same materials as used for MN-IC-LC-HPC-2. The bridge has two equal span lengths of 106 ft (32.3 m), for a total length of 212 ft (64.6 m). The deck has a 34 ft (10.4 m) wide roadway with a 12 ft (3.7 m) sidewalk and a 1 ft-3 in. (0.4 m) wide barrier on the west side, and a 1 ft-8 in. (0.5 m) wide barrier on the east side, for a total deck width of 48 ft-11 in. (14.9 m). The deck thickness includes a 7-in. (178-mm) subdeck and a 2-in. (51-mm) thick overlay, for a total thickness of 9 in. (229mm).

The sidewalk and the overlay placed on the deck did not incorporate IC; the deck is supported by prestressed concrete girders with no skew.

One of the MN-IC-LC-HPC-2 abutments was used as a trial placement. Although KU researchers were not in attendance during the trial placement, they were informed that concrete properties met the specification limits with no problems observed during pumping.

The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 24.9% and 1.33, respectively, which differed slightly from the values in the original mixture proportions (23.5% and 1.35, respectively). No adjustments were made to the mixture proportions based on the differences in the LWA properties between those obtained by KU and those in the original design. Prior to casting, KU researchers measured a total moisture content of 32% (of the LWA), which was used by the ready-mix plant personnel.

The design and actual (based on the average of trip tickets) mixture proportions of the subdeck are provided in Table 4.17. MN-IC-LC-HPC-3, which had the same mixture proportions as used for MN-IC-LC-HPC-2, had a design *w/cm* ratio of 0.45 and a 27.3% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 26%. The design quantity of internal curing water was 8% (by the weight of binder). Based on the trip tickets, either 25 or 33 lb/yd^3 (15 or 20 kg/m^3) of water was withheld during batching, resulting in a *w/cm* ratio as low as 0.40. A portion of the withheld water, ranging from 4 to 17 lb/yd^3 [2.3 to 10 kg/m^3], was added back at the jobsite, increasing the *w/cm* ratio to an average of 0.42. Based on the trip tickets, individual paste contents ranged from 24.5 to 25.6%, with an average of 25.2% and the actual quantities of IC water ranged from 8.2 to 9%, with an average of 8.7% by total weight of binder. The air-entraining admixture dosage varied between 0.8 and 0.9 oz/cwt (0.5 and 0.6 mL/kg) throughout batching. The dosages of the mid-range water-reducing and viscosity modifying admixtures were held constant throughout batching at 3 and 2 oz/cwt (2 and 1.3 mL/kg), respectively. A set-retarding admixture was added to truckloads at a varied dosage between 0 and 3 oz/cwt (0 and 2 mL/kg).

Table 4.17: MN-IC-LC-HPC-3 subdeck mixture proportions (SSD/PSD basis)

Material		Mixture proportions (lb/yd^3)	
		Design	Actual[a]
Cement (Type I/II)		410	414
Grade 100 slag cement		154	154
Water		254	240
Fine lightweight aggregate		238	247
Coarse aggregate		1411	1415
Fine aggregate		1141	1144
Chemical Admixture (oz/cwt)			
GRT	**Type**	**Design**	**Actual[a]**
Polyheed SA50	Air-Entraining	As needed	0.8-0.9
KB 1200	Mid-range Water Reducing	3-12	3
Polychem VMA	Viscosity Modifying	2-5	2
Polychem Renu	Set Retarding	3-6	0-3[b]

[a] Actual values based on average of trip tickets
[b] Set retarder dosage stepped down from 3 to 0 oz/cwt throughout the placement
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.18. Slump ranged from 2½ to 4 in. (65 to 100 mm), with an average of 3½ in. (90 mm); air contents ranged from 8 to 9.1%, with an average of 8.2%; concrete temperatures ranged from 73 to 77 °F (23 or 25 °C), with an average of 75 °F (24 °C), all of which were within the specifications. The 28-day compressive strengths ranged from 4160 to 6250 psi (28.7 to 43.1 MPa), with an average of 5140 psi (35.4 MPa).

Table 4.18: Concrete test results-MN-IC-LC-HPC-3 subdeck

MN-IC-LC-HPC-3 subdeck	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	2½	8	73	4160
Maximum	4	9.1	77	6250
Average	3½	8.2	75	5140

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

MN-IC-LC-HPC-3 was located approximately 25 minutes away from the ready-mix plant. Construction of the subdeck started on June 29, 2017 at 9:00 am, at the north end of the deck, continued to the south end, and was completed at 12:30 pm. The concrete was placed using two pumps positioned at opposite ends of the deck, consolidated using a single spud vibrator, and finished using two vibrating screeds (one 17 ft [5.2 m] motor long and the other 24 ft [7.3 mm] long), each with a carpet drag. There was a gap of about 2 ft (0.6 m) between the two screeds, as well as gaps of about 1 ft (0.3 m) between the end of the screeds and the barrier reinforcement. Concrete in these gaps was consolidated by the spud vibrator and finished with a bullfloat. At multiple locations, it was observed that contractor personnel walked in the consolidated concrete through the 2 ft (0.6 m) wide gap between the screeds, disturbing the concrete. These locations were later finished using trowels, as shown in Figure 4.4, resulting in insufficient consolidation.

Figure 4.4: Walking through freshly consolidated concrete

During the construction, environmental conditions were recorded, with wind speed ranging from 1 to 5 mph (1.6 to 8 km/hr), relative humidity ranging from 59 to 71%, and ambient air temperature ranging from 69 to 79 °F (23 to 29 °C), resulting in low evaporation rates, ranging from 0.03 to 0.06 lb/ft^2/hr (0.15 to 0.29 kg/m^2/hr), well below 0.2 lb/ft^2/hr (1 kg/m^2/hr), the maximum specification limit. No significant issues arose during concrete pumping, placement, or finishing. The time between batching and discharge ranged from 15 to 65 minutes, with an average of 25 minutes. The deck was finished efficiently with an average time of 5 minutes after placement.

One work bridge was used to place wet burlap on the deck. A layer of burlap was placed in an average time of 16 minutes after strikeoff. Similar to MN-IC-LC-HPC-2, on some occasions, it was observed that water dripped onto the deck from rolls of burlap stacked on the work bridge, leaving puddles of water on the east side of the deck, as shown in Figure 4.5.

(a) (b)

Figure 4.5: Water from burlap dripping onto the deck (a) an overview; (b) a close-up view

MN-IC-LC-HPC-3 received a 2-in. (25-mm) wearing course (overlay) on September 7 and September 9, 2017. KU researchers were not in attendance during overlay placements. The procedures for placing the overlay were similar to that described in Section 4.4.3. The overlay mixture had a *w/c* ratio of 0.32 with a paste content of 31.8%. The two cylinders made from the September 7, 2017 placement had 28-day compressive strengths of 9030 and 9270 psi (62.3 and 63.9 MPa); the three cylinders made from September 9, 2017 placement had 28-day compressive strengths of 8860, 9000, and 9050 psi (61.1, 62.1, and 62.4 MPa).

4.4.6 MN-IC-LC-HPC-4

MN-IC-LC-HPC-4 is a two-way bridge that carries traffic on 38th St. over I-35W in Minneapolis. The deck was constructed in one placement on May 15, 2018. The concrete supplier and the contractor were Aggregate Industries U.S. and Lunda Construction Co., respectively. The bridge has four spans with lengths of 28 ft-10 in. (8.8 m), 77 ft-8 in. (23.8 m), 77 ft-8 in. (23.7 m), and 24 ft-10 in. (7.6 m), for a total length of 209 ft (63.7 m). The deck has a 36 ft (10.9 m) wide roadway, a 1 ft-7 in. (0.4) wide barrier and a 10 ft (3.0 m) sidewalk on each side, for a total deck width of 56 ft (17.1 m). The 6-in. (150 mm) thick sidewalk placed on the deck at a later date did not incorporate IC. The nominal deck thickness is 9 in. (229 mm). The bridge deck is supported by prestressed concrete girders with no skew.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-4 was an expanded clay stored in a garage at the ready-mix plant. The LWA was pre-wetted using a lawn sprinkler on top of the aggregate stockpile. The stockpile was approximately 10 ft (3 m) high, greater than the recommended 5-ft (1.5-m) limit.

MN-IC-LC-HPC-4 had two trial placements. The first trial placement, attempted on May 3, 2018, was a failure. The initial mixture had a binary binder composition, a 28% replacement by weight of portland cement with slag cement. The design paste content and the *w/cm* ratio were 25.5% (by concrete volume) and 0.43, respectively. The design quantity of internal curing water was 8% (by the weight of binder), the lightweight aggregate design absorption was 23.6% (OD basis), and the slump was 4 in. (100 mm). KU researchers were not in attendance for the first trial placement. The concrete produced at the ready-mix plant could not be pumped, also most likely presenting issues for placement and finishing of the deck. The contractor and pump operator believed a higher slump range was required to ensure the pumpability of the concrete. The specifications permitted slumps between 1½ and 4 in. (40 to 100 mm). The problem was, in fact, the incorrect measurement of free-surface moisture of the LWA. Lightweight aggregate is highly porous, with relatively large pores compared to normalweight aggregates. The absorption of LWA is highly dependent on the pre-wetting method and duration. Although the LWA stockpile was pre-wetted for more than two weeks, no absorption or specific gravity tests were performed at the ready-mix plant. Without measuring the actual absorption of the LWA, the concrete supplier simply subtracted the design absorption value from the total moisture content of a LWA sample, determined the free-surface moisture of the LWA, and batched the concrete, which is not correct.

A second trial placement was performed successfully on May 8, 2018 with KU researchers in attendance. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption before batching. The average absorption (OD basis) of the LWA obtained by KU researchers was 30.3%, which differed significantly from the value indicated in the original mixture proportions (23.6%). With the way that moisture corrections are made, a higher absorption results in a lower calculated value for the free-surface moisture, increasing the risk of holding excess water, and thus increasing pumping issues. With a true 30.3% absorption instead of 23.6%, the incorrect modifications in the batch weights would have decreased the mixture water, the *w/cm*, and the paste content by 16 lb/yd^3 (9.5 kg/m^3), 0.03, and 0.95%, respectively.

The major changes in the mixture proportions for the second trial placement included using the correct LWA properties, increasing the paste content from 25.5 to 26%, and increasing the VMA dosage from 3 to 5 oz/cwt (1.9 to 3.3 mL/kg), which allowed the concrete to pump efficiently. Additionally, MnDOT allowed a maximum slump of 5½ in. (140 mm) to relieve the contractor's concerns and further aid pumping. Studies published after the original specification were developed have demonstrated that for paste contents similar to MN-IC-LC-HPC decks, slump as high as 5¾ (145 mm) does not adversely affect bridge deck cracking (Lafikes et al. 2016 and 2020). The concrete was tested after a simulated haul time of 15 minutes. The concrete slumps (with an average of 4¼ in. [105 mm]) and air contents (with an average of 8.9%) after pumping were within the specifications. Approvals were made for the revised mixture proportions following the successful trial placements.

Another shipment of LWA was delivered to the ready-mix plant the next day to ensure a sufficient supply of LWA for the construction. KU researchers found similar absorption values in the new composite samples, and confirmed the revised mixture proportions. The sprinkler was turned off on the morning of deck placement, letting the material drain for approximately 14 hours prior to batching.

The initial, revised, and actual (based on the average of trip tickets) mixture proportions are listed in Table 4.19. The initial mixture proportions correspond to the first trial batch mix, and the revised mixture proportions correspond to the second trial and deck placements. MN-IC-LC-HPC-4 had a design *w/cm* ratio of 0.43 and a 28% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 26%. The design quantity of internal curing water was 8% (by the weight of binder). Prior to casting, KU researchers measured a total moisture content of 37.4% (of the LWA), which was used by the ready-mix plant personnel. Based on the trip tickets, approximately 5 lb/yd^3 (5 kg/m^3) of water was held from most of the truckloads during the construction, reducing the actual *w/cm* ratio to an average of 0.42. Crushed gravel and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, paste contents ranged from 25.5 to 26%, with an average of 25.7% and the actual quantity of IC water ranged from 7.9 to 8.6%, with an average of 8% by total weight of binder. The air-entraining admixture dosage varied between 0.28 and 0.33 oz/cwt (0.18 and 0.22 mL/kg) throughout batching. The dosage of the high-range water-reducing admixture varied between 1.75 and 2.75 oz/cwt (1.1 and 1.8 mL/kg) throughout batching; the dosage of viscosity modifying admixture was held constant throughout batching at 5 oz/cwt (3.3 mL/kg).

Table 4.19: MN-IC-LC-HPC-4 mixture proportions (SSD/PSD basis)

Material	Mixture proportions (lb/yd^3)		
	Initial	Revised	Actual[a]
Cement (Type I/II)	410	418	416
Grade 100 slag cement	160	164	165
Water	245	250	245
Fine lightweight aggregate	239	201	201
Coarse aggregate	1731	1701	1708
Fine aggregate	908	970	973
Chemical Admixture (oz/cwt)			
Sika	**Type**	**Initial**	**Actual[a]**
Air-260	Air-Entraining	0.21	0.28-0.33
Viscocrete-1000	High-Range Water-Reducing	2.5	1.75-2.75
Stabilizer-4R	Viscosity Modifying	3	5

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are provided in Table 4.20. During construction, slumps ranged from 3½ to 6 in. (90 to 150 mm), with an average of 4¾ in. (120 mm); air contents ranged from 7.4 to 11.2%, with an average of 8.9%. The slumps and air contents in the first three tests had an average value of 5¾ in. (145 mm) and 10.3%, respectively, exceeding the specification limits. Although none of the trucks were rejected, the supplier was urged to reduce the dosage of high-range water-reducing admixture as well as the water content in subsequent batches. Concrete temperatures ranged from 58 to 70 °F (14 to 21 °C), with an average of 64 °F

(18 °C) and 28-day compressive strengths ranged from 4750 to 6820 psi (32.8 to 42.4 MPa), with an average of 5540 psi (38.2 MPa).

Table 4.20: Average concrete test results-MN-IC-LC-HPC-4

MN-IC-LC-HPC-4	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3½	7.4	58	4750
Maximum	6	11.2	70	6820
Average	4¾	8.9	64	5540

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

MN-IC-LC-HPC-4 was located approximately 15 minutes away from the ready-mix plant. Placement started on May 15, 2018 at 9:50 pm, at the east end of the deck, continued to the west end, and completed on May 16, 2018 by 6:00 am. The concrete was placed using two pumps positioned at opposite ends of the deck and consolidated using a single spud vibrator as the only method used throughout the deck. The concrete was finished using a double-drum roller screed, followed by metal pans and burlap drags. The concrete was placed in strips about 10 ft (3 m) along the length of the deck. During construction, environmental conditions were recorded, with wind speed ranging from 0 to 1 mph (0 to 1.6 km/hr), relative humidity ranging from 37 to 58%, and ambient air temperature ranging from 52 to 63 °F (11 to 17 °C), resulting in low evaporation rates, ranging from 0.02 to 0.03 lb/ft^2/hr (0.08 to 0.15 kg/m^2/hr), well below 0.2 lb/ft^2/hr (1 kg/m^2/hr), the maximum specification limit. The time between batching and discharge ranged from 15 to 39 minutes, with an average of 24 minutes. A 48-minute delay occurred during the construction due to the breakdown of the finishing machine. The time between placement and strikeoff ranged from 10 to 48 minutes, with an average of 18 minutes.

The concrete appeared easily pumpable throughout construction and was able to flow in a continuous stream. Occasionally, however, construction personnel were observed stepping on areas that had been recently vibrated, causing disturbance to the concrete, as shown in Figure 4.6.

These sections were later covered by the strike-off augers and subsequent paving roller instead of reconsolidation. As discussed in Section 5.3.1.6, some short longitudinal and transverse cracks (crack lengths below 1 ft [305 mm]) were observed in these regions at an age of 48.7 months. The sidewalks received no finishing after being briefly consolidated by the spud vibrator and then covered with wet burlap.

Figure 4.6: Disturbance of concrete observed near the north end

A single work bridge was used for bullfloating, tining, and spraying curing compound on the deck, resulting in long delays between strikeoff and application of curing compound. As discussed in Section 5.3.1.6, some surface damage was observed due to poor tining of the deck. The time between strikeoff and application of curing compound ranged from 52 to 79 minutes. The sidewalks received only wet curing (wet burlap) within an hour after placement. KU researchers were informed that the roadway would be covered by wet burlap at dawn.

4.4.7 MN-IC-LC-HPC-5

MN-IC-LC-HPC-5 is a pedestrian bridge deck located at 40th St. over I-35W in Minneapolis. The deck was constructed in one placement on July 23, 2019. The concrete supplier and the contractor were Aggregate Industries U.S. and Lunda Construction Co., respectively. The bridge has two equal span lengths of 95 ft-9 in. (29.2 m), for a total length of 191 ft-6 in. (58.4 m). The deck has a 14 ft (4.3 m) wide walkway, a 1 ft-5 in. (0.43 m) wide barrier on each side, for a total deck width of 16 ft-10 in. (5.1 m). The nominal deck thickness is 7 in. (178 mm); the deck is supported by prestressed concrete girders and has no skew.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-5 was an expanded clay stored in a garage at the ready-mix plant. The LWA was pre-wetted using a whirling sprinkler on top of the aggregate stockpile, as shown in Figure 4.7. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit. The whirling sprinkler was turned off on the morning of deck placement, letting the material drain approximately 11 hours prior to batching. At KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching. When sampling the materials from the stockpile, KU researchers noticed some clumps of LWA, as shown in Figure 4.8. These clumps were removed from the samples before testing.

The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 27.6% and 1.30, respectively, which differed from the values indicated in the original mixture proportions (30.2% and 1.27, respectively). Having a lower absorption than indicated can result in a lower than the intended quantity of internal curing water. KU researchers revised the mixture proportions to get 8% of internal curing water by the weight of binder.

Figure 4.7: Lightweight aggregate stockpile for MN-IC-LC-HPC-5

Figure 4.8: A dense clump of LWA observed in the stockpile for MN-IC-LC-HPC-5

Two trial batches were produced on July 23, 2019 based on the revised mixture proportions. Considering that the elapsed time for testing the concrete after batching was approximately 10 minutes and that the construction site was just 10 to 15 minutes away from the ready-mix plant, no haul time was considered. For the first trial batch, slump and air content were 3½ in. (90 mm) and 6%, respectively, with a concrete temperature of 76 ˚F (24 °C). The concrete supplier decided to increase the dosage of air-entraining admixture (from 0.5 oz/cwt to 0.75 oz/cwt) since the air content was lower than the minimum specified value by MnDOT IC-LC-HPC specifications (6.5%). Additionally, the concrete supplier decided to increase the dosage of the water-reducer admixture (from 1.25 oz/cwt to 1.75 oz/cwt) to slightly increase the slump. As a result, the second trial batch was made with the slump (5 in. [125 mm]), air content (8.2%), and concrete temperature (74 ˚F [23 °C]) within the specifications. A trial placement was not required due to successful construction of the MN-IC-LC-HPC-4, which had the same initial mixture proportions, concrete supplier, and contractor.

The initial, revised, and actual (based on the average of trip tickets) mixture designs submitted to MnDOT are listed in Table 4.21. MN-IC-LC-HPC-5 had identical mixture proportions as MN-IC-LC-HPC-4, with a design *w/cm* ratio of 0.43 and a 28% replacement of cement (by total weight of binder) with Grade 100 slag cement, and a design paste content of 26%. The design quantity of internal curing water was 8% (by the weight of binder). Based on the trip tickets, 8 lb/yd^3 (5 kg/m^3) of water was held from all the trucks, reducing the actual *w/cm* ratio to an average of 0.41. Prior to batching, KU researchers measured a total moisture content of 37.6% (of the LWA), while a total moisture content of 35.3% was determined and used by the ready-mix plant personnel. This deviation increased the mixing water and the *w/cm* by 3.9 lb/yd^3 (2 kg/m^3) and 0.007, respectively. Crushed gravel and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, individual paste contents ranged from 25.2 to 25.5%, with an average of 25.3% and the actual quantities of IC water ranged from 7.9 to 8%, with an average of 8% by total weight of binder. The dosages of high-range water-reducing and viscosity modifying admixtures were held constant throughout batching at 1.75 and 5 oz/cwt (1.1 and 3.3 mL/kg), respectively. A set-retarding admixture was added to some trucks per MnDOT Standard Specifications for Construction (2018), Section F.3.b(1). The specification requires that the contractor *"place concrete at a rate that concrete will remain plastic for at least one-half a span length back of an intermediate support until the placement has proceeded to a point one-half of the span length ahead of that support."* The set-retarding admixture was used to delay concrete setting to meet the requirement. As discussed later, during construction, the concrete setting was significantly delayed, resulting in delayed brooming and curing of the concrete.

Table 4.21: MN-IC-LC-HPC-5 mixture proportions (SSD/PSD basis)

Material	**Mixture proportions (lb/yd^3)**		
	Initial	**Revised**	**Actual[a]**
Cement (Type I/II)	418	418	416
Grade 100 slag cement	164	164	165
Water	250	250	240
Fine lightweight aggregate	201	216	215
Coarse aggregate	1701	1701	1697
Fine aggregate	970	948	949
Chemical Admixture (oz/cwt)			
Sika	**Type**	**Initial**	**Actual[a]**
Air-260	Air-Entraining	0.1-3	0.6-0.75
Viscocrete-1000	High-Range Water-Reducing	0.1-3	1.75
Sikatard-440	Set-Retarding	0.1-8	0-1[b]
Stabilizer-4R	Viscosity Modifying	0.1-7	5

[a] Actual values based on average of trip tickets
[b] Set retarder dosage stepped down from 1 to 0 oz/cwt throughout the placement
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.22. Slumps ranged from 4 to 5½ in. (115 to 140 mm), with an average of 3¾ in. (95 mm), within the MnDOT specifications (2½ to 5½ in.). Two initial tests for air content were below 6.5%, the lower limit of the specifications. Therefore, a second test was performed for each, which showed air contents higher than 6.5%. Air contents ranged from 6.6 to 8.4%, with an average of 7.3%, within the specifications (6.5 to 10%). Concrete temperatures ranged from 75 to 80 °F (24 to 27 °C), with an average of 77 °F (25 °C), and 28-day compressive strengths ranged from 4750 to 6150 psi (32.8 to 42.4 MPa).

Table 4.22: Concrete test results-MN-IC-LC-HPC-5

MN-IC-LC-HPC-5	**Slump (in.)**	**Air content (%)**	**Concrete temperature (°F)**	**28-day compressive strength (psi)**
Minimum	4	6.6	75	4750
Maximum	5½	8.4	80	6150
Average	3¾	7.3	77	5320

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The MN-IC-LC-HPC-5 was located approximately 10 minutes away from the ready-mix plant. Placement started on July 23, 2019 at 11:30 pm, at the west end of the deck, continued to the east end, and with the final strikeoff being finished in the early morning of July 24, 2019 at 2:05 am. The concrete was placed using a pump, consolidated using a single spud vibrator, and finished using a vibrating screed, as shown in Figure 4.9. The concrete was placed in strips about 5 ft along the length of the deck. During placement, wind speeds at the deck ranged from 0 to 0.1 mph (0 to 0.2 km/hr). Relative humidity at the deck ranged between 54 and 80%. Ambient air temperature during construction ranged from 66 to 82 °F (19 to 28 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.02 to 0.03 lb/ft^2/hr (0.09 to 0.15 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit. The time between batching and discharge ranged from 17 to 40 minutes, with an average of 30 minutes. The time between placement and strikeoff ranged from 4 to 22 minutes, with an average of 8 minutes.

Figure 4.9: Placement, consolidation, and finishing of MN-IC-LC-HPC-5

Similar to consolidation observed during placements of other MN-IC-LC-HPC decks in Minnesota, the vibrator was inserted at regularly spaced intervals. Occasionally, however, construction personnel were observed stepping on areas that had been recently vibrated as well as rapidly pulling out the vibrator from the concrete, leaving holes on the concrete surface, as shown in Figure 4.10. These actions have been observed to leave the concrete susceptible to settlement cracking (McLeod et al. 2009, Khajehdehi and Darwin 2018). While KU personnel informed the MnDOT representative and construction personnel about this issue, the construction personnel opposed the argument. They believed that the vibrating screed would solve this problem. Crack survey results shown in Chapter 5 identified a number of transverse cracks along the entire deck, cracks that, as demonstrated in Chapter 5, do not appear on the other two pedestrian bridges in this study, MN-IC-LC-HPC-1 and MN-Control-1.

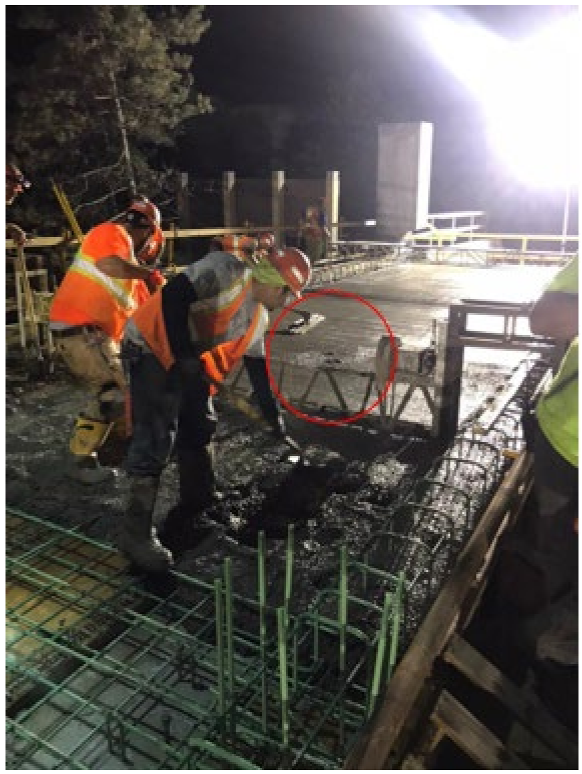


Figure 4.10: Holes in the concrete surface duo to rapid removal of the spud vibrator

Significant bleed water was observed on the deck, as indicated by the reflective water sheen in Figure 4.11, which delayed brooming and curing. While waiting for bleed water to evaporate, construction workers bullfloated the deck repeatedly in an attempt to accelerate evaporation of the bleed water, leading to a thin paste layer with a high *w/cm* at the concrete surface. As discussed in Chapter 5, surface damage in the form of scaling is observed, which is likely the result of the overfinishing.

Figure 4.11: Presence of bleed water on the surface

A transverse broom finish was applied in accordance with the MnDOT MN-IC-LC-HPC specifications for pedestrian decks. The contractor tried brooming the west end of the deck, which had the thin paste layer. The operation resulted in disturbance of the surface, as shown in Figure 4.12. Brooming concrete deck when bleeding water is on the surface can lead to dusting and scaling damage. Brooming started around 2:15 am, after concrete placement was complete for the entire deck, and proceeded slowly due to the presence of bleed water.

Shortly after brooming, a single layer of curing compound was sprayed on the bridge deck. The application of the curing compound began at 3:00 am at the west end of the deck and finished at the east end of the deck at 3:55. The time between strikeoff and application of the curing compound ranged from 70 to 155 minutes. Figure 4.13 shows the completed deck prior to the application of wet curing using wet burlap, as described below.

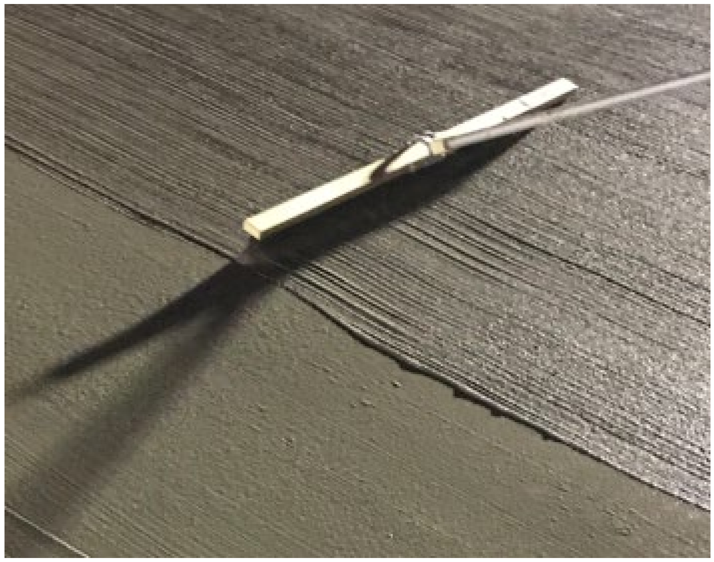


Figure 4.12: Brooming of the deck with the presence of excess water at the surface

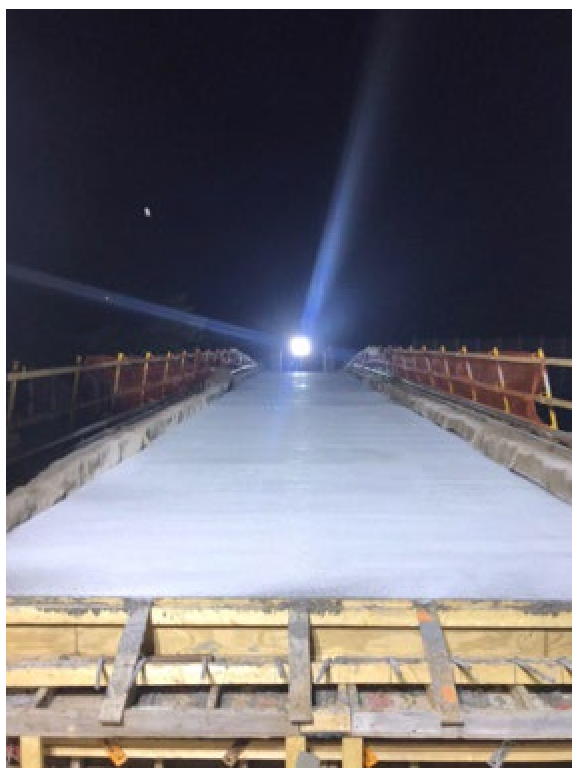


Figure 4.13: The application of the curing compound on the bridge deck

Concrete adjacent to the barrier reinforcement on each side of the bridge did not receive any curing compound or finishing. Wet burlap, instead, was placed on these sections during construction within an hour of being consolidated, as shown in Figure 4.14.

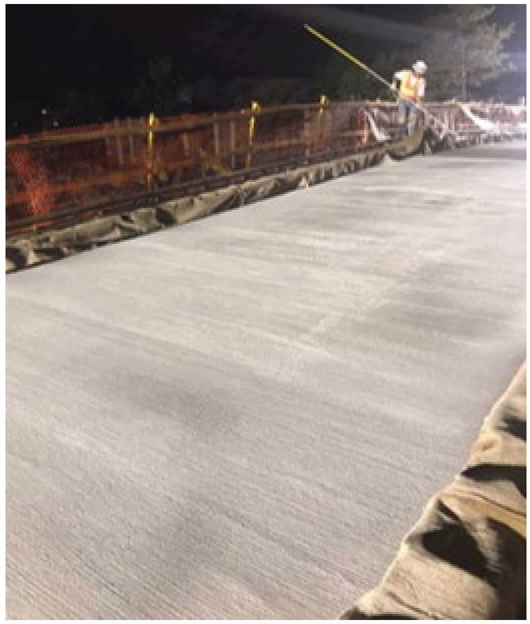


Figure 4.14: Burlap placement on the barrier reinforcement

KU researchers were informed that the bridge deck would be covered by wet burlap when the concrete could be walked on without producing imprints deeper than $^{1}/_{16}$ in (1.6 mm). The burlap rolls were soaked in water for a minimum of 12 hours prior to the application, and then they were transferred to the work bridge for placing. According to the construction personnel, the application of wet burlap to the bridge began on the morning of July 24, 2019 at 6:00 am and completed within an hour.

4.4.8 MN-IC-LC-HPC-6

MN-IC-LC-HPC-6 is a two-lane bridge that carries traffic on C.S.A.H. 7 over I-35W near Pine City. The deck was constructed in one placement on September 19, 2019. The concrete supplier and the contractor were Cemstone Products Co. and Ames Construction, respectively. The bridge has two equal span lengths of 94 ft (28.7 m), for a total length of 188 ft (57.4 m). The deck has a 49 ft (14.9 m) wide roadway with a 7 ft-10 in. (1.2 m) sidewalk on the north side, a 1 ft-5 in. (0.43 m) wide barrier on the north side, and a 1 ft-6 in. (0.46 m) wide barrier on the south side, for a total deck width of 59 ft-9 in. (18.2 m). The 6-in. (150 mm) thick sidewalk placed on the deck at a later date did not incorporate IC. The nominal deck thickness is 9 in. (229 mm); the deck is supported by prestressed concrete girders and has a skew of 16º 2’ 30”.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-6 was an expanded clay stored in an open area at the ready-mix plant. The LWA was pre-wetted using a whirling sprinkler on top of the aggregate stockpile (Figure 4.15). The stockpile was approximately 8 ft (2.4 m) high, greater than the recommended 5-ft (1.5-m) limit. The whirling sprinkler was turned off due to overnight rain a day before the deck placement. Upon KU researchers’ request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 32.9% and 1.21, respectively, which differed from the values indicated in the original mixture proportions (27.2% and 1.23, respectively). Having a higher absorption than indicated has the potential of holding excess water with the way moisture corrections are made and can lead to pumping issues and a lower than intended quantity of internal curing water. KU researchers revised the mixture proportions to get 7% of internal curing water by the weight of binder.

Figure 4.15: Lightweight aggregate stockpile for MN-IC-LC-HPC-6

KU researchers were not in attendance during a trial placement, an abutment used for the deck, on August 15, 2019. According to MnDOT representatives, the pour went well, with concrete properties within the specifications. On the day of batching, the concrete supplier decided to test the concrete for slump, air content, and temperature at the ready-mix plant before sending the first truck to the job site. For this batch, slump and air content were 4 in. (100 mm) and 7.6%, respectively, with a concrete temperature of 72 ˚F (22 °C), all within the specifications.

The initial, revised, and actual (based on the average of trip tickets) mixture designs submitted to MnDOT are listed in Table 4.23. MN-IC-LC-HPC-6 had a design *w/cm* ratio of 0.43 and a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 26%. The design quantity of internal curing water was 7% (by the weight of binder). Crushed granite and river sand were used as coarse and fine aggregates, respectively.

Although the mixture proportions were revised based on the findings of KU researchers on the LWA absorption and specific gravity, the concrete supplier mistakenly did not consider the absorbed water content of all aggregates prior to batching the materials. This resulted in a reduction in wet materials to be batched, lowering the cement paste, *w/cm* ratio, and quantity of IC water. The concrete in the first ten trucks was stiff, and the contractor had difficulty pumping it, a problem tied to both the incorrect batch weights and withholding a portion of mixing water. Although according to MnDOT specifications, after batching, no water is allowed to be added at the job site, 2.5 to 4.2 lb/yd^3 [1.4 to 2.5 kg/m^3] of water, respectively, was added to the first and the second trucks at the job site. Additionally, the concrete supplier added either 5 or 8 lb/yd^3 [3 or 5 kg/m^3] of water to three truckloads at the ready-mix plant. Based on the trip tickets, between 8 to 17 lb/yd^3 (5 to 10 kg/m^3) of water was withheld from the trucks (17 lb/yd^3 [10 kg/m^3] from the first eight trucks and 38th truck, 13 lb/yd^3 [7 kg/m^3] from 9th and 10th trucks, and 8 lb/yd^3 [5 kg/m^3] from the rest of them), reducing the actual *w/cm* ratio to an average of 0.40.

Based on the trip tickets, individual paste contents ranged from 24.5 to 25.2%, with an average of 25.0% and the actual quantities of IC water ranged from 4.9 to 5.6%, with an average of 5.2% by total weight of binder. A mid-range water-reducing admixture (MRWRA) with a dosage of either 3 or 4 oz/cwt (2 or 2.6 mL/kg) was added to the concrete. A set-retarding admixture was also added to some trucks. The dosage of a viscosity modifying admixture was held constant throughout batching at 4 oz/cwt (2.6 mL/kg). KU researchers observed no excessive bleed water on the surface of the deck.

Table 4.23: MN-IC-LC-HPC-6 mixture proportions (SSD/PSD basis)

Material	Mixture proportions (lb/yd^3)		
	Initial	Revised	Actual[a]
Cement (Type I/II)	406	406	406
Grade 100 slag cement	174	174	174
Water	248	248	232
Fine lightweight aggregate	192	164	122
Coarse aggregate	1641	1641	1631
Fine aggregate	1096	1092	1084
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual[a]**
Air AE 90	Air-Entraining	0.1-10	3-8
Polyheed 1020	Water-Reducing	1-12	3-4
Set Delvo	Set-Retarding	0-5	0-1[b]
Matrix VMA 358	Viscosity Modifying	0-6	4

[a] Actual values based on average of trip tickets
[b] Set retarder dosage stepped down from 1 to 0 oz/cwt throughout the placement
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.24. Four tests for slump, air content, and temperature were performed. Slumps ranged from 3 to 3¾ in. (75 to 95 mm), with an average of 3½ in. (90 mm), within the specifications (1½ to 5 in.). For the first truck at the job site, an initial test for air content was 6%, below the lower limit of the specifications. The dosage of the air-entraining admixture was then adjusted to increase the air content slightly. A second test was performed on this load, which showed an air content of 7.6%. Air contents ranged from 6.8 to 9.2%, with an average of 7.9%, within the specifications (6.5 to 10%). Concrete temperatures ranged from 65 to 78 °F (18 to 26 °C), with an average of 71 °F (22 °C), and 28-day compressive strengths ranged from 5310 to 7680 psi (36.6 to 52.9 MPa).

Table 4.24: Concrete test results-MN-IC-LC-HPC-6

MN-IC-LC-HPC-6	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3	6.8	65	5310
Maximum	3¾	9.2	78	7680
Average	3½	7.9	71	6490

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The MN-IC-LC-HPC-6 was located approximately 5 minutes away from the ready-mix plant. Placement started on September 19, 2019 at 6:25 am, at the west end of the deck, continued to the east end, and with the final strikeoff being finished the same morning at 11:57 am. The concrete was placed using two pumps positioned at opposite ends of the deck (one with a smaller diameter used on one-third of the deck), and consolidated using a single spud vibrator. The roadway was finished using a double-drum roller screed followed by two metal pans and a burlap drag, and cured with a layer of curing compound. The sidewalk concrete, however, was only consolidated, with no finishing or application of curing compound. Both the roadway and sidewalk received wet curing. Figure 4.16 shows the placing, consolidation, and finishing equipment of the MN-IC-LC-HPC-6 construction.

Figure 4.16: Placing, consolidation, and finishing equipment

No significant issues arose during concrete pumping, placement, or finishing. The concrete was placed in strips about 5 ft (1.5 m) along the length of the deck. Similar to consolidation observed during placements of other MN-IC-LC-HPC decks in Minnesota, the vibrator was inserted at regularly spaced intervals. Occasionally, however, construction personnel were observed stepping in concrete that had been previously vibrated, shoveling concrete, causing deconsolidation and disturbance of the concrete, as shown in Figure 4.17; crack surveys at an age of 32.2 months, discussed in Section 5.3.1.8, however, did not identify any cracks in these regions.

Figure 4.17: Walking through consolidated concrete

A highway straightedge was used in place of a bullfloat. The deck was tined about 10 minutes after bullfloating, before the application of the curing compound, as shown in Figure 4.18. As discussed in Section 5.3.1.6, the deck was heavily tined, disrupting the aggregates near the upper surface. Shortly after tining, a single layer of curing compound was sprayed on the roadway, as shown in Figure 4.19. The application of the curing compound began at the west end and continued to the east end of the deck.

(a) (b)

Figure 4.18: Tining of the deck (a) an overview; (b) a close-up view

Figure 4.19: The application of the curing compound on the roadway of the deck

During placement, wind speeds at the deck ranged from 0 to 0.8 mph (0 to 1.3 km/hr). Relative humidity at the deck ranged between 68.2 and 78.9%. Ambient air temperature during construction ranged from 68 to 75 °F (20 to 24 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.01 to 0.02 lb/ft^2/hr (0.05 to 0.09 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit. The time between batching and discharge ranged from 10 and 50 minutes, with an average of 26 minutes. The time between placement and strikeoff for the roadway ranged from 2 to 31 minutes, with an average of 7 minutes. Two work bridges were used for bullfloating, tining, and applying the curing compound. The time between strikeoff and bullfloating ranged from 14 minutes to 35 minutes, with an average of 22 minutes. The average time between bullfloating and tining ranged from 25 to 50 minutes, with an average of 39 minutes. The time between tining and curing compound application ranged from 5 to 48 minutes, with an average of 15 minutes.

4.4.9 MN-IC-LC-HPC-7

MN-IC-LC-HPC-7 is a two-way bridge that carries traffic on Dale St. over I-35 in St. Paul. The deck was constructed in two placements; each placement one-half of the total deck width, dividing the deck into east and west sides from the centerline of the roadway. The first placement (MN-IC-LC-HPC-7-P1) was constructed on June 24, 2020, starting from the north end of the deck. Placement 1 was completed by placing approximately 390 yd^3 (298.2 m^3) of concrete on the deck. The remaining portion of the deck (MN-IC-LC-HPC-7-P2) was completed on September 22, 2020. The concrete supplier and the contractor for both placements were Cemstone Products Co. and Redstone Construction, respectively. The bridge has two equal span lengths of 89 ft-11½ in. (27.4 m), for a total length of 179 ft-11 in. (54.8 m). The deck has a 76 ft (23.2 m) wide roadway, and a 16 ft (4.9 m) sidewalk on each side, for a total deck width of 113 ft-4 in. (34.5 m). The nominal deck thickness is 9 in. (229 mm). The bridge deck is supported by prestressed concrete girders with a skew of 2º 24’38”.

The fine lightweight aggregate (LWA) used for both placements was an expanded clay stored in an open area at the ready-mix plant. The LWA was pre-wetted using an oscillating sprinkler near the aggregate stockpile on the ground. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit, as shown in Figure 4.20.

Figure 4.20: MN-IC-LC-HPC-7 lightweight aggregate stockpile

KU personnel were not in attendance during the trial batches for this project on June 18, 2020. According to the concrete supplier, two truckloads (with 7 yd^3 [5.4 m^3] of concrete each) were produced; the concrete properties were within the specifications, with air contents of 9.5 and 9.1%, slumps between 3 and 4 in. (75 and 100 mm), and concrete temperatures of 78 and 80 °F (26 and 27 °C).

The concrete supplier for the deck proposed the same mixture proportions as the one used for MN-IC-LC-HPC-6 in Pine City in 2019. KU researchers traveled to St. Paul and worked with the concrete supplier to determine the LWA properties and provide adjustments in the mixture proportions to maintain the desired quantity of internal curing water before batching the concrete. The mixture had a binary binder composition, a 30% replacement by weight of portland cement with slag cement. The design paste content and the water-cementitious material (*w/cm*) ratio were 25.9% (by concrete volume) and 0.43, respectively. The design quantity of IC water was 7% (by the weight of binder). The design LWA absorption and specific gravity values were 32.9% and 1.21 (OD basis), respectively.

4.4.9.1 MN-IC-LC-HPC-7-P1

Placement 1 of the MN-IC-LC-HPC-7 was constructed on June 24, 2020. The LWA stockpile was pre-wetted for at least three days before batching. The sprinkler was turned off on the morning of June 24, 2020, letting the material drain for approximately 15 hours prior to batching. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free-surface moisture prior to batching. The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 34% and 1.20, respectively, which differed slightly from the values indicated originally in the mixture proportions. KU researchers revised the mixture proportions to get 7% of IC water by the weight of binder. The initial and actual (based on the average of trip tickets) mixture proportions for the first placement of MN-IC-LC-HPC-7 are listed in Table 4.25. Crushed granite and river sand were used as coarse and fine aggregates, respectively, in both placements.

Based on the trip tickets, between 8 and 21 lb/yd^3 (5 and 12 kg/m^3) of water was withheld during batching, reducing the actual *w/cm* ratio to an average of 0.41. Additionally, prior to casting, KU personnel measured a free-surface moisture of 9.2%, while a free-surface moisture of either 8 or 11.5% was determined and used by the ready-mix plant personnel. This deviation slightly decreased the mixing water and the *w/cm* by 1 lb/yd^3 (0.6 kg/m^3) and 0.001, respectively. Based on the trip tickets, individual *w/cm* ratios ranged from 0.40 to 0.43, paste contents ranged from 25.0 to 25.7%, with an average of 25.4% and the actual quantities of IC water ranged from 6.6 to 10.5%, with an average of 7.1% by total weight of binder. An air-entraining admixture was added at a varied dosage between 0.9 and 1.2 oz/cwt (0.6 and 0.8 mL/kg). A mid-range water-reducing admixture (MRWRA) with a dosage of 5 oz/cwt (3.3 mL/kg) was added to all truckloads. A set-retarding admixture with varied dosages between 1 and 3 oz/cwt (0.7 and 2 mL/kg) was also added to all truckloads. The dosages of viscosity modifying and workability-retaining admixtures were held constant throughout batching at 3 and 1 oz/cwt (2 and 0.7 mL/kg), respectively.

Table 4.25: MN-IC-LC-HPC-7-P1 mixture proportions (SSD/PSD basis)

Material	**Mixture proportions (lb/yd^3)**		
	Initial	**Revised**	**Actual**[a]
Cement (Type I/II)	406	406	406
Grade 100 slag cement	174	174	173
Water	248	248	239
Fine lightweight aggregate	164	159	163
Coarse aggregate	1641	1643	1637
Fine aggregate	1092	1098	1095
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual**[a]
Air AE 90	Air-Entraining	0.1-10	0.9-1.2
Polyheed 1020	Mid-Range Water-Reducing	1-12	5
Set Delvo	Set-Retarding	0-5	1-3[b]
Matrix VMA 358	Viscosity Modifying	0-6	3
Sure Z 60	Workability Retaining	-[c]	1

[a] Actual values based on average of trip tickets
[b] Set retarder dosage stepped down from 3 to 1 oz/cwt throughout the placement
[c] The dosage was not indicated
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.26. Seven tests for slump, air content, and temperature were performed. Slumps ranged from 4 to 4¾ in. (100 to 120 mm), with an average of 4½ in. (115 mm), within the specifications. One initial test for air content was above 10%, the maximum limit of the specifications. Therefore, a second test was performed, which also showed an air content of 10%. Air contents ranged from 7.5 to 10%, with an average of 8.9%, within the specifications. Concrete temperatures ranged from 71 to 75 °F (22 to 24 °C), with an average of 73 °F (23 °C), and 28-day compressive strengths ranged from 5470 to 7310 psi (37.7 to 50.4 MPa).

Table 4.26: Concrete test results-MN-IC-LC-HPC-7-P1

MN-IC-LC-HPC-7-P1	**Slump (in.)**	**Air content (%)**	**Concrete temperature (°F)**	**28-day compressive strength (psi)**
Minimum	4	7.5	71	5470
Maximum	4¾	10	75	7310
Average	4½	8.9	73	6630

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The MN-IC-LC-HPC-7 was located approximately 10 minutes away from the ready-mix plant. Placement 1 started on June 24, 2020, at 10:15 pm, at the north end of the deck and continued to the south end, with the final strikeoff on June 25, 2020, at 4:25 am. The concrete was placed using two pumps (the first pump was positioned near the north end, and the second pump was located near the south end of the bridge). The roadway was consolidated using a spud vibrator and finished by a double-drum roller screed. The sidewalk, however, was consolidated by a spud vibrator followed by a vibrating screed, as shown in Figure 4.21.

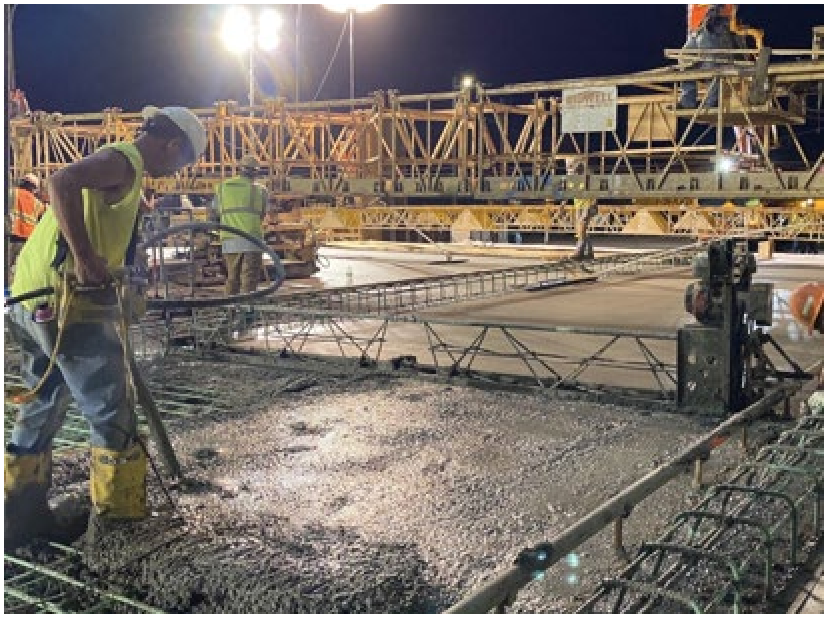


Figure 4.21: Placement equipment

During placement, wind speeds at the deck ranged from 0 to 0.6 mph (0 to 1 km/hr). Relative humidity at the deck ranged between 59.8 and 80.1%. Ambient air temperature during construction ranged from 61 to 70 °F (16 to 21 °C). These environmental conditions resulted in evaporation rates, ranging from 0.02 to 0.03 lb/ft^2/hr (0.09 to 0.14 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit.

No significant issues arose during concrete pumping, placement, or finishing. The time between batching and discharge ranged from 22 to 33 minutes, with an average of 28 minutes. Occasionally, construction personnel were observed stepping in concrete that had been recently vibrated, shoveling concrete, causing deconsolidation and disturbance of the concrete, as shown in Figure 4.22. As will be described in Section 5.3.1.9, some cracks with lengths below 6 in. (152.4 mm and widths between 0.002 in. to 0.006 in. (0.05 to 0.15 mm) were observed mostly on the roadway within 5 ft (1.5 m) from the barrier in these regions. As discussed in Section 4.4.7, the loss of consolidation can lead to settlement, which can lead to increased cracking (Khajehdehi and

Darwin 2018). The time between placement and strikeoff for the sidewalk ranged from 2 to 17 minutes, with an average of 5 minutes; the time between placement and strikeoff for the roadway ranged from 13 to 41 minutes, with an average of 25 minutes.

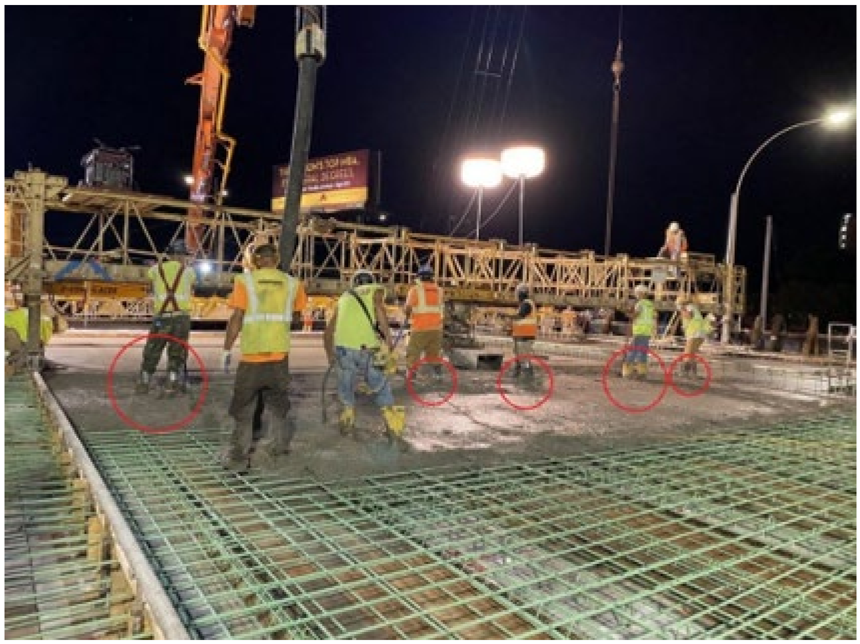


Figure 4.22: Walking observed on freshly consolidated concrete

One work bridge was used for bullfloating, and one work bridge was used for the application of curing compound (including on the sidewalk) and placing wet burlap on the roadway). Trowels were used for finishing the edges, concrete adjacent to the barrier reinforcement on each side, and near abutments. Shortly after bullfloating, the concrete was broomed. Due to using a single work bridge for the application of curing, the contractor decided to initiate the application of curing for both roadway and sidewalk at the same time. With the appearance of bleed water on the concrete surface, as indicated by the reflective water sheen in Figure 4.23(a), the contractor stopped applying the curing compound on the sidewalk and placing wet burlap on the roadway. This incident resulted in a long delay between strikeoff and curing application, mostly near the abutments and the central pier. While waiting for the bleed water to disappear, the construction workers bullfloated the deck repeatedly at some locations in an attempt to accelerate the evaporation of bleed water, as shown in Figure 4.23. As discussed in Section 4.4.7, overfinishing may result in map cracking by bringing excess paste to the surface (Pendergrass and Darwin 2014). As discussed in Section 5.3.1.9, no map cracking was observed on the deck through the first two years of crack surveys. The tendency to exhibit cracking over the long term, however, usually becomes apparent only after 36 months (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014).

(a) (b)

Figure 4.23: Bullfloating the deck in the presence of bleed water (a) an overview; (b) a close-up view

For the sidewalk, the time between strikeoff and application of curing compound ranged from 68 to 112 minutes; for the roadway, the time between strikeoff and placing wet burlap ranged from 32 to 67 minutes. Figure 4.24 shows the application of curing on both the roadway and sidewalk of the deck.

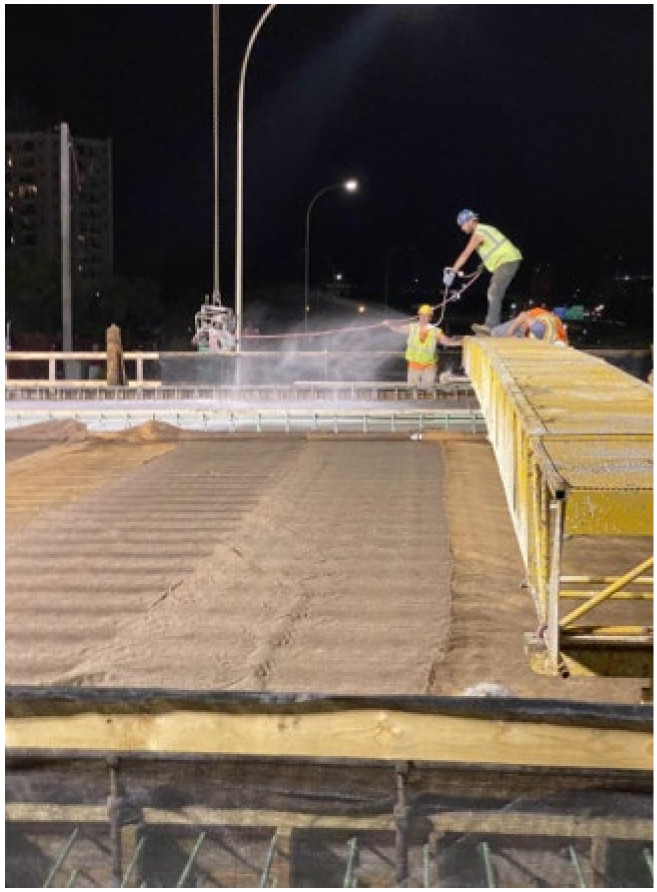


Figure 4.24: The application of curing of the MN-IC-LC-HPC-7-P1

4.4.9.2 MN-IC-LC-HPC-7-P2

Placement 2 of MN-IC-LC-HPC-7 was constructed on September 22, 2020. A new shipment of LWA was delivered to the ready-mix plant. The LWA stockpile was approximately 8 ft (2.4 m) high, and it was pre-wetted for at least three weeks before batching. The sprinkler was turned off on September 22, 2020, at 11:00 am, letting the material drain approximately 9 hours prior to batching. A composite sample was obtained to measure the LWA absorption and free-surface moisture prior to batching. The absorption and the specific gravity of the LWA (OD basis) obtained by KU and KDOT personnel were 35.1% and 1.20, respectively. KU researchers revised the mixture proportions to get 7% of IC water per weight of binder.

The initial and actual (based on the average of trip tickets) mixture proportions for the second placement of MN-IC-LC-HPC-7 are listed in Table 4.27. Based on the trip tickets, between 8 and 17 lb/yd^3 (5 and 10 kg/m^3) of water was withheld during batching, reducing the actual *w/cm* ratio to an average of 0.41. Additionally, prior to casting, KU personnel measured a free-surface moisture of 4.9%, while a free-surface moisture of either 5.5 or 0% was determined and used by the ready-mix plant personnel. Based on the trip tickets, individual *w/cm* ratios ranged from 0.39 to 0.42, paste contents ranged from 24.9 to 25.5%, with an average of 25.3% and the actual quantities of IC water ranged from 6.8 to 8.2%, with an average of 7.0% by total weight of binder. An air-entraining admixture was added at a constant dosage of 0.9 oz/cwt (0.6 mL/kg). A mid-range water-reducing admixture (MRWRA) with a dosage of 4 oz/cwt (2.6 mL/kg) was added to all truckloads; a set-retarding admixture with a constant dosage of 1 oz/cwt (0.7 mL/kg) was also added to all truckloads. The dosages of viscosity modifying and workability-retaining admixtures were held constant throughout batching at 3 and 1 oz/cwt (2 and 0.7 mL/kg), respectively.

Table 4.27: MN-IC-LC-HPC-7-P2 mixture proportions (SSD/PSD basis)

Material	Mixture proportions (lb/yd^3)		
	Initial	Revised	Actual[a]
Cement (Type I/II)	406	406	406
Grade 100 slag cement	174	174	173
Water	248	248	237
Fine lightweight aggregate	164	156	156
Coarse aggregate	1641	1643	1637
Fine aggregate	1092	1105	1103
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual[a]**
Air AE 90	Air-Entraining	0.1-10	0.9
Polyheed 1020	Mid-Range Water-Reducing	1-12	4
Set Delvo	Set-Retarding	0-5	1
Matrix VMA 358	Viscosity Modifying	0-6	3
Sure Z 60	Workability Retaining	-[b]	1

[a] Actual values based on average of trip tickets
[b] The dosage was not indicated
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.28. In contrast with the construction of the first placement, the concrete properties were, for the most part, measured before pumping because MnDOT personnel observed a no loss slump and just a 1% air loss due to pumping; therefore, except for one test, slumps were measured before pumping and ranged from 1 to 4¼ in. (25 to 105 mm), with an average of 3½ in. (90 mm). The single slump measured after pumping equaled 3¾-in. (95-mm). Similarly, except for three tests, air contents were measured before pumping and ranged from 7.5 to 8.5%, with an average of 8.2%, within the specifications (6.5 to 10%). With the exception of one test (air content of 5.5% after pumping), the two air contents measured after pumping had an air content of 7.5% each. Concrete temperatures ranged from 69 to 76 °F (21 to 24 °C), with an average of 73 °F (23 °C), and 28-day compressive strengths ranged from 4080 to 6950 psi (28.1 to 47.9 MPa).

Table 4.28: Concrete test results[a]-MN-IC-LC-HPC-7-P2

MN-IC-LC-HPC-7-P2	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	1	7.5	69	4080
Maximum	4¼	8.5	76	6950
Average	3½	8.2	73	5830

[a] Values measured before pumping; cylinders were filled from truck discharge
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Placement 1 started on September 24, 2020, at 8:45 pm, at the south end of the deck and continued to the north end, with final strikeoff on September 25, 2020, at 2:20 am. As with the first placement, the concrete was placed using two pumps positioned at opposite ends of the deck. The roadway was consolidated using a spud vibrator and finished by a double-drum roller screed. The sidewalk, however, was consolidated by a spud vibrator followed by a vibrating screed

During placement, wind speeds at the deck ranged from 0 to 2.3 mph (0 to 3.7 km/hr). Relative humidity at the deck ranged between 52.7 and 61.7%. Ambient air temperature during construction ranged from 70 to 79 °F (21 to 26 °C). These environmental conditions resulted in evaporation rates, ranging from 0.02 to 0.05 lb/ft^2/hr (0.09 to 0.24 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit.

No significant issues arose during concrete pumping, placement, or finishing. During the placement, KU personnel, however, did observe trapped air pockets on the finished surface of the concrete, mainly near the south end abutment. "Air pockets" result in small openings through which water and fines appear on the concrete surface. Examples are shown in Sections 4.4.10 and 4.4.11.

The time between placement and strikeoff for the sidewalk ranged from 4 to 32 minutes, with an average of 7 minutes; the time between placement and strikeoff for the roadway ranged from 14 to 50 minutes, with an average of 27 minutes.

Similar to the construction of the first placement, long delays occurred between strikeoff and the application of curing compound and burlap due to the presence of bleed water on the surface. As described in Section 5.3.1.9, cracks with lengths below 6 in. (152.4 mm) and widths between 0.003 to 0.025 in. (0.08 to 0.64 mm) were observed primarily on the roadway within 5 ft (1.5 m) of the barrier in these regions. For the sidewalk, the time between strikeoff and curing compound ranged from 105 to 150 minutes; for the roadway, the time between strikeoff and placing wet burlap ranged from 75 to 135 minutes.

4.4.10 MN-IC-LC-HPC-8

MN-IC-LC-HPC-8 is a two-lane bridge that carries traffic on C.S.A.H. 12 over I-90 in Winona. The deck was constructed in one placement on August 20, 2020. The concrete supplier and the contractor were Modern Ready Mix Inc. and Icon Constructors, respectively. The bridge has two equal span lengths of 114 ft-6½ in. (34.9 m), for a total length of 229 ft-1 in. (69.8 m). The deck has a 36 ft (10.9 m) wide roadway and a 1 ft-6 in. (0.46 m) wide barrier on each side, for a total deck width of 39 ft (11.9 m). The nominal deck thickness is 9 in. (229 mm); the deck is supported by prestressed concrete girders with a skew of 4º 6’ 7”.

The fine lightweight aggregate (LWA) used in MN-IC-LC-HPC-8 was an expanded clay stored in an open area at the ready-mix plant. The LWA was pre-wetted using a lawn sprinkler on top of the aggregate stockpile for at least two weeks prior to the construction date. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit. The sprinkler was turned off on the evening of August 19, 2020, letting the material drain approximately 12 hours prior to batching. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

Three trial placements were completed before the construction of MN-IC-LC-HPC-8. The first trial placement was completed on August 12, 2020, with no KU personnel in attendance. The mixture had a binary binder composition, a 30% replacement by weight of portland cement with Grade 100 slag cement. The design paste content and the *w/cm* ratio were 25.6% (by concrete volume) and 0.43, respectively. The design quantity of internal curing water was 8% (by the weight of binder). The lightweight aggregate was pre-wetted for more than two weeks prior to batching, and the design absorption value was 30% (OD basis). The air content and slump of the concrete were 8.4% and 4 in. (100 mm) after pumping, respectively. Although the concrete properties were within MnDOT specifications, there were concerns regarding placement and finishing of the concrete. During the trial placement, MnDOT personnel observed bleeding water channeling, as well as the appearance of trapped air pockets on the finished surface of the concrete, as shown in Figure 4.25. Additional bleeding water pockets appeared for at least 1½ hours after placement. The contractor also had difficulties in finishing the concrete. KU researchers and MnDOT representatives held an online meeting on August 17, 2020 to discuss the issues arisen during the trial placement. At the meeting, KU researchers recommended reducing the dosage of set retarding admixture in the mixture proportions as well as providing on-site guidance to provide moisture content correctly.

Figure 4.25: The appearance of air pockets on the concrete surface (image provided by MnDOT)

A second trial placement was completed at the ready-mix plant on August 18, 2020 with KU and MnDOT personnel in attendance. The concrete was placed in a box with dimensions of 2 × 4 ft (0.3 × 0.6 m) with a depth of 2 ft (0.3 m) (Figure 4.26). The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 31.1% and 1.27, respectively, which slightly differed from the values indicated in the original mixture proportions (30.0% and 1.40, respectively). KU researchers revised the mixture proportions and also provided free-surface moisture to the concrete supplier prior to batching. The concrete supplier also reduced the dosage of the set retarding admixture by half. Two truckloads (each 3 yd^3 [2.3 m^3]) of concrete were made based on these adjustments at the ready-mix plant, one without and one with set retarding admixture. The air content and slump in the first truck, which contained no set retarding admixture, were 7.5% and 3½ in. (90 mm), respectively, after approximately 30 minutes of haul time. The air content and slump in the second truck, which contained 1.5 oz/cwt of set retarding admixture, were 8% and 5½ in. (140 mm), respectively. Both truckloads were placed successfully without any issues, as shown in Figure 4.26.

Figure 4.26: Placement of second truckload in second trial placement (containing set retarding admixture) with no observable air pockets on the concrete surface

A third trial placement was completed at the job site on August 19, 2020 with KU and MnDOT personnel in attendance. The concrete was placed in a larger box than in the second trial placement. The concrete properties at the job site were within MnDOT specifications, except for the slump, which was 5½ in. (140 mm). Small trapped air pockets appeared on the surface of the concrete, as shown in Figure 4.27, but MnDOT personnel approved the trial placement.

(a) (b)

Figure 4.27: Small trapped air pockets at edges of third trial placement (a) overview; (b) close-up (image provided by MnDOT)

The initial, revised, and actual (based on the average of trip tickets) mixture proportions submitted to MnDOT are listed in Table 4.29. MN-IC-LC-HPC-8 had a design *w/cm* ratio of 0.43 and a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 25.6%. The design quantity of internal curing water was 8% (by the weight of binder).

Based on the trip tickets, between 13 and 34 lb/yd^3 (8 and 20 kg/m^3) of water was initially withheld from the trucks, resulting in very stiff concretes with *w/cm* ratios as low as 0.37. Therefore, the concrete supplier added a portion of the withheld water ranging from 3 to 25 lb/yd^3 [2 to 15 kg/m^3] to the trucks at the ready-mix plant. MnDOT inspectors also had difficulties tracking the amount of water in the trucks, and the concrete supplier added undocumented water (approximately 21 lb/yd^3 [12 kg/m^3]) at the jobsite. The MnDOT inspector believed that some trucks were not emptying their drums of wash water before getting a new load, as the specification requires, and adjustments were made at the batch plant to compensate for that water, resulting in the actual *w/cm* ratio averaging close to 0.42.

Crushed gravel and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, individual paste contents ranged from 24.7 to 26.1%, with an average of 25.3% and the actual quantities of IC water ranged from 7.7 to 8.2%, with an average of 8% by total weight of binder. The dosage of a mid-range water reducer admixture (MRWRA) and a set-retarding admixture were held constant throughout batching at 6 and 1.5 oz/cwt (3.9 and 1 mL/kg), respectively. No viscosity modifying admixtures (VMA) were used.

Table 4.29: MN-IC-LC-HPC-8 mixture proportions (SSD/PSD basis)

Material	**Mixture proportions (lb/yd^3)**		
	Initial	**Revised**	**Actual**[a]
Cement (Type I/II)	400	400	400
Grade 100 slag cement	170	170	171
Water	245	245	239
Fine lightweight aggregate	194	192	193
Coarse aggregate	1583	1583	1579
Fine aggregate	1099	1074	1071
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual**[a]
Air AE 90	Air-Entraining	-[b]	0.99
Polyheed 1020	Water-Reducing	1-12	6
Set Delvo	Set-Retarding	0-5	1.5
Matrix VMA 358	Viscosity Modifying	0-10	Not used

[a] Actual values based on average of trip tickets
[b] As needed
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.30. Five tests for slump, air content, and temperature were performed. The slumps were measured only before pumping and ranged from 4 to 6 in. (100 to 150 mm), with an average of 4½ in. (115 mm). Only one test for slump (6 in. [150 mm]) showed a value higher than 5 in. (125 mm), the maximum limit in the specifications. While the second test was performed, the concrete had been pumped and placed on the deck; the second test showed a slump of 5¼ in. (130 mm). Except for one test, air contents were measured before pumping and ranged from 7.4 to 9.5%, with an average of 8.8%, within the specifications (6.5 to 10%). In the single after pumping, the air content was 7.4%. After placing approximately 90 yd^3 (69 m^3) of the concrete, the pump became clogged. The concrete was stiff and the MnDOT personnel stated that water was not allowed to be added to the truck at the job site and, as a result, rejected the truck. The next truck had a slump of 4½ (115 mm) with an air content of 8.6% and was pumped with no issues. Concrete temperatures ranged from 74 to 78 °F (23 to 26 °C), with an average of 76 °F (24 °C) and 28-day compressive strengths ranged from 5780 to 7750 psi (39.9 to 53.4 MPa), all above the specified limit of 5500 psi (37.9 MPa).

Table 4.30: Concrete test results[a]-MN-IC-LC-HPC-8

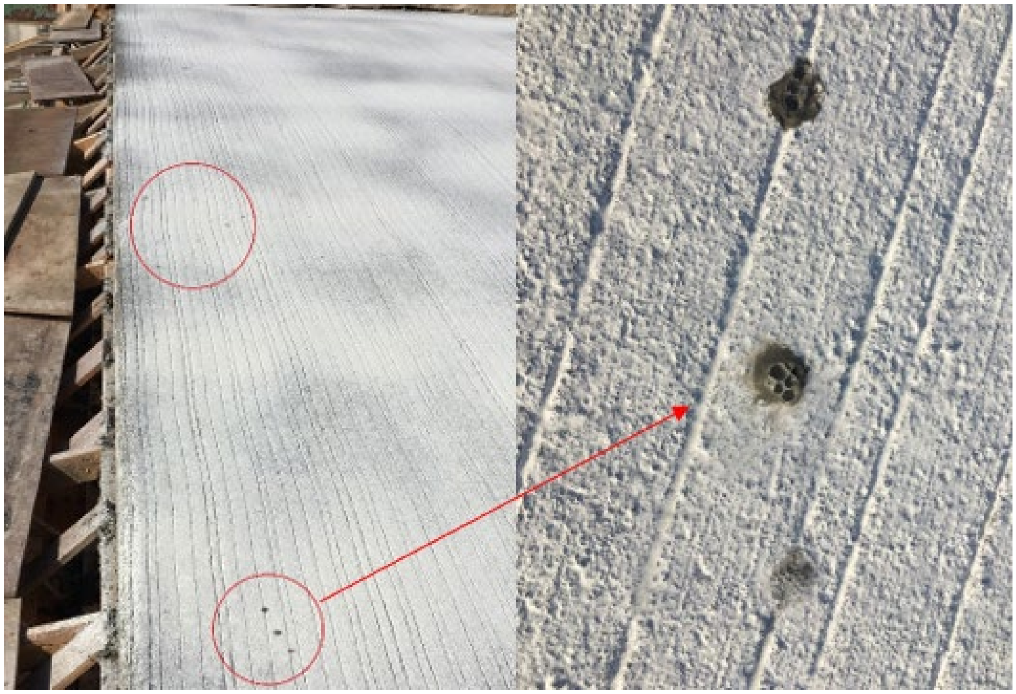
MN-IC-LC-HPC-8	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	4	6.8	65	5780
Maximum	5¼[b]	9.5	78	7750
Average	4½	7.9	71	6500

[a] Values measured before pumping, cylinders were filled from truck discharge
[b] First test showed a 6-in slump, and another test was performed with a slump of 5¼ in.
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The MN-IC-LC-HPC-8 was located approximately 25 minutes away from the ready-mix plant. Placement started on August 20, 2020 at 6:25 am, at the east end of the deck and continued to the west end. The placement was finished with the final strikeoff on August 20, 2020 at 11:45 am. The concrete was placed using two pumps (the second pump was used after placing approximately 130 ft [40 m] of the deck), consolidated using a spud vibrator, and finished using a single-drum roller followed by a metal pan (as shown in Figure 4.28). The concrete was placed in strips about 5 ft (1.5 m) along the length of the deck. During placement, wind speeds at the deck ranged from 2.5 to 5.9 mph (4 to 9.5 km/hr). Relative humidity at the deck ranged between 60.1 and 74.5%. Ambient air temperature during construction ranged from 65 to 77 °F (18 to 25 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.05 to 0.07 lb/ft^2/hr (0.24 to 0.34 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit. The time between batching and discharge ranged from 45 and 70 minutes, with an average of 58 minutes. The time between placement and strikeoff ranged from 5 to 24 minutes, with an average of 12 minutes.

Figure 4.28: Finishing equipment

During the placement, MnDOT personnel observed trapped air pockets appearing on the finished surface of the concrete, mainly near the east end abutment, as shown in Figure 4.29.



(a) (b)

Figure 4.29: Trapped air pockets on top of the east end abutment (a) overview; (b) close-up (image provided by MnDOT)

The vibrator was inserted at regularly spaced intervals, close enough to the last location so that the radius of action overlapped the last one. Two work bridges were used for bullfloating, brooming, tining, the application of curing compound, and wet burlap. A highway straight edge was used in place of a bullfloat. Trowels were used for finishing the edges, concrete adjacent to the barrier reinforcement on each side, and near abutments. The deck was then tined before the application of the curing compound, as shown in Figure 4.30.

Figure 4.30: Tining the deck before the application of curing compound

Shortly after tining, a single layer of curing compound was sprayed non-uniformly on the deck, as shown in Figure 4.31. As discussed in Section 5.3.1.10, one possible cause of the poor cracking performance of this deck could be this non-uniform distribution of curing compound, which can result in plastic shrinkage in regions with poor coverage. The time between strikeoff and application of curing compound ranged from 13 to 28 minutes.

Figure 4.31: Non-uniform distribution of curing compound on the deck

The application of the curing compound began at the east end and continued to the west end of the deck. The concrete adjacent to the barrier reinforcement was covered with wet burlap, as shown in Figure 4.32, within an hour of consolidation.

Figure 4.32: Burlap placement on the barrier reinforcement

KU researchers were informed that the deck would be covered by wet burlap when the concrete could be walked without producing imprints deeper than $^{1}/_{16}$ in (1.6 mm). The burlap rolls were soaked in water until they were transferred to the work bridge for placement. After the concrete had set, the application of wet burlap and plastic sheeting began from the east end and finished within an hour of curing compound application without any considerable delays, as illustrated in Figure 4.33.

Figure 4.33: Covering the deck with wet burlap and plastic sheeting

4.4.11 MN-IC-LC-HPC-9

MN-IC-LC-HPC-9 carries eastbound traffic on I-90 over Dakota Valley in Winona. The deck was constructed in one placement on September 4, 2020. The concrete supplier and the contractor were the same as MN-IC-LC-HPC-8. The bridge has three spans with lengths of 44 ft-1 in. (13.4 m), 63 ft-10 in. (19.5 m), and 35 ft-2 in. (10.7 m), with a total length of 143 ft-1 in. (43.6 m). The deck has a 40 ft (12.2 m) wide roadway and a 1 ft-6 in. (0.46 m) wide barrier on each side, for a total deck width of 43 ft (13.1 m). The nominal deck thickness is 9 in. (229 mm); the deck is supported by prestressed concrete girders with a skew of 13º 45’ 24”.

As with MN-IC-LC-HPC-8, the LWA used in this project was an expanded clay stored in an open area at the ready-mix plant. The LWA was pre-wetted using a lawn sprinkler on top of the aggregate stockpile for at least a week prior to the construction date. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit. The sprinkler was turned off on the evening of September 3, 2020, letting the material drain approximately 12 hours prior to batching. Upon KU researchers’ request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

The average absorption (OD basis) and the specific gravity (OD basis) of the LWA obtained by KU researchers were 30.8% and 1.28, respectively, which differed slightly from the values used in MN-IC-LC-HPC-8 mixture proportions (31.1% and 1.27, respectively). The main difference between the mixture proportions of the two decks was the design quantity of internal curing water, which was 7% (by the weight of binder) based on KU researchers' recommendations for bridge decks cast late in the construction season to minimize durability problems (Lafikes et al. 2020). KU researchers revised the mixture proportions to get 7% of internal curing water by the weight of binder.

Although KU personnel recommended that the bottom 6 to 12 in. (150 to 300 mm) of the LWA stockpile not be used in batches, when the material was accumulated by the loader for placing into the aggregate bins, the bottom of the stockpile was completely disturbed as shown in Figure 4.34. It is commonly found a significant difference between the moisture content of the aggregates at the bottom and the top portions of the piles.

Figure 4.34: Disturbance of the bottom of the stockpile

A trial placement was not required due to successful construction of the MN-IC-LC-HPC-8, which had similar mixture proportions, same concrete supplier, and contractor.

The initial, revised, and actual (based on the average of trip tickets) mixture proportions submitted to MnDOT are listed in Table 4.31. As with MN-IC-LC-HPC-8, MN-IC-LC-HPC-9 had a design *w/cm* ratio of 0.43 and a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement, with a design paste content of 25.6%. The design quantity of internal curing water, however, was 7% (by the weight of binder).

Based on the trip tickets, similar to MN-IC-LC-HPC-8, on average 34 lb/yd^3 (20 kg/m^3) of water was initially withheld in the trucks, resulting in very stiff concrete with a *w/cm* ratio as low as 0.37. Therefore, the concrete supplier added a portion of the withheld water, ranging from 3 to

17 lb/yd^3 (2 to 10 kg/m^3), to the trucks at the ready-mix plant, increasing the *w/cm* ratio to 0.38. In contrast to MN-IC-LC-HPC-8, MnDOT inspectors verified that all trucks emptied their drums before getting a new load.

Crushed gravel and river sand were used as coarse and fine aggregates, respectively. Based on the trip tickets, the actual *w/cm* ratio was 0.38 and individual paste contents ranged from 23.8 to 24.7%, with an average of 24.0% and the actual quantities of IC water ranged from 6.8 to 7.3%, with an average of 7.0% by total weight of binder. The dosages of a mid-range water reducer admixture (MRWRA) and a set-retarding admixture were held constant throughout batching at 6 and 1.5 oz/cwt (3.9 and 1 mL/kg), respectively. No viscosity modifying admixtures (VMA) was used.

Table 4.31: MN-IC-LC-HPC-9 mixture proportions (SSD/PSD basis)

Material	Mixture proportions (lb/yd^3)		
	Initial	**Revised**	**Actual[a]**
Cement (Type I/II)	400	400	401
Grade 100 slag cement	170	170	170
Water	245	245	219
Fine lightweight aggregate	194	169	170
Coarse aggregate	1583	1583	1579
Fine aggregate	1099	1113	1108
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual[a]**
Air AE 90	Air-Entraining	-[b]	0.85 to 0.99
Polyheed 1020	Water-Reducing	1-12	6
Set Delvo	Set Retarding	0-5	1.5
Matrix VMA 358	Viscosity Modifying	0-10	Not used

[a] Actual values based on average of trip tickets
[b] As needed
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.32. Five tests for slump, air content, and temperature were performed. Except for one test, slump was measured before pumping and ranged from 3 to 4 in. (75 to 100 mm), with an average of 3¼ in. (80 mm). Only the first truck was rejected due to out-of-specification slump. This truckload had an initial slump of 7 in. (175 mm), higher than 5 in. (125 mm), the maximum limit in the MnDOT specifications. A second test showed a slump of 6¾ in. (170 mm), resulting in the rejection of the truckload. In the single test performed after pumping the slump was 3½ in. (90 mm).

Except for two tests, air contents were measured before pumping and ranged from 6.2 to 9%, with an average of 7.9%, within the specifications (6.5 to 10%). The two air contents measured after pumping were 8.7 and 10.2%, respectively. Concrete temperatures ranged from 67 to 73 °F (19 to 23 °C), with an average of 72 °F (22 °C) and 28-day compressive strengths ranged from 5860 to 6880 psi (40.4 to 47.4 MPa), all above the specified limit of 5500 psi (37.9 MPa).

Table 4.32: Concrete test results[a]-MN-IC-LC-HPC-9

MN-IC-LC-HPC-9	Slump[b] (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	3	6.2	67	5860
Maximum	4	9.0	73	6880
Average	4½	7.9	72	6320

[a] Values measured before pumping; cylinders were filled from truck discharge
[b] One initial test showed a 7-in slump, and another test was performed, eventually rejected
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The MN-IC-LC-HPC-9 was located approximately 30 minutes away from the ready-mix plant. Placement started on September 4, 2020 at 6:50 am, at the east end of the deck and continued to the west end. Placement finished with the final strikeoff on August 20, 2020 at 10:35 am. As with the construction of MN-IC-LC-HPC-8, the concrete was placed using one pump, consolidated using a spud vibrator, and finished using a single-drum roller screed followed by a metal pan. The concrete was placed in strips about 5 ft (1.5 m) along the length of the deck. The MN-IC-LC-HPC-9 placement is shown in Figure 4.35.

Figure 4.35: MN-IC-LC-HPC-9 placement

During placement, wind speeds at the deck ranged from 0 to 2 mph (0 to 3.2 km/hr). Relative humidity at the deck ranged between 43.3 and 70.3%. Ambient air temperature during construction ranged from 66 to 74 °F (19 to 23 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.03 to 0.05 lb/ft^2/hr (0.14 to 0.24 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specifications limit. The time between batching and discharge ranged from 46 to 83 minutes, with an average of 59 minutes. There were transmission problems with the third truck, causing a delay during placement; the 83-minute delay between batching and discharging was due to this delay. The time between placement and strikeoff ranged from 5 to 20 minutes, with an average of 11 minutes. The vibrator was inserted at regularly spaced intervals, close enough to the last location so that the radius of action overlapped the last one. Two work bridges were used for bullfloating, brooming, tining, the application of curing compound and wet burlap. A highway straight edge was used in place of a bullfloat. Trowels were used for finishing the edges, concrete adjacent to the barrier reinforcement on each side, and near abutments. The deck was then tined followed by a single layer of curing compound sprayed on the deck. As discussed in Section 5.3.1.11, a notable amount of map cracking was observed on the deck surface, especially in the middle of spans 1 and 3, at an age of 20.6 months. The majority of cracks were longitudinal (lengths of 2 ft [0.6 m] or less) distributed over the entire deck area. As will be discussed in Section 5.3.1.11, a possible reason for the poor cracking performance of this deck could be the non-uniform distribution of curing compound applied during construction, as shown in Figure 4.36, which can result in plastic shrinkage. The time between strikeoff and application of curing compound ranged from 5 to 35 minutes.

Figure 4.36: Application of the curing compound on the deck

The application of the curing compound began at the east end and continued to the west end of the deck. The concrete adjacent to the barrier reinforcement was covered with wet burlap during construction within an hour of each section being consolidated, as shown in Figure 4.37.

Figure 4.37: Burlap placement on the barrier reinforcement

During the placement, MnDOT personnel observed trapped air pockets appearing on the finished surface of the concrete, mainly near the east end abutment, as shown in Figure 4.38.

(a) (b)

Figure 4.38: Trapped air pockets on the deck (a) overview; (b) close-up

As with MN-IC-LC-HPC-8, KU researchers were informed that the deck would be covered by wet burlap when the concrete could be walked without producing imprints deeper than $^1/_{16}$ in (1.6 mm). The burlap rolls were soaked in water until they were transferred to the work bridge prior to placement. The application of wet burlap, as illustrated in Figure 4.39, and plastic sheeting began from the east end and finished within an hour of application of curing compound without any considerable delays. It was observed, however, that the personnel stepped on the deck while placing wet burlap.

Figure 4.39: Wet curing application on MN-IC-LC-HPC-9

4.4.12 Failed MN-IC-LC-HPC bridge deck placement in 2016

In 2016, MN-IC-LC-HPC deck (Br. 58821) was an additional deck that was bid under the MnDOT IC-LC-HPC specifications, but was not constructed following those specifications. The lessons learned from the failed placement are summarized in this section. Br.58821 is a two-lane bridge deck that carries southbound traffic on I-35 over Corix Valley Railroad near Hinckley. The deck was constructed in one placement on October 6, 2016. The concrete supplier and the contractor were Cemstone Products Co. and Redstone Construction, respectively. The bridge has three spans with lengths of 68 ft-3 in. (20.8 m), 83 ft-6 in. (25.5 m), and 68 ft-3 in. (20.8 m), with a total length of 220 ft-1 in. (67.1 m). The deck has a 42 ft (12.8 m) wide roadway and a 1 ft-8 in. (0.51 m) wide barrier on each side, for a total deck width of 45 ft-4 in. (13.8 m). The nominal deck thickness is 9 in. (229 mm); the deck is supported by prestressed concrete girders with a skew of -49^{o} 29’ 30”.

The main factors contributing to this failed placement consist of (1) failure to measure LWA properties within the hour prior to batching, (2) failure to add all required admixtures at the time of batching, and (3) failure to place concrete with the same equipment that was used in the trial placement.

A new shipment of pre-wetted LWA materials was delivered to the ready-mix plant on October 5, 2016. Upon KU researchers’ request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture. The average absorption (OD basis) and the free-surface moisture (OD basis) of the LWA obtained by KU researchers were 26 and 7.5% (measured approximately 15 hours before deck placement), respectively, which slightly differed from the values (25.6 and 8.4%, respectively) determined by the concrete supplier personnel. Concrete supplier personnel did not conduct any additional tests for free-surface moisture after loading the LWA into the aggregate hopper, even though the materials were allowed to drain for approximately 15 hours before deck placement. On the day of batching, KU researchers measured a free-surface moisture of 4.3%, while the concrete supplier personnel used the initial obtained free-surface moisture (8.4%). This deviation decreased the mixing water and the *w/cm* by 6 lb/yd^3 (3.5 kg/m^3) and 0.01, respectively.

The concrete supplier was responsible for producing concrete for the deck and the approach slabs, with and without IC, respectively. While the east approach slab was being constructed, the first truckload containing IC had to wait for approximately 40 minutes at the plant before departing for the job site. As a result, the concrete supplier produced four more IC truckloads and sent them to the job site to accelerate the construction. After pumping, the first truckload had a 1¾ in. (45 mm) slump. Based on the trip tickets, 8 lb/yd^3 (5 kg/m^3) of water were being withheld during batching. Therefore, trim water was added back at the jobsite to improve pumpability and workability. This load was rejected due to the long delay between the time of batching and discharging. It was also noticed that the concrete supplier had not added VMA to the truckloads at the time of batching. A dosage of either 3 or 6 oz/cwt (1.9 or 3.9 mL/kg) of VMA was added to the four other truckloads at the job site. In spite of these changes, the concrete remained out-of-specification for air content and slump, resulting in the rejection of the truckloads. Due to insufficient LWA at the ready-mix plant, with the approval of MnDOT personnel, the placement was resumed using standard MnDOT HPC mixture proportions without IC.

During the construction, it was revealed that a larger pump was used for deck placement than was used for the trial placement. Larger pumps (longer lines) operate at lower pressures than smaller pumps, resulting from greater friction and higher head losses. This reinforces the importance of using the same equipment for the trial placement and the deck (Lindquist et al. 2008, McLeod et al. 2009).

4.5 KDOT IC-LC-HPC SPECIFICATIONS

As described in Chapter 1, Low-Cracking High-Performance (LC-HPC) specifications have been modified over the years based on lessons learned in the laboratory and in the field. While KDOT and the University of Kansas (KU) were working together on finalizing the specifications, one IC deck had been let, in 2019, with an earlier version of the specifications. The earlier and the most recent specifications included the use of internal curing with or without incorporating supplementary cementitious materials (SCMs) as partial replacement of portland cement in an effort to reduce further cracking. The major differences between the two versions are discussed in the following sections.

The IC decks constructed in Kansas followed the requirements of the most recent LC-HPC specifications: 1102 "Aggregate," 401 "General Concrete," Sections 1102.2f.(2). and 401.3(g), respectively, for designing internally-cured concrete mixtures that reduce cracking by incorporating pre-wetted fine lightweight aggregate, 402 "Structural Concrete," and 710 "Construction." As described in Chapter 1, the specifications provide materials, concrete properties, and construction requirements. Since all the LC-HPC decks constructed between 2019 and 2022 included internal curing, they are referred to KDOT IC-LC-HPC decks in this study. The most recent KDOT IC-LC-HPC specifications are provided in Appendix E. Although most of the MnDOT and KDOT specifications requirements are similar, there are some differences.

4.5.1 Aggregates

The special provisions cover the requirement for fine lightweight aggregate. In contrast with MnDOT IC-LC-HPC specifications, KDOT IC-LC-HPC specifications do not impose any maximum volume replacement of total aggregate with pre-wetted LWA. The specifications indicate that a portion of normalweight fine aggregate must be replaced with pre-wetted LWA to provide 7% IC water by the weight of binder for IC-LC-HPC decks. As with MnDOT specifications, KDOT specifications place a maximum size aggregate of ⅜ in. (9.5 mm) on LWA. The LWA is required to be pre-wetted using sprinklers for at least 72 hours or until an acceptable absorption is achieved prior to batching. The specifications indicate that the sprinklers must be turned off to allow the materials to drain 24 hours prior to batching. The LWA stockpile height is limited to 5 ft (1.5 m) and is required to be turned daily to provide a uniform moisture content, especially before taking samples and batching. The specifications also enforce requirements pertaining to handling and stockpiling LWA, including protection from contamination, segregation, and non-uniform grading and moisture distribution.

The pre-wetted LWA absorption and specific gravity must be measured 24 hours prior to batching. It is also required to obtain free-surface moisture of the LWA within an hour prior to batching. The specifications also require the use of a centrifuge to obtain the pre-wetted LWA. The mixture proportions are required to be revised based on the LWA properties obtained 24 hours prior to batching to ensure the design quantity of IC water (7% by the weight of binder) is provided.

The specifications also include the requirements for the normalweight coarse and fine aggregates. The coarse aggregate must be gravel, chat, or crushed stone, with a minimum soundness (KTMR-21) of 0.9 and no upper limit for absorption. The specifications allow the use of either natural sand or chat as fine aggregate, complying with requirements specified in Section 1102.2e (see Appendix E). Limestone (with nominal absorption ranging from 1 to 2%) and natural sand were used as the coarse and fine aggregates for the construction of IC-LC-HPC decks in Kansas, respectively. The provisions also require that a composite gradation of the aggregates comply with requirements specified in accordance with Table 1102-3, Section 1102.2b using a proven optimization method, such as the Shilstone Method or the KU Mix Method (Lindquist et al. 2008, 2015) (Appendix E). A maximum size aggregate of 1 in. (25 mm) is required in accordance with the specifications.

4.5.2 Concrete

Table 4.33 summarizes the requirements for structural concrete in the KDOT IC-LC-HPC specifications. The specifications limit the cementitious material content to 500 to 560 lb/yd^3 (297 to 332 kg/m^3), with a slightly higher maximum limit compared to the earlier specifications (550 lb/yd^3 [326 kg/m^3]), with a water-to-cementitious material (*w/cm*) ratio between 0.43 and 0.45. The specifications also limit mass replacement of portland cement with each supplementary cementitious material. In the 2019 IC deck, the specifications allowed slag cement and silica fume with maximum replacement of 30 and 3%, respectively, by weight of binder. For subsequent decks, the maximum replacement level for silica fume was 2%. Although paste content can vary based on the types, replacement levels of cementitious materials, and *w/cm* ratios, it is limited to 26% by concrete volume. The allowable air content for the 2019 IC deck ranged from 5 to 8%, while this range changed to 6.5 to 9.5% for subsequent decks. The maximum allowable slump is 4 in. (100 mm) ± 1 in. (25 mm). To reduce the chance of thermal and plastic shrinkage cracking, the temperature of the fresh concrete is required between 50 and 80 ºF (10 and 27 ºC)

In contrast with MnDOT IC-LC-HPC specifications, KDOT IC-LC-HPC specifications allow the concrete suppliers to withhold a maximum of 17 lb/yd^3 (10 kg/m^3) of mixing water at the batch plant and, if required, added back at the job site. The specifications also allow the addition of set retarding admixtures as with MnDOT IC-LC-HPC specifications.

Table 4.33: Requirements for concrete in KDOT IC-LC-HPC decks

<table>
<tr><th>Construction year</th><th>Cementitious materials contents (lb/yd^3)</th><th>w/cm ratio</th><th>Maximum SCM (fly ash/slag cement/silica fume [%])</th><th>Air content (%)</th><th>Maximum slump (in)[a]</th></tr>
<tr><td>2019</td><td>500-550</td><td rowspan="4">0.43-0.45</td><td>0/30/3</td><td>5-8</td><td rowspan="4">4</td></tr>
<tr><td>2020</td><td rowspan="3">500-560</td><td rowspan="3">0/30/2</td><td rowspan="3">6.5-9.5</td></tr>
<tr><td>2021</td></tr>
<tr><td>2022</td></tr>
</table>

[a] The tolerance is ±25% of the designated slump
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The specifications also include requirements for 28-day compressive strength, rapid chloride permeability, freeze-thaw durability, and drying shrinkage for hardened concrete.

In contrast with the MnDOT IC-LC-HPC specifications, the KDOT specifications limit only the minimum of 28-day compressive strengths to 3500 psi (24.1 MPa). Based on the work of Khajehdehi and Darwin (2018), higher strength concrete is no longer thought to be an issue in bridge deck cracking.

The requirements for ion conductivity and resistivity of hardened concrete include the maximum charge passed to be less than 1500 coulombs at 56 days in accordance with ASTM C1202 and a minimum of 19 kΩ-cm surface resistivity measurements at 56 days in accordance with KT-79, Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration. It also specifies requirements for the freeze-thaw resistance of the concrete in accordance with KTMR-22, Resistance of Concrete to Rapid Freezing and Thawing, that includes the use of ASTM C666-Procedure B, with a failure limit of 95% of the initial dynamic modulus of elasticity at 660 cycles. Drying shrinkage at 365 days is limited to 700 microstrain.

4.5.3 Construction

A qualification batch containing at least 6 yd^3 (4.5 m^3) is required at least 60 days before the actual deck placement. The qualification batch is required to be successfully placed on a qualification slab to demonstrate that the concrete supplier and the contractor can properly produce, pump, and place IC-LC-HPC. Contractors are required to employ the same supplier, batch plant, materials, equipment, and methods used on both the qualification slab and the bridge deck.

As with the MnDOT specifications, the KDOT specifications specify a maximum evaporation rate of 0.2 lb/ft^2/hr (1.0 kg/m^2/hr). When required, the specifications specify the use of protective measures, such as cooling the concrete by replacing some of the mixing water with ice, providing early application of wet curing, and using windbreaks to protect the concrete from direct wind to reduce the potential for plastic shrinkage cracking. Fogging is allowable only if it does not cause water to drip, flow, or puddle on the deck during the construction. According to the specifications, the use of finishing aids or the addition of water to the concrete surface is prohibited.

A mechanical device with concrete vibrators of the same type and size is required to consolidate uniformly IC-LC-HPC decks. Vibrators should be extracted smoothly from the plastic concrete to prevent voids or holes from appearing on the deck. To remove any voids left by workers on the deck, the vibrator must be reinserted within one-half of its action radius to fully reconsolidate the concrete. Dragging the vibrators horizontally and walking through freshly consolidated concrete are prohibited. Hand-held vibrators should be used to consolidate areas that the mechanical device cannot reach. Vibrators must be inserted for 3 to 15 seconds, and the insertions must be made in small steps less than 12 in. (25 mm) apart.

KDOT IC-LC-HPC decks must be struck off with a self-propelled finishing machine or a drum roller screed and finished by one or more metal pans, a burlap drag, or both, followed by bullfloating if required (to remove local irregularities).

The KDOT specifications indicate covering the entire deck with a first layer of pre-soaked burlap (for at least 12 hours) with no visible openings on the deck within 15 minutes after the final strikeoff, followed by a second layer within 10 minutes. The concrete surface is required to remain continuously wet for at least 14 calendar days. In contrast with MnDOT specifications, the use of curing compounds is prohibited during the 14-day wet curing period on the deck.

4.6 DECK CONSTRUCTION-KANSAS

Table 4.34 summarizes the information on bridge decks included in this section. The KDOT IC-LC-HPC decks were constructed between 2019 and 2021. KS-IC-LC-HPC decks are numbered in the order they were constructed. In the cases where the bridge decks were constructed in multiple placements, the placement number (P#) is added at the end of the bridge ID. The decks are located in Edgerton and Ottawa. KS-IC-LC-HPC-1 is supported by prestressed concrete girders, while the other two decks are supported by steel girders. All the decks carry vehicular traffic and have no sidewalks.

The placements were constructed September or November. Except for KS-IC-LC-HPC-2, the decks were placed in one placement. Table 4.35 lists the bridge dimensions, concrete suppliers, and construction contractors for the Kansas decks in this study.

Table 4.34: KDOT IC-LC-HPC deck information

Bridge ID	Bridge No.	Location	Structure type	Subdeck placement date
KS-IC-LC-HPC-1	35-46 KA 3083-01	Sunflower Rd. over I-35, Edgerton	Prestressed concrete girders	11/26/2019
KS-IC-LC-HPC-2-P1[a]	35-30 KA-3102-01	Montana Rd over I-35, Ottawa	Steel Girders	11/3/2020
KS-IC-LC-HPC-2-P2				11/11/2020
KS-IC-LC-HPC-3	35-46 KA 3929-01	199th St. over I-35, Edgerton	Steel Girders	9/16/2021

[a] P# stands for placement.

The IC deck placements have between two and four spans, with skews between -55° 8’ 20” and 25°. The lengths of the bridges range from 237 to 610 ft (72.2 to 185.9 m), and the widths range from 42.5 to 60.8 ft (12.9 to 18.5 m).

Table 4.35: KDOT IC-LC-HPC deck geometry, project supplier, and contractors

Bridge ID	Skew (deg.)	No. of spans	Length (ft)	Width (ft)	Concrete supplier	Contractor
KS-IC-LC-HPC-1	18° 32’ 0”	2	237	60.8	Fordyce	Pyramid
KS-IC-LC-HPC-2-P1[a]	25°	4	338	21.3	Builders Choice Concrete	A.M. Cohron & Son
KS-IC-LC-HPC-2-P2				21.3		
KS-IC-LC-HPC-3	-55° 8’ 20”	4	610	43	Fordyce	Pyramid

[a] P# stands for placement.

4.6.1 Concrete Mixture Proportions

The cementitious material percentages and aggregate proportions for each bridge deck are given in Table 4.36. The mixture proportions for KDOT IC-LC-HPC decks contained either a binary composition system including 30% cement replacement with slag cement by weight of binder or a ternary composition system including 30% cement replacement with slag cement and either 2 or 3% replacement with silica fume by weight of binder.

Table 4.36: Cementitious material percentages and aggregate proportions (SSD/PSD basis)[a]

Bridge ID	Cementitious material percentages[c] (lb/yd^3)	Coarse Agg. (lb/yd^3)		Fine Agg. (lb/yd^3)		LWA Agg. (lb/yd^3)	
		Design	Actual	Design	Actual	Design	Actual
KS-IC-LC-HPC-1[b]	67% C, 30% S, 3% SF	1193	1189	1103	1101	306	304
		286	290				
KS -IC-LC-HPC-2-P1	70% C, 30% S	1683	1681	841	841	280	279
KS -IC-LC-HPC-2-P2			1680	841	840	280	279
KS -IC-LC-HPC-3[b]	68% C, 30% S, 2% SF	1299	1304	1098	1097	161	162
		272	278				

[a] Actual values are based on the average of trip tickets.
[b] KS-IC-LC-HPC-1, and-3 used two size fractions for coarse aggregate (¾ and ½ in., first and second row, respectively)
[c] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; SF = Silica Fume
Note: 1 in. = 25.4 mm, 1 lb/yd^3 = 0.593 kg/m^3.

Table 4.37 shows the LWA properties obtained by KU/KDOT personnel, as well as the values used in design, as given by the concrete suppliers.

Table 4.37: Average LWA properties, design and actual values obtained by KU researchers

Bridge ID	Absorption (%, OD basis)		Specific gravity (OD basis)	
	Design	KU/KDOT measurements	Design	KU measurements
KS-IC-LC-HPC-1	14.3	13.7	1.44	1.54
KS-IC-LC-HPC-2-P1	14.1	15.5	1.31	1.61
KS-IC-LC-HPC-2-P2		15		1.51
KS-IC-LC-HPC-3	30	43	1.31	1.26

Table 4.38 provides the design and actual values of the total weight of cementitious materials, water contents, water-to-cementitious materials (*w/cm*) ratio, paste contents, and IC water contents for each deck. The actual values are based on the average of values from trip tickets. KS-IC-LC-HPC-2 had a design *w/cm* ratio of 0.43, the lowest in this study. The design *w/cm* ratios for the IC-LC-HPC decks were either 0.43 or 0.45, with actual average *w/cm* ratios ranging from 0.42 to 0.44. The design paste contents for the IC-LC-HPC decks ranged from 24.2 to 24.6%, with actual paste contents ranging from 23.8 to 24.2%. The design IC water content for the IC-LC-HPC decks was 7%, with actual values ranging from 6.7 to 8.5%. The quantity of IC water is based on the amount of absorbed water in and the quantity of LWA in the mixture proportions. The variation in LWA absorption observed in this study resulted in a significant difference between the design value and the actual quantity of IC water for some decks, as illustrated in Table 4.38. This can also result in incorrect amounts of mixing water being batched or withheld during batching, affecting actual *w/cm* ratios and paste contents if the LWA absorption and free-surface moisture are not measured within 24 and one hour, respectively, prior to batching. Data from individual trip tickets are shown in Appendix F.

Table 4.38: Cementitious material content, water content, *w/cm* ratio, paste, and IC water contents for KDOT IC-LC-HPC decks[a]

Bridge ID	Cementitious material content (lb/yd^3)[b]		Water content (lb/yd^3)		*w/cm* ratio		Paste content (%)		IC water (% of binder weight)	
	Design	Actual	Design	Actual	Design	Actual	Design	Actual	Design	Actual
KS-IC-LC-HPC-1	530	530	238	233	0.45	0.44	24.6	24.2	7	6.7
KS-IC-LC-HPC-2-P1	540	540	232	225	0.43	0.42	24.2	23.8	7	6.9
KS-IC-LC-HPC-2-P2		540		230		0.43		24.1		6.7
KS-IC-LC-HPC-3	530	529	238	231	0.45	0.44	24.4	24.0	7	8.5

[a] Actual values are based on the average of trip tickets.
[b]See Table 4.36 for details.
Note: 1 lb/yd^3 = 0.593 kg/m^3.

4.7 BRIDGE DECKS

Table 4.39 summarizes the concrete properties, including the average slump, air content, concrete temperature, and 28-day compressive strength for the KDOT IC decks included in this study. The projects are discussed in greater detail in Sections 4.7.1 through 4.7.3. The average slumps ranged from 4¾ to 5¾ in. (120 to 145 mm). Air contents were all within the corresponding specification limits, ranging from 6.3 to 8.6%. Concrete temperatures were also within the specification limits (50 to 80 °F [10 to 27 °C]), ranging from 64 to 76 °F (18 to 24 °C). The average 28-day compressive strengths of the decks ranged from 3570 to 7070 psi (24.6 to 48.7 MPa).

Table 4.39: Average KDOT IC-LC-HPC concrete properties

Bridge ID	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength
KS-IC-LC-HPC-1	5	6.3	69	5660
KS-IC-LC-HPC-P1[a]	5¾	8.6	64	7070
KS-IC-LC-HPC-P2	4¾	8.3	71	6850[a]
KS-IC-LC-HPC-3	5¾	7	76	3570

[a] Values measured before pumping
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

4.7.1 KS- IC-LC-HPC-1

KS-IC-LC-HPC-1 is a two-lane bridge that carries traffic on Sunflower Rd. over I-35 in Edgerton, Kansas. The deck was constructed in one placement on November 26, 2019. The concrete supplier and the contractor were Fordyce and Pyramid Contractors, respectively. The bridge has two equal span lengths of 118 ft-6 in. (36.1 m), for a total length of 237 ft (72.2 m). The deck has a 58 ft (17.7 m) wide roadway and a 1 ft-4½ in. (0.41 m) wide barrier on each side, for a total deck width of 60 ft-9 in. (18.5 m). The nominal deck thickness is 8½ in. (216 mm) with 9½-in. (241-mm) thick overhangs; the deck is supported by prestressed concrete girders with a skew of 18º 32'0".

The lightweight aggregate (LWA) was shipped to the batch plant four days prior to the placement date. The LWA used in KS-IC-LC-HPC-1 was an expanded shale stored in an open area at the batch plant. The LWA was pre-wetted using an oscillating sprinkler on top of a retaining wall near the aggregate stockpile (shown in Figure 4.40). The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit. The sprinkler was turned off on the evening of November 25, 2020, letting the material drain for approximately 15 hours prior to batching. Upon KU researchers' requests, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching.

The average absorption and specific gravity (both OD basis) of the LWA obtained by KU researchers were 13.7% and 1.75, respectively, which differed from the values indicated in the original mixture proportions (14.3% and 1.65, respectively), which were used to determine the batch weights. Having a lower absorption than the design value resulted in a lower internal curing water content (6.7% by the weight of binder) than the design value (7% by the weight of binder).

Figure 4.40: KS-IC-LC-HPC-1 lightweight aggregate stockpile

A qualification slab was successfully placed on October 22, 2019 with KU and KDOT personnel in attendance to verify the concrete workability, pumpability, and finish ability. The LWA was shipped to the batch plant a day before the qualification placement, and it was stored in an open area at the batch plant. The LWA exhibited variable absorption values prior to wetting. The LWA was pre-wetted using an oscillating sprinkler for approximately 9 hours and allowed to drain for only two hours before batching. A single truck (with a capacity of 9.5 yd^3 [7.2 m^3]) was batched. The qualification slab was a garage ramp with dimensions of 7 ft-10 in. (2.4 m) by 20 ft-10 in. (6.3 m) with a variable depth between 7 in. (178 mm) and 13 in. (307 mm), as shown in Figure 4.41.

Figure 4.41: The qualification slab for KS-IC-LC-HPC-1 prior to placement

The mixture proportions included a ternary binder composition (a 30% replacement by weight of portland cement with slag cement and a 3% replacement by weight of portland cement with silica fume). The design paste content and the water-to-cementitious material (*w/cm*) ratio were 24.6% (by concrete volume) and 0.45, respectively. The design quantity of internal curing water was 7% (by the weight of binder). One test was performed for slump and air content after pumping at the job site. The concrete slump (4¾ in. [120 mm]) was within KDOT specifications (5 in. [125 mm]), but the air content (4.9%) was below the specified values (5 to 8%). The qualification slab was placed using a pump, consolidated using a single hand-held vibrator, and finished with a bullfloat. The application of curing was not observed by KU personnel. During the placement, no issues were observed, and KDOT approved the qualification slab.

The initial and actual (based on average of trip tickets) mixture proportions are listed in Table 4.40. KS-IC-LC-HPC-1 had a design *w/cm* ratio of 0.45 and a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement and a 3% replacement of cement (by total weight of binder) with silica fume, with a design paste content of 24.6%. The design quantity of internal curing water was 7% (by the weight of binder). Limestone (with two maximum aggregate sizes of ¾ and ½ in. [19 and 12.5 mm]) and river sand were used as coarse and fine aggregates, respectively.

Table 4.40: KS-IC-LC-HPC-1 mixture proportions (SSD/PSD basis)

Material		**Mixture proportions (lb/yd^3)**	
		Initial	**Actual[a]**
Cement (Type I/II)		355	355
Grade 100 slag cement		159	159
Silica Fume		16	16
Water		238	233
Fine lightweight aggregate		306	304
¾ in. Coarse aggregate		1193	1189
½ in. Coarse aggregate		286	290
Fine aggregate		1103	1101
Chemical Admixture (oz/cwt)			
Euclid	**Type**	**Initial**	**Actual[a]**
Eucon AEA 92S	Air-Entraining	0.5-2	0.45-0.6
Plastol 6420	Water-Reducing	2-10	4-5
Eucon Retarder 100	Set-Retarding	2-6	1.5

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

Based on the trip tickets, 4 lb/yd^3 (2 kg/m^3) of water was held from all the truckloads, except for the first three trucks, that had 8 lb/yd^3 (5 kg/m^3) withheld, reducing the actual *w/cm* ratio to an average of 0.44 for the full deck. Prior to casting, KU personnel measured a free-surface moisture of 2.6%, while a free-surface moisture of either 3.5 or 4% was determined and used by the batch plant personnel. This deviation decreased the mixing water and the *w/cm* by 3.5 lb/yd^3 and 0.006, respectively. Based on the trip tickets, individual paste contents ranged from 23.9 to 24.4%, with an average of 24.2% and the actual quantities of IC water ranged from 6.6 to 6.9%, with an average of 6.7% by total weight of binder. A superplasticizer was added to the trucks at dosage rates between 4 and 5 oz/cwt (2.6 and 3.3 mL/kg) to achieve the desired slump. A set-retarding admixture was added to the trucks at a constant dosage of 1.5 oz/cwt (1 mL/kg).

The concrete properties and compressive strengths are listed in Table 4.41. Four tests for slump, air content, and temperature were performed during construction, before pumping, and ten tests were performed after pumping. Before pumping, the slumps ranged from 4 to 6 in. (100 to 175 mm), with an average of 4¾ in. (120 mm), and the air contents ranged from 6.3 to 6.8%, with an average of 6.6%. After pumping, the slumps ranged from 4 to 7 in. (100 to 175 mm), with an average of 5 in. (125 mm), the air contents ranged from 5.5 to 7.6%, with an average of 6.3%, all within the deck specification limits (5 to 8%), and the concrete temperatures ranged from 66 to 70 °F (19 to 21 °C), with an average of 69 °F (20 °C), and the 28-day compressive strengths ranged from 5020 to 6180 psi (34.6 to 42.5 MPa), after pumping. The 28-day compressive strength for a single test performed before pumping was 6180 psi (42.6 MPa).

Table 4.41: Concrete test result-KS-IC-LC-HPC-1

KS-IC-LC-HPC-1	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	4	5.5	66	5020
Maximum	7	7.6	70	6170
Average	5	6.3	69	5660

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The KS-IC-LC-HPC-1 bridge deck location was approximately 20 minutes away from the batch plant. Placement started on November 26, 2019 at 6:30 am at the north end of the deck and continued to the south end, finishing with the final strikeoff at 3:30 pm. The concrete was placed using two pumps (one at the north end and the other near the south end), consolidated using a manually operated gang vibration system, including four hand vibrators mounted on a moveable frame followed by a spud vibrator near the edges of the deck, and finished using a double-drum roller screed followed by two metal pans and a burlap drag system mounted on a work bridge.

Figures 4.42 and 4.43 show the placement equipment used for the construction. The concrete was placed in strips about 5 ft (1.5 m) wide along the length of the deck.

(a) (b)

Figure 4.42: Placement equipment (a) Manually operated gang vibration system; (b) Double-drum roller screed followed by two metal pans

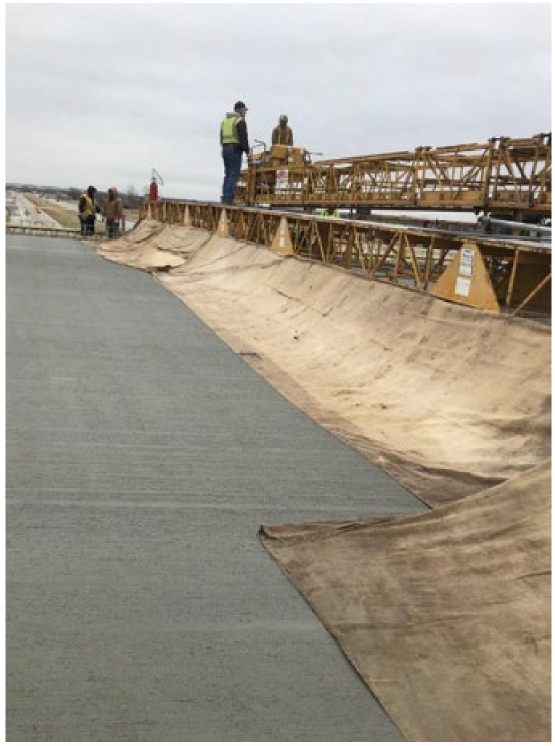


Figure 4.43: Burlap drag system

During placement, wind speeds at the deck ranged from 0.4 to 10 mph (1 to 16 km/hr). Relative humidity at the deck ranged between 58.0 and 78.5%. Ambient air temperature during construction ranged from 38 to 49 °F (3 to 9 °C). These environmental conditions resulted in evaporation rates, ranging from 0.04 to 0.16 lb/ft^2/hr (0.19 to 0.78 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit. To help reduce the evaporation rate near the surface, the contractor occasionally turned on a fogging system mounted on the backside of the finishing equipment. On one occasion, one of the pipes in the fogging system caused water droplets to accumulate on the surface, as shown in Figure 4.44. Contractor personnel were notified, and the issue was resolved.

Figure 4.44: Ponded water on the surface of the bridge deck

Delays in finishing occurred on three occasions. The northern pump became clogged after placing approximately 150 yd^3 (114.6 m^3) of concrete. The problem was resolved quickly after repairing the pump. A 35-minute delay occurred about halfway through placement (after placing 408 yd^3 [311.9 m^3]) due to equipment problems at the batch plant. During this delay, the double-roller screed passed several times over previously finished concrete. KU researchers notified the contractor, and the finishing equipment was turned off. Another delay occurred when changing the pumps (after placing 437 yd^3 [334.1 m^3] of concrete), leaving the concrete exposed to the environment for approximately 10 minutes. Crack surveys at an age of 30.9 months, discussed in Section 5.3.2.1, indicated the presence of cracks, near these locations, on either side of the piers.

The contractor accommodated all requests made by KU researchers regarding consolidation and finishing. Initially, the vibrators were quickly extracted from the concrete, leaving a series of holes on the surface and were not lifted high enough, causing the vibrators to drag across the surface. At the request of KU researchers, the contractor raised the vibrators and slowed down extraction of the vibrators. It should be noted, however, that the vibrators were lowered and lifted manually by two construction workers, and occasionally holes were left in the concrete, as shown in Figure 4.45.

(a) (b)

Figure 4.45: Holes left on the surface of the bridge deck. (a) overview; (b) close-up view

Occasionally, construction personnel were observed stepping in areas that had been recently vibrated, to shovel the concrete, causing deconsolidation of the concrete, as shown in Figure 4.46. Crack surveys at an age of 30.9 months, discussed in Section 5.3.2.1, however, did not indicate any cracks in these regions.

Figure 4.46: Walking through consolidated concrete

The time between batching and discharge ranged from 25 to 54 minutes, with an average of 40 minutes. The time between placement and strikeoff ranged from 8 to 33 minutes, with an average of 16 minutes. Bullfloats were used in the transverse direction on the deck; near the barriers, the concrete was tined with a broom, as shown in Figure 4.47. Shortly after bullfloating, wet burlap was placed on the bridge deck. The burlap rolls were soaked in water for at least 24 hours. Figure 4.48 shows the deck covered with wet burlap.

(a) (b)

Figure 4.47: Bullfloating and brooming (a) bullfloating the deck; (b) brooming

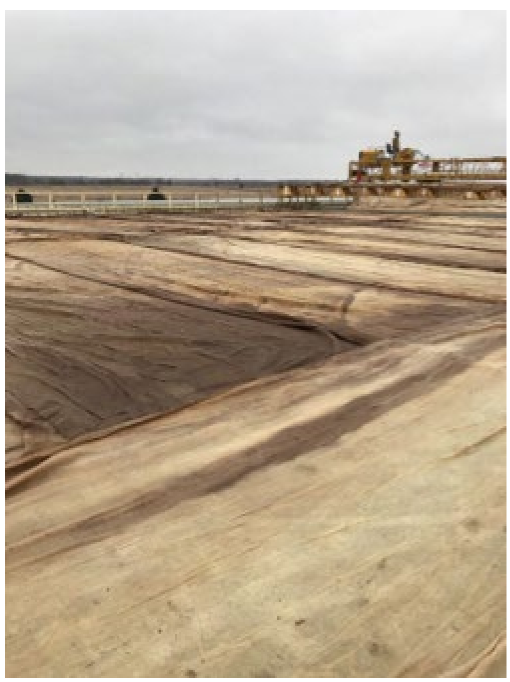


Figure 4.48: Burlap placement on the deck

4.7.2 KS- IC-LC-HPC-2

KS-IC-LC-HPC-2 is a two-lane bridge that carries traffic on Montana Rd over I-35 in Ottawa, Kansas. The deck was constructed in two placements. The first placement (KS- IC-LC-HPC-2-P1) was constructed on November 3, 2020, starting from the north end of the deck. Placement 1 was completed after placing approximately 120 yd^3 (91.7 m^3) of concrete on the deck. The remaining portion of the deck (KS- IC-LC-HPC-2-P2) was completed on November 11, 2020. Placement 1 has a length of 50 ft (15.2 mm), while Placement 2 has a length of 288 ft (87.8 mm). The concrete supplier and the contractor were Builders Choice Concrete and A. M. Cohron & Son, respectively. The bridge has four spans with lengths of 68 ft (20.7 m), 101 ft (30.8 m), 101 ft (30.8 m), and 68 ft (20.7 m), for a total length of 338 ft (103.0 m). The deck has a 40 ft (12.2 m) wide roadway and a 1 ft-3 in. (0.38 m) wide barrier on each side, for a total deck width of 42 ft-6 in. (12.9 m). The nominal deck thickness is 8½ in. (216 mm) with 9½-in. (241-mm) deep overhangs; the deck is supported by steel girders with a skew of 25º.

The fine lightweight aggregate (LWA) used in both placements was an expanded shale stored in an open area at the batch plant. The LWA was pre-wetted using a lawn sprinkler on top of the aggregate stockpile for at least three days prior to construction day. The stockpile was approximately 7 ft (2.1 m) high, greater than the recommended 5-ft (1.5-m) limit, as shown in Figure 4.49.

Figure 4.49: KS-IC-LC-HPC-2 lightweight aggregate stockpile

Two qualification batches were completed before the construction of the bridge deck. The first qualification batch was completed on June 4, 2020. The mixture contained a binary binder composition, a 30% replacement by weight of portland cement with slag cement. The design paste content and the water-cementitious material (*w/cm*) ratio were 24.2% (by concrete volume) and 0.43, respectively. The design quantity of internal curing water was 7% (by the weight of binder). The lightweight aggregate was pre-wetted for more than three days prior to batching, and the design absorption value was 14.1% (OD basis). On the day of batching, the average absorption (OD basis) and the free-surface moisture of the LWA obtained by KU and KDOT representatives were 16.8 and 4.3%, respectively, which differed from the values obtained by the concrete supplier (14.1 [given by the LWA producer] and 8.8%, respectively). With the KDOT approval, the mixture proportions were adjusted, and the concrete supplier batched the concrete averaging the two values (with values of 15.5 and 6.6%, respectively) for the LWA to get 7% of IC water by the weight of binder.

A single truckload with a 6 yd^3 (4.6 m^3) of concrete was batched, with 8 lb/yd^3 (5 kg/m^3) of water withheld in the truck. No pump was used during the first qualification batch and the concrete properties were measured out of the truck. Two tests for slump, air content, and temperature were performed. The first test had a slump and an air content of 3½ in. (90 mm) and 6%, respectively, with a concrete temperature of 87 °F (31 °C). To increase the slump, the supplier added back the withheld water (8 lb/yd^3 [5 kg/m^3]) and added a high-range water-reducing admixture with a dosage of 10.8 oz/yd^3 (417.7 mL/m^3). To increase the air content, the air-entraining admixture was increased from 5.5 to 6.5 oz/yd^3 (212.7 to 251.4 mL/m^3). The concrete was mixed for additional 10 minutes and tested again for the slump and air content. For the second test, the slump and air content of the concrete were 4¾ in. (145 mm) and 8%, respectively, with a concrete temperature of 88 °F (31 °C).

The second qualification batch was completed on October 13, 2020 at the batch plant with representatives of the contractor in attendance. A single truckload with a 2 yd^3 [1.5 m^3] of concrete was batched, with 17 lb/yd^3 (10 kg/m^3) of water withheld in the truck. The concrete properties (after pumping) after approximately 15 minutes of haul time were out of the specifications for air content (with a value of 6%, lower than the lower Kansas IC-LC-HPC specification limit of 6.5%) and slump (with a value of 6¾ in. [170 mm], well above the upper Kansas IC-LC-HPC specification limit of 5 in. [125 mm]). The concrete temperature was 77°F (25 °C). For the bridge deck construction, the concrete supplier was required to increase the air-entraining admixture dosage in concrete batches.

4.7.2.1 KS-IC-LC-HPC-2-P1

Placement 1 of the KS-IC-LC-HPC-2 was constructed on November 3, 2020. The LWA stockpile was pre-wetted for at least three days before batching. The sprinkler was turned off on the morning of November 2, 2020, letting the material drain for approximately 24 hours prior to batching. Upon KU researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free-surface moisture prior to batching. The average absorption (OD basis), the specific gravity (OD basis), and the free-surface moisture of the LWA obtained by KU and KDOT personnel were 15.5%, 1.85, and 1.25%, respectively.

The initial and actual (based on average of trip tickets) mixture proportions for the first placement of KS-IC-LC-HPC-2 are listed in Table 4.42. KS-IC-LC-HPC-2 had a design *w/cm* ratio of 0.43, a 30% replacement of cement (by total weight of binder) with Grade 100 slag cement, and a design paste content of 24.2%. The design quantity of internal curing water was 7% (by the weight of binder). Limestone and river sand were used as coarse and fine aggregates, respectively.

Based on the trip tickets, 17 lb/yd^3 (10 kg/m^3) of water was held from the first five truckloads, reducing the actual *w/cm* ratio to an average of 0.42. Prior to casting, KU and KDOT personnel measured a free-surface moisture of 1.25%, which was provided to the concrete supplier. For reasons that are not clear, the supplier used free-surface moisture values of 15 (in 11 batches), 20 (in two batches), or 24% (in one batch) to establish the batch weights. The large difference between the actual free-surface moisture and the values used to batch the concrete, resulted in a decrease in mixing water and *w/cm* to 42 lb/yd^3 (25 kg/m^3) and 0.08, respectively. Based on the trip tickets, individual paste contents ranged from 23.1 to 24.2%, with an average of 23.8% and the actual quantities of IC water ranged from 6.9 to 7.1%, with an average of 6.9% by total weight of binder. An air-entraining admixture was added at a varied dosage between 1.5 and 4 oz/cwt (1 and 2.6 mL/kg). A mid-range water-reducing and high-range water-reducing admixtures were added to all trucks at a constant dosage of 8 oz/cwt (5.2 mL/kg) and a varied dosage between 3 and 5 oz/cwt (2 and 3.3 mL/kg), respectively, to achieve the desired slump. A portion of the mixing water (either 30 or 40%) was replaced with hot water to control the concrete temperature.

Table 4.42: KS-IC-LC-HPC-2-P1 mixture proportions (SSD/PSD basis)

Material	Mixture proportions (lb/yd^3)		
	Initial	Revised	Actual[a]
Cement (Type I/II)	378	378	378
Grade 100 Slag cement	162	162	162
Water	232	232	225
Fine Lightweight Aggregate.	316	280	279
Coarse Aggregate.	1671	1683	1681
Fine Aggregate.	800	841	841
Chemical Admixture (oz/cwt)			
BASF	**Type**	**Initial**	**Actual [a]**
MB AE-90	Air-Entraining	1.1	1.5-4
Polyheed 900	Mid-Range Water-Reducing	5	8
Glenium 7500	High-Range Water-Reducing	2	3-5

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties are listed in Table 4.43. Seven tests for slump, air content, and temperature were performed before pumping; two tests were performed after pumping. The first truckload was rejected due to having out-of-specifications values for air content and slump, with the values of 4.2% and 1½ in. (40 mm), respectively, before pumping. Although the second truckload had a 4¼-in. (105-mm) slump, the air content (5.5%) was still lower than the minimum allowable limit stated in the specifications (6.5%). After redosing the admixtures, a second test was performed, and the air content and slump values increased to 9.9% and 10½ in. (260 mm), respectively. This load was placed in the north abutment. Because of the incorrect free-surface moisture used to develop the batch weights, the concrete supplier had difficulty producing concrete within the specifications throughout the placement. In an attempt to provide concrete with adequate workability, high-range water reducer and air-entraining admixtures were added at the job site to multiple truckloads. The fourth truckload was tested before and after pumping for slump and air content. For tests performed before pumping, the slumps ranged from 4 to 10½ in. (100 to 260 mm), with an average of 5¾ in. (145 mm). The air contents ranged from 6.8 to 9.9%, with an average of 8.6%, within the specifications. Concrete temperatures ranged from 60 to 68 °F (16 to 20 °C). For the two tests performed after pumping, the slumps were 3 and 3½ in. (75 to 90 mm), and the air contents were 8 and 6.2%. The 28-day compressive strengths ranged from 6870 to 7270 psi (47.4 to 48.7 MPa), before pumping.

Table 4.43: Concrete test results[a]-KS-IC-LC-HPC-2-P1

KS-IC-LC-HPC-2-P1	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	4	6.8	60	6870
Maximum	10½	9.9	68	7270
Average	5¾	8.6	64	7070

[a] Values measured before pumping
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The KS-IC-LC-HPC-2 bridge deck location was approximately 10 minutes away from the batch plant. Placement 1 started on November 3, 2020, at 9:10 am, at the north end of the deck and continued to the south end, and finished with the final strikeoff at 11:45 am. The concrete was placed using a pump positioned near the north end and consolidated using a machine-mounted gang vibration system, including two sets of four-hand vibrators spaced within 15 ft from each other, mounted on a moveable frame followed by a spud vibrator near the edges of the deck, and finished using a double-drum roller screed followed by one metal pan, as shown in Figure 4.50.

Figure 4.50: Consolidation and finishing equipment

During placement, wind speeds at the deck ranged from 0.5 to 1.4 mph (1 to 2km/hr). Relative humidity at the deck ranged between 38.5 and 50.5%. Ambient air temperature during construction ranged from 61 to 71 °F (16 to 22 °C). These environmental conditions resulted in evaporation rates, ranging from 0.02 to 0.04 lb/ft^2/hr (0.1 to 0.2 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

As mentioned earlier, the concrete supplier had difficulty producing concrete meeting the specifications throughout the placement, resulting in an increased time between batching and discharging concrete. The time between batching and discharge ranged from 69 to 90 minutes, with an average of 80 minutes. Similar to the construction of KS-IC-LC-HPC-1, construction personnel walked in areas that had been recently vibrated to shovel concrete, as shown in Figure 4.51, causing deconsolidation. As indicated in a number of studies, the loss of consolidation can lead to settlement that can lead to increased cracking (Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2020). As discussed in Section 5.3.2.2, no settlement cracking was observed on the deck through the first two years of crack surveys. The tendency to exhibit cracking over the long term, however, usually becomes apparent only after 36 months (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014)

Figure 4.51: Walking observed on freshly consolidated concrete

About an hour after construction started, the roller screed broke, resulting in an hour delay between placing and finishing the concrete. While the contractor was placing more concrete on the deck, the concrete was left unconsolidated and unprotected, as shown in Figure 4.52, with the contractor personnel observed walking on that. Crack surveys at an age of 19.7 months, discussed in Section 5.3.2.2, however, did not indicate any cracks in these regions. The time between placement and strikeoff ranged from 11 to 61 minutes, with an average of 33 minutes.

Figure 4.52: Concrete was left unconsolidated and unprotected due to inoperable roller screed

A highway straightedge was used in place of a bullfloat. Trowels were used for finishing the edges of the concrete adjacent to the barrier reinforcement on each side of the deck and near the abutments. Significant bleed water was observed on the deck, as indicated by the reflective water sheen in Figure 4.53. While waiting for bleed water to dissipate, construction workers bullfloated the deck repeatedly in an attempt to accelerate the evaporation of bleed water. As discussed later in Section 5.3.2.2, scaling damage was observed in multiple spots on the surface of the deck. Overfinishing the deck in the presence of bleed water, leads to a thin paste layer with a high *w/cm* at the concrete surface, which can result in scaling damage.

Figure 4.53: Overfinishing the deck in the presence of bleed water

When delivered to the jobsite, the burlap had not been soaked in water (Figure 4.54(a)). Contractor personnel wet the burlap at the job site using a water hose (Figure 4.54(b)), delaying its application. The time between strikeoff and curing application ranged from 57 to 70 minutes. The Kansas IC-LC-HPC specifications state that the burlap should be soaked in water for a minimum of 12 hours prior to placement on the deck. Crack surveys, discussed later in Section 5.3.2.2, indicated an area with surface damage approximately 15 ft [4.6 m] from the north abutment), possibly caused by the direct spraying of water by the contractor from a work bridge on the surface (Figure 4.54(b)) in an attempt to wet the burlap.

(a) (b)

Figure 4.54: Burlap placement of KS-IC-LC-HPC-2 (a) dry burlap; (b) wetting the burlap on the deck

Later, ponding was observed along the west edge of the deck, mainly due to the contractor spraying water to wet the burlap, as shown in Figure 4.55. Due to a number of issues observed during the first placement, it was decided to complete the construction of the deck in another placement (KS-IC-LC-HPC-2-P2). KU researchers and KDOT personnel discussed the issues that arose during the first placement. As a point of special interest, this contactor has, on many decks, repeatedly allowed its workers to walk through consolidated concrete, and those decks have cracked far more than others in Kansas, and using dry burlap, not only fails to meet the specifications, it will increase, rather than decrease cracking (Khajehdehi and Darwin 2018).

Figure 4.55: Ponding was observed on the deck

4.7.2.2 KS-IC-LC-HPC-2-P2

Placement 2 of the KS-IC-LC-HPC-2 was constructed on November 11, 2020. A new shipment of LWA was delivered to the batch plant. The LWA stockpile was approximately 8 ft (2.4 m) high; it was pre-wetted for at least three days before batching. The sprinkler was turned off on November 2, 2020 at noon, letting the material drain for approximately 21 hours prior to batching. A composite sample was obtained to measure the LWA absorption and free-surface moisture prior to batching. The average absorption (OD basis) and the free-surface moisture of the LWA obtained by KU and KDOT personnel were 15 and 1.5%, respectively. Due to obtaining similar absorption for LWA, no adjustments were made to the mixture proportions. In contrast to the first placement, the concrete supplier used the values provided by KU and KDOT for the value of the free-surface moisture.

The initial and actual (based on the average of trip tickets) mixture proportions for the second placement of KS-IC-LC-HPC-2 are listed in Table 4.44. Based on the trip tickets, individual *w/cm* ratios ranged from 0.40 to 0.43, with an average of 0.43, individual paste contents ranged from 23.1 to 24.2%, with an average of 24.1%, and the actual quantities of IC water ranged from 6.5 to 6.9%, with an average of 6.7% by total weight of binder. An air-entraining admixture was added at a dosage between 2.4 and 4 oz/cwt (1 and 3.3 mL/kg). A mid-range water-reducing and high-range water-reducing admixtures were added to all truckloads at a constant dosage of 8 oz/cwt (5.2 mL/kg) and a varied dosage between 3 oz/cwt and 4 oz/cwt (2 and 3.3 mL/kg), respectively. A portion of the mixing water (20 to 50%) was replaced with hot water to control the concrete temperature.

Table 4.44: KS-IC-LC-HPC-2-P2 mixture proportions (SSD/PSD basis)

<table>
<tr><th rowspan="2">Material</th><th colspan="3">Mixture proportions (lb/yd³)</th></tr>
<tr><th colspan="2">Initial</th><th>Actual[a]</th></tr>
<tr><td>Cement (Type I/II)</td><td colspan="2">378</td><td>378</td></tr>
<tr><td>Grade 100 Slag cement</td><td colspan="2">162</td><td>162</td></tr>
<tr><td>Water</td><td colspan="2">232</td><td>230</td></tr>
<tr><td>Fine Lightweight Aggregate.</td><td colspan="2">280</td><td>279</td></tr>
<tr><td>Coarse Aggregate.</td><td colspan="2">1683</td><td>1680</td></tr>
<tr><td>Fine Aggregate.</td><td colspan="2">841</td><td>840</td></tr>
<tr><th colspan="4">Chemical Admixture (oz/cwt)</th></tr>
<tr><th>BASF</th><th>Type</th><th>Initial</th><th>Actual[a]</th></tr>
<tr><td>MB AE-90</td><td>Air-Entraining</td><td>1.1</td><td>2.4-4</td></tr>
<tr><td>Polyheed 900</td><td>Mid-Range Water-Reducing</td><td>5</td><td>8</td></tr>
<tr><td>Glenium 7500</td><td>High-Range Water Reducing</td><td>2</td><td>3-4</td></tr>
</table>

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties are listed in Table 4.45. As with the first placement, the concrete supplier had difficulty producing concrete within the specifications throughout the placement, and the dosage rates of the high-range water reducer and air-entraining admixtures were increased at the job site in multiple truckloads. Twenty-five tests for slump, air content, and temperature were performed before pumping; seven tests were performed after pumping. The concrete supplier withheld 17 lb/yd^3 (10 kg/m^3) of water in the first truckload, resulting in a 2-in. (50-mm) slump after pumping. KDOT personnel asked the concrete supplier to add the entire mixing water, at the batch plant, in all trucks afterward before sending them to the job site. For tests performed before pumping, the slumps ranged from 4½ to 10¼ in. (115 to 260 mm), with an average of 7 in. (175 mm). The air contents ranged from 6.1 to 10%, with an average of 8%, within the specifications, and the concrete temperatures ranged from 54 to 72 °F (12 to 22 °C). For the seven tests performed after pumping, the slumps ranged from 2 to 7¼ in. (50 to 185 mm), with an average of 4¾ in. (120 mm), and the air contents ranged from 6.9 to 11%, with an average of 8.3%. Concrete temperatures ranged from 68 to 75 °F (20 to 24 °C). The 28-day compressive strengths ranged from 6700 to 7010 psi (46.2 to 48.3 MPa), before pumping.

Table 4.45: Concrete test results[a]-KS-IC-LC-HPC-2-P2

KS-IC-LC-HPC-2-P2	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	2	6.9	68	6700
Maximum	7¼	11	75	7010
Average	4¾	8.3	71	6850

[a] Values measured after pumping
Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

Placement 2 started on November 11, 2020, at 9:16 am and finished with the final strikeoff at 5:35 pm. The concrete was placed using three pumps (the first pump was positioned near the north end, the second pump was located below the bridge, between the second and third spans, and the third pump was placed near the south end of the bridge). The concrete was consolidated and finished using the same equipment employed for constructing the first placement.

During placement, wind speeds at the deck ranged from 0 to 0.7 mph (0 to 1 km/hr). Relative humidity at the deck ranged between 31.7 and 53.6%. Ambient air temperature during construction ranged from 40 to 67 °F (4 to 19 °C). These environmental conditions resulted in evaporation rates, ranging from 0.02 to 0.04 lb/ft^2/hr (0.1 to 0.2 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

Similar to the construction of KS-IC-LC-HPC-2-P1, construction personnel walked in areas that had been recently vibrated to shovel concrete, as shown in Figure 4.56, causing deconsolidation of the concrete. This occurred, however, only at the beginning of this placement. Crack surveys at an age of 19.7 months, discussed in Section 5.3.2.2, however, did not indicate any cracks in these regions. The time between placement and strike-off ranged from 15 to 55 minutes, with an average of 38 minutes.

Figure 4.56: Walking observed on freshly consolidated concrete

One hour after beginning of the placement, one of the two sets of the gang vibrators failed due to hydraulic issues, and therefore, contractor personnel had to manually push the machine-mounted gang vibrators into the concrete, as shown in Figure 4.57. The hydraulic issues were fixed within 15 minutes, and the consolidation resumed with both sets of gang vibrators.

Figure 4.57: Malfunctioning of the machine-mounted gang vibrators

According to Kansas IC-LC-HPC specifications, no finishing aids are permitted. In spite of this, the contractor applied a finishing aid on the concrete for the entire deck, as shown in Figure 4.58. The use of the finishing aid increases the *w/cm* ratio at the surface, which may also contribute to increased scaling (Section 5.3.2.2). This shortcoming was pointed out to the contracted (non-KDOT) inspector who said that this was “not a big deal at this point.”

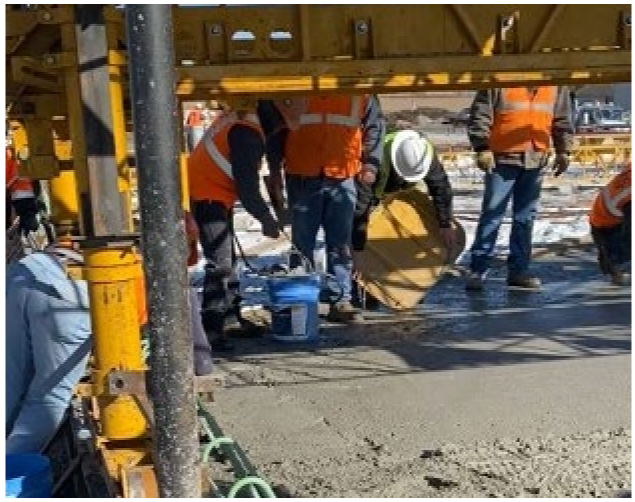


Figure 4.58: Applying finishing aid to the concrete surface

A fogging system was mounted on the backside of the finishing equipment. On one occasion, one of the pipes in the fogging system deposited water droplets on the concrete surface, as shown in Figure 4.59. Contractor personnel were notified about this incident, which was then resolved.

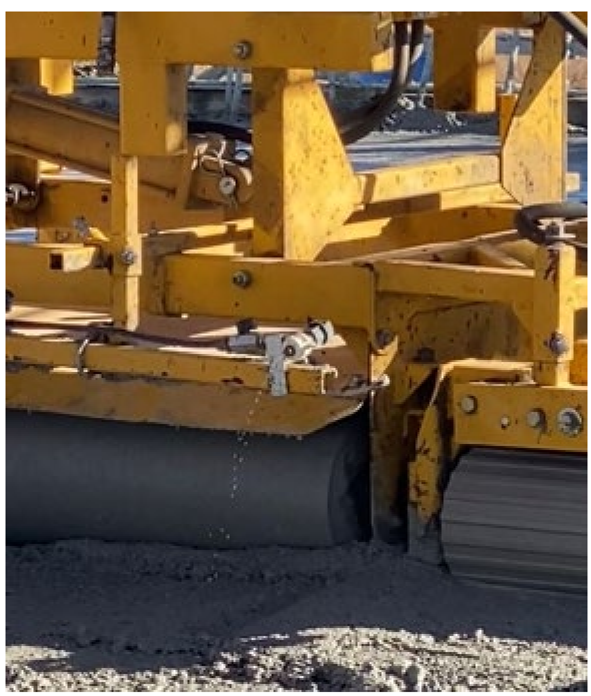


Figure 4.59: Malfunctioning of the fogging system mounted on the finishing machine

A highway straight edge was used in place of a bullfloat. Trowels were used for finishing the edges of the concrete adjacent to the barrier reinforcement on each side of the deck and near abutments. Significant bleed water was observed on the deck, as indicated by the reflective water sheen shown in Figure 4.60. As observed for the first placement, contractor personnel worked the excess water back into the concrete surface. Some scaling damage was observed in these regions (Section 5.3.2.2).

(a) (b)

Figure 4.60: Overfinishing the deck in the presence of bleed water (a) overview; (b) close-up view

As with the KS-IC-LC-HPC-2-P1, contractor personnel wet the burlap at the job site using a water hose, delaying its application. The time between strikeoff and curing application ranged from 18 to 152 minutes, with an average of 88 minutes. According to the Kansas IC-LC-HPC specifications, two layers of wet burlap should be applied on the deck, one within 15 and another within 10 minutes of strikeoff by the screed.

4.7.3 KS- IC-LC-HPC-3

KS-IC-LC-HPC-3 is a two-lane bridge that carries traffic on 199th St. over I-35 in Edgerton, Kansas. The deck was constructed in one placement on September 16, 2021. The concrete supplier and the contractor were Fordyce and Pyramid Contractors, respectively. The bridge has four spans with lengths of 125 ft (38.1 m), 180 ft (54.9 m), 180 ft (54.9 m), and 125 ft (38.1 m) for a total length of 610 ft (186 m). The deck has a 41 ft (12.5 m) wide roadway and a 1 ft (0.3 m) wide barrier on each side of the deck, for a total deck width of 43 in. (13.1 m). The nominal deck thickness is 8½ in. (216 mm) with 9½-in. (241-mm) thick overhangs; the deck is supported by steel girders with a skew of -55º8’20”.

The LWA used in KS-IC-LC-HPC-3 was an expanded clay stored in an open area at the batch plant. The LWA was pre-wetted using an oscillating sprinkler on top of the aggregate stockpile (shown in Figure 4.61). The stockpile was approximately 8 ft (2.4 m) high, greater than the recommended 5-ft (1.5-m) limit.

Figure 4.61: KS-IC-LC-HPC-3 lightweight aggregate stockpile

A qualification slab was placed on May 5, 2020, with KU and KDOT personnel in attendance to verify the concrete workability, pumpability, and finish ability. The LWA was shipped a few weeks before the qualification placement, and it was stored in an open area at the batch plant. The LWA was pre-wetted using an oscillating sprinkler for three weeks, but it was allowed to drain for only two hours before batching. The absorption of the lightweight aggregate measured by KU and KDOT personnel was 40% (OD basis, on average), higher than the design value (30%, OD basis). Longer pre-wetting of the materials and failure to stop sprinkling the stockpile (24 hours before batching) are the probable reasons for the higher value. No adjustments were made to the mixture proportions based on the differences in the lightweight aggregate properties from those used in the original design and batched for the qualification slab. Having a higher absorption than indicated has the potential of holding excess water with the way moisture corrections are made and can lead to pumping issues and a higher than intended amount of internal curing water (8.1 instead of 7%). The concrete supplier, however, used the value obtained by KU and KDOT for the free-surface moisture (7%) of LWA.

A single truck (with a capacity of 7.5 yd^3 [5.7 m^3]) was batched. The qualification slab was located near an Ace Hardware store in Gardner, Kansas. The slab had dimensions of 33 ft (10.0 m) by 26 ft (7.9 m) with a depth of 6 in. (152 mm), as shown in Figure 4.62.

Figure 4.62: The qualification slab for KS-IC-LC-HPC-3

The mixture had a ternary binder composition (a 30% replacement by weight of binder with slag cement and a 2% replacement by weight of binder with silica fume). The design paste content and the water-to-cementitious material (*w/cm*) ratio were 24.4% (by concrete volume) and 0.45, respectively. The design quantity of internal curing water was 7% (by the weight of binder). The concrete properties were tested before and after pumping at the job site. The air content and slump were 7% and 6½ in. (165 mm), respectively, before pumping. After adding 4 oz/yd^3 (155 mL/m^3) of air-entraining admixture, the air content measured after pumping was 7.9%. Concrete and ambient temperatures were 65 and 59 °F (18 and 15 °C), respectively.

The concrete was placed using a pump, consolidated using a single hand-held vibrator, and finished by a single-drum roller screed, as shown in Figure 4.63. Application of curing was not observed. No issues were observed, and KDOT approved the qualification placement.

Figure 4.63: The qualification slab placement equipment

The sprinkler was turned off on the evening of September 15, 2021, letting the material drain approximately 9 hours prior to batching. Upon KU and KDOT researchers' request, the LWA stockpile was turned several times before collecting a composite sample to measure the LWA absorption and free surface moisture prior to batching. The absorption of the lightweight aggregate measured by KU and KDOT personnel was 43% (OD basis, on average), higher than the design value (30%, OD basis). No adjustments, however, were made to the mixture proportions based on the differences in lightweight aggregate properties from those used in the original mixture proportions, which resulted in 8.5% of IC water (an average rather) than the design value of 7%.

The initial and actual (based on the average of trip tickets) mixture proportions used for KS-IC-LC-HPC-3 are listed in Table 4.46. Limestone (with two maximum aggregate sizes of ¾ and ½ in. [19 and 12.5 mm]) and river sand were used as coarse and fine aggregates, respectively. There were 87 trucks used for the placements. Each truck contained 10 yd^3 (7.6 m^3) of concrete.

Based on the trip tickets, 4 lb/yd^3 (2 kg/m^3) of water was held from all truckloads, reducing the actual *w/cm* ratio to an average of 0.44. Prior to casting, KU and KDOT personnel measured a free-surface moisture of 5% (on average), which was used initially (in 34 truckloads) by the concrete supplier. The concrete supplier, however, stepped down the free-surface moisture used for calculating batch weights from 5 to 0% throughout the placement. Based on the trip tickets, individual paste contents ranged from 22.0 to 24.8%, with an average of 24.0%, and the actual quantities of IC water ranged from 8.3 to 9.5%, with an average of 8.5% by total weight of binder. A water-reducing admixture was added to the trucks at dosages between 3 and 3.5 oz/cwt (1.9 and 2.3 mL/kg) to achieve the desired slump. Due to high air temperatures during the construction (between 64 and 96 °F [18 and 36 °C]), the concrete supplier used chilled water and ice to control the concrete temperature. KDOT inspectors also had difficulty tracking the amount of water in the trucks, and believed that the concrete supplier did not account for the addition of ice as part of the mixing water, which resulted in higher *w/cm* ratios (between 0.47 to 0.56) and lower compressive strengths than intended.

Table 4.46: KS-IC-LC-HPC-3 mixture proportions (SSD/PSD basis)

Material		Mixture proportions (lb/yd^3)	
		Initial	Actual[a]
Cement (Type I/II)		361	360
Grade 100 slag cement		159	159
Silica Fume		10	10
Water		238	231
Fine lightweight aggregate		161	162
¾ in. Coarse aggregate		1299	1304
½ in. Coarse aggregate		272	278
Fine aggregate		1098	1097
Chemical Admixture (oz/cwt)			
Euclid	**Type**	**Initial**	**Actual[a]**
Eucod AEA 92S	Air-Entraining	0.5	0.6-1.1
Plastol 6420	Water-Reducing	4.5	3-3.5

[a] Actual values based on average of trip tickets
Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The concrete properties and compressive strengths are listed in Table 4.47. Seventeen tests for slump, air content, and temperature were performed during construction, all after pumping. Two trucks experienced overtime and were rejected. The slumps ranged from 5 to 9 in. (125 to 230 mm), with an average of 5¾ in. (125 mm). The air contents ranged from 6.2 to 8.8%, with an average of 7%, within the specifications. Concrete temperatures ranged from 71 to 81 °F (22 to 27 °C), with an average of 76 °F (24 °C) and 28-day compressive strengths ranged from 3150 to 3990 psi (21.7 to 27.5 MPa), after pumping. This was the only deck in Kansas with a 28-day compressive strength below 5000 psi. The low strength was likely the result of not accounting for the ice added to the mixture.

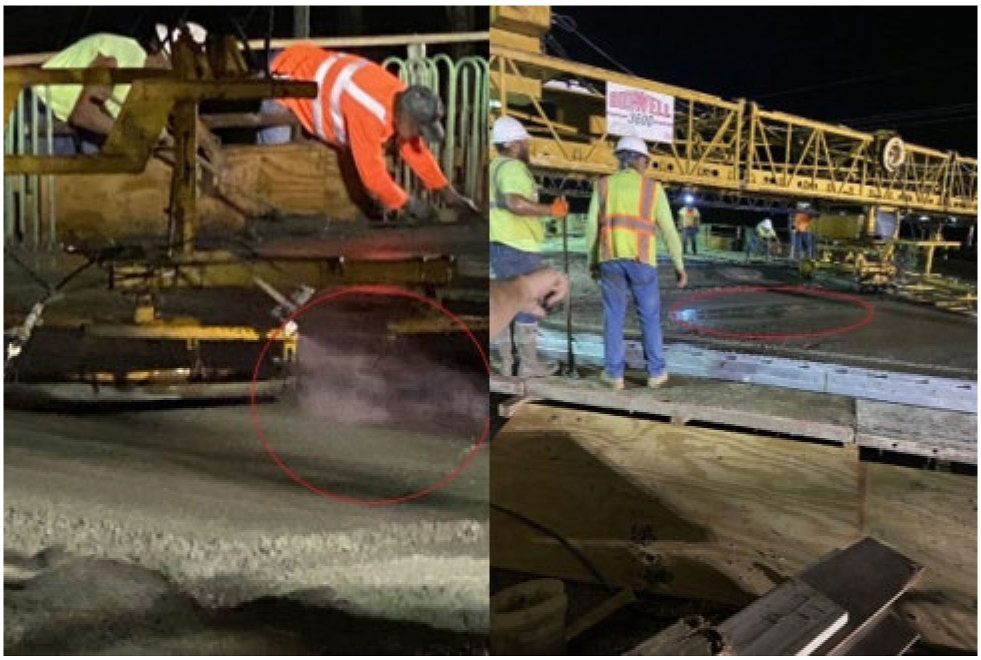
Table 4.47: Concrete test results-KS-IC-LC-HPC-3

KS-IC-LC-HPC-3	Slump (in.)	Air content (%)	Concrete temperature (°F)	28-day compressive strength (psi)
Minimum	5	6.2	71	3150
Maximum	9	8.8	81	3990
Average	5¾	7	76	3570

Note: 1 in. = 25.4 mm; °C = (°F-32)×5/9; 1 psi = 6.89×10^{-3} MPa

The KS-IC-LC-HPC-3 bridge deck location was approximately 15 minutes away from the batch plant. Placement started on September 16, 2021 at 3:10 am, at the east end of the deck, continued to the west end, and finished with final strikeoff at 5:00 am. The concrete was placed using three pumps (the first pump was positioned near the east end, the second pump was located below the bridge, between the second and third spans, and the third pump was placed near the west end of the bridge), consolidated using a manually operated gang vibration system, including four hand vibrators mounted on a moveable frame followed by a spud vibrator near the edges of the deck, and finished using a double-drum roller screed followed by two metal pans and a burlap drag system mounted on a work bridge.

During placement, wind speeds at the deck ranged from 0.2 to 3.2 mph (0.3 to 5.1 km/hr). Relative humidity at the deck ranged between 44.9 and 83.7%. Ambient air temperature during construction ranged from 64 to 96 °F (18 to 36 °C). These environmental conditions resulted in evaporation rates, ranging from 0.02 to 0.04 lb/ft^2/hr (0.1 to 0.2 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit. To help reduce the evaporation rate near the surface, the contractor occasionally turned on a fogging system mounted on the backside of the finishing equipment. On one occasion, shortly after concrete placement started, the fogging system sprayed the mist directly into the concrete surface, causing excessive water to deposit on the deck surface, as shown in Figure 4.64. Contractor personnel were notified about this incident, and the direction of the nozzles was corrected. Approximately 40 ft (12.1 m) from the east end of the deck, one of the pipes in the fogging system again caused water droplets to accumulate on the surface, as shown in Figure 4.65. The droplets were worked back into the concrete surface as the metal pans passed over it, increasing a layer of excess paste on the surface. After this incident, KDOT personnel directed the contractor to turn off the fogging equipment for the rest of the construction.



(a) (b)

Figure 4.64: Excessive water on the deck (a) not adjusted nozzles; (b) ponded water on the surface

Figure 4.65: A leaking pipe leaving water droplets on the deck surface

According to Kansas IC-LC-HPC specifications, no finishing aids are permitted. In spite of this, the contractor applied a finishing aid on the concrete for the first 50 ft (15.2 m) at the east end, as shown in Figure 4.66. The use of the finishing aid increases the *w/cm* ratio at the surface, which may also contribute to increased scaling (Section 5.3.2.3). Use of the finishing aid was stopped after the problem was pointed out to KDOT and contractor personnel.

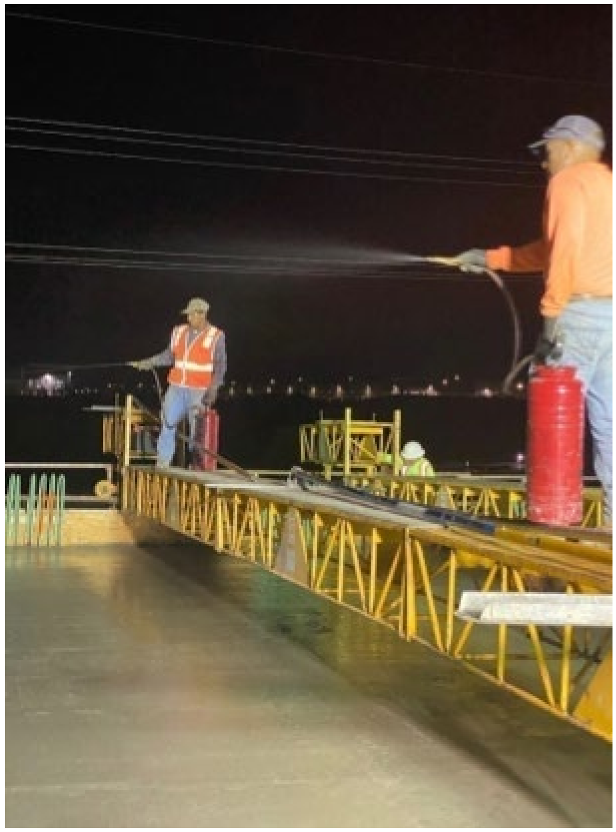


Figure 4.66: Applying finishing aid to the concrete surface

A 65-minute delay occurred about 100 ft (30.5 m) from the west end of the deck due to equipment problems. The time between placement and strikeoff ranged from 3 to 65 minutes, with an average of 18 minutes.

At first, it was observed that the contractor was bullfloating the deck in the longitudinal direction. KU researcher asked the contractor to bullfloat in the transverse direction to prevent delays in the application of curing. Also, as indicated by the reflective water in Figure 4.67, a bullfloat was repeatedly used in the longitudinal direction while the excess water was visible on the surface. Crack surveys, discussed later in Section 5.3.2.3, showed a number of cracks and scaling damage, mainly at these locations (spans 3 and 4).

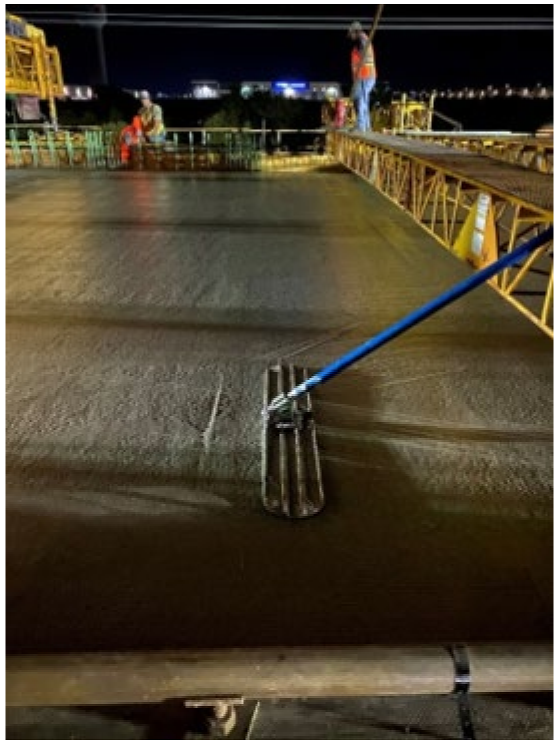


Figure 4.67: Bullfloating in the longitudinal direction along with sheen water on the surface

A single layer of wet burlap was placed within 15 minutes of bullfloating. The burlap rolls were soaked for at least 24 hours prior to construction. Later during construction, as the temperature began to rise, it was observed that the burlap on some portions of the deck had dried. It was asked to rewet the burlap by sprinkling it with a garden hose, as shown in Figure 4.68. It was, however, observed that some portions of the deck had not been wet completely. The time between strikeoff and curing application ranged from 14 to 75 minutes, with an average of 37 minutes.

Figure 4.68: Rewetting the burlap on the deck

CHAPTER 5 – EVALUATION OF CRACKING PERFORMANCE OF INTERNALLY CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE (IC-LC-HPC) AND CONTROL BRIDGE DECKS

5.1 GENERAL

This chapter evaluates cracking performance of internally-cured low-cracking high-performance concrete (IC-LC-HPC) and associated Control decks constructed in Minnesota and Kansas. The construction procedures of these decks are described in Chapter 4. Annual crack surveys were performed on the bridge decks between 2017 and 2022 to evaluate cracking in terms of crack density (expressed in m/m^2). This chapter describes the crack survey methods, discusses crack survey results, and presents the crack maps showing crack distribution, crack density, as well as bridge deck information for the most recent crack surveys of each deck. The cracking performance of IC-LC-HPC decks is compared with survey data obtained from previous studies, including LC-HPC decks and paired control decks in Kansas and a number of IC and control decks in Utah and Indiana. Crack maps from previous surveys in Minnesota are included in Appendix G. Factors that affect bridge deck cracking are discussed in Chapter 6.

5.2 CRACK SURVEY METHOD

The crack surveys were performed using a standardized procedure that enables survey crews to provide consistent results (Lindquist et al. 2005, 2008, Pendergrass and Darwin 2014). The crack survey procedure is summarized next. The full bridge deck survey specifications are provided in Appendix H.

5.2.1 Crack Survey Procedure

Crack surveys are conducted on a day with a minimum air temperature of 60 °F (16 °C), with weather that is mostly sunny. Crack surveys are only conducted when the bridge deck surface is completely dry. No surveys are permitted on a wet surface. Crack survey results obtained under conditions that don't meet these requirements are invalid.

A plan view of the deck for drawing the crack map, with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) and a 10 × 10 ft (3.1 × 3.1 m) grid, is prepared before conducting the cracking survey. To establish the scaled length and location of the cracks, a 5 ft × 5 ft (1.5 m × 1.5 m) grid with a scale of 1 in. = 10 ft (25.4 mm = 3.1 m) is printed separately and is placed underneath the crack map. The grid should be aligned so that the grid points spaced at 5 ft × 5 ft (1.5 m × 1.5 m) match the grid lines on the crack map. The crack map also indicates the north compass direction to further assist the crack survey crews.

State department of transportation (DOT) crews provide traffic control by closing at least one lane to traffic. The surveyors start marking the grids on the deck at 40-ft (12.1-m) increments in the longitudinal and 5-ft (1.5 m) increments in the transverse directions using sidewalk chalk corresponding with the scaled crack map. The surveyors then only mark cracks with sidewalk chalk that are visible when bending at the waist to waist height as they walk over the deck. Once a crack is observed, surveyors are allowed to bend closer to the deck to complete marking the crack. Once a crack is marked, surveyors must resume the identification of cracks that are only visible from waist height. Each portion of the deck is surveyed by at least two surveyors. The cracks marked on the bridge deck are transferred to the crack map, using the 5 ft × 5 ft (1.5 m × 1.5 m) grid map. The hand-drawn map is used to calculate the crack density of the bridge deck.

To calculate crack density, the hand-drawn map is scanned and converted into an AutoCAD file, and the crack lengths are measured using the built-in AutoCAD command, Data Extraction. The output is an Excel file in a CAD output folder showing the measured crack lengths of the individual cracks (in AutoCAD units). The summation of these measurements is the total crack length in AutoCAD units. Two scaling factors are defined to convert the AutoCAD unit measurements. One scaling factor is defined as the ratio between the actual bridge length and the length of the bridge drawn in AutoCAD (measured after scanning the hand-drawn crack map into AutoCAD). Similarly, the second scaling factor is defined as the ratio between the actual bridge width and the width of the bridge in AutoCAD. The average of these two scaling factors is used for the calculations. The actual crack lengths are obtained by multiplying the crack lengths in AutoCAD units by the average scaling factor. It is important to note that because of the scaling factor, the cracks shown on the crack map images in this report can be deceiving in terms of the length of the crack. The images shown in this report range in size from $^{1}/_{4}$ to $^{3}/_{8}$ of the crack survey maps and from $^{1}/_{480}$ to $^{1}/_{320}$ of the bridge decks. This difference in scale can be deceiving. As will be demonstrated, for example in Figure 5.11, cracks that are just $^{1}/_{16}$ in. (1.6 mm) long in the images represent cracks that are 2.4 ft (0.7 m) long on the bridge deck. The crack density is calculated by dividing the crack length by the deck area and reported in m/m^2.

5.2.2 Crack Width

A number of randomly selected cracks from the bridge deck are measured for crack width. Cracks are selected so as to be representative based on length (short or long), orientation (transverse, parallel, or diagonal to traffic), and shape (straight or nonlinear). The width of cracks generally increases along with crack density. The widest point of the crack is measured and reported as the crack width. A bank card-sized crack width comparator, with an accuracy of 0.001 in. (0.03 mm), is used for the measurements.

5.3 CRACK SURVEYS AND RESULTS

The cracking performance of the 11 bridge decks in Minnesota (nine IC-LC-HPC and two Control decks) and three IC-LC-HPC bridge decks in Kansas surveyed in this study is described in this Section.

5.3.1 Minnesota Bridge Deck Crack Survey Results

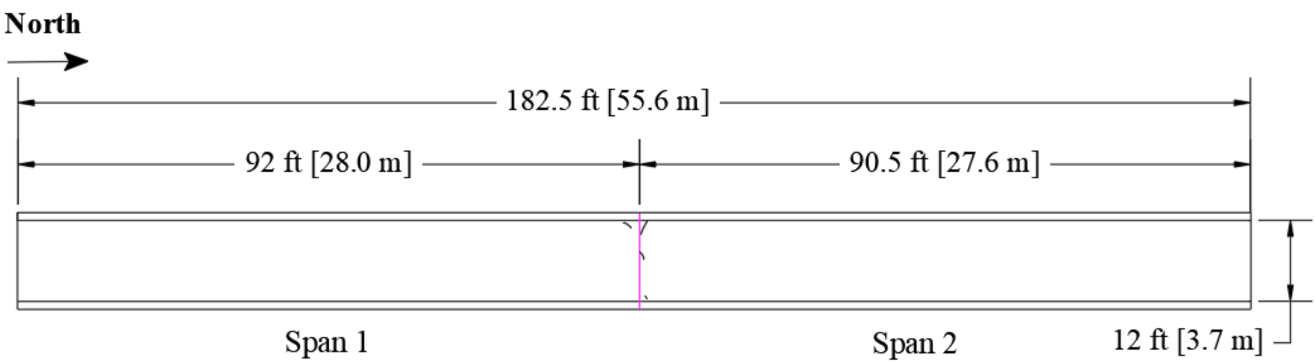
Crack surveys on two pedestrian bridge decks constructed in 2016, MN-IC-LC-HPC-1 and MN-Control-1, were performed in June 2017 (approximately 9 months after construction), May 2018 (approximately 19 months after construction), June 2019 (approximately 32 months after construction), June 2020 (approximately 45 months after construction), June 2021 (approximately 57 months after construction), and May 2022 (approximately 68 months after construction). Crack surveys on the three bridge decks constructed in 2017 (MN-IC-LC-HPC-2, MN-IC-LC-HPC-3, and MN-Control-2), which contain a 2-in. (50-mm) overlay, were performed in May 2018 (8 to 10 months after construction of the subdecks), June 2019 (21 to 23 months after construction of the subdecks), and July 2020 (34 to 37 months after construction of the subdecks). Crack surveys on one bridge deck constructed in 2018, MN-IC-LC-HPC-4, were performed in September 2019 (approximately 16 months after construction), June 2021 (approximately 37 months after construction), and May 2022 (approximately 48 months after construction). Crack surveys on two bridge decks constructed in 2019, MN-IC-LC-HPC-5 (a pedestrian bridge) and MN-IC-LC-HPC-6, were performed in June and August 2020, respectively (approximately 11 months after construction), June 2021 (21 to 23 months after construction), and May 2022 (32 to 34 months after construction). Crack surveys on three bridge decks constructed in 2020, MN-IC-LC-HPC-7, MN-IC-LC-HPC-8, and MN-IC-LC-HPC-9, were performed in June 2021 (9 to 12 months after construction) and May 2022 (20 to 23 months after construction).

5.3.1.1 MN-IC-LC-HPC-1

MN-IC-LC-HPC-1 is a pedestrian bridge deck located at Mackubin St. over I-94 in St. Paul. The deck was constructed in one placement on September 22, 2016. This deck has been surveyed six times (Surveys 1 to 6), exhibiting very low crack densities (below 0.02 m/m^2). Survey 1 was performed at a deck age of 9.2 months with a crack density of 0.013 m/m^2. The crack density remained relatively constant between the second and fourth years after construction, with a crack density of 0.007 m/m^2, with cracks observed only over the center pier during the first five years after the construction, as shown in Figure 5.1. Some scaling damage and a decrease in the crack density to zero was observed during Survey 6. This decrease in cracking may be the result of a reduction in the camber of the prestressed concrete girders and concrete creep. The most recent crack maps (Surveys 4, 5, and 6 performed at deck ages of 45.0, 56.8, and 68.0 months, respectively) are shown in Figures 5.2 to 5.4. Additional details associated with Surveys 1 to 3 of MN-IC-LC-HPC-1 are documented by Lafikes et al. (2020). The average crack width decreased from 0.004 in. (0.10 mm) for Survey 1 to 0.002 in. (0.05 mm) for Survey 5, and eventually, to 0.000 in. (0.00 mm) for Survey 6.

(a) (b)

Figure 5.1: Comparison of the center pier of MN-IC-LC-HPC-1 (a) from Survey 5; (b) from Survey 6

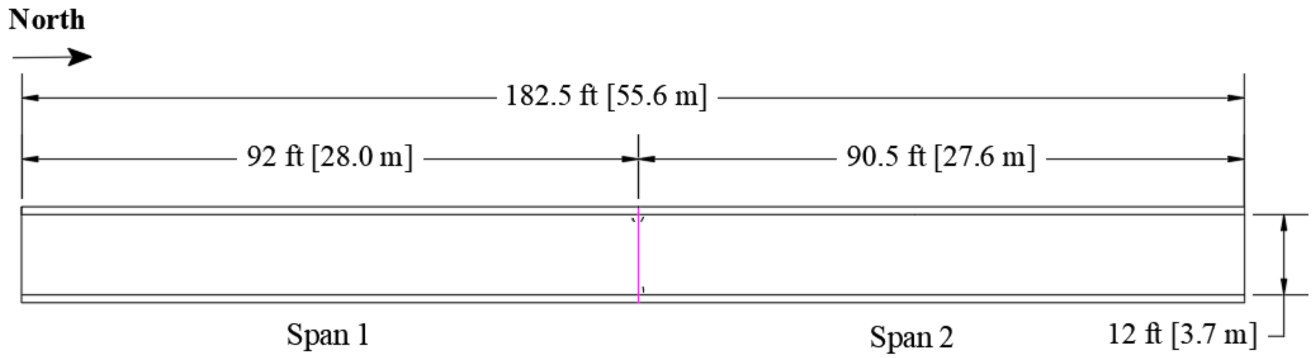


Bridge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94, St. Paul, MN
Construction Date: 9/22/2016
Crack Survey Date: 6/22/2020

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 45.0 months
Crack Density: 0.007 m/m^2
Span 1: 0.004 m/m^2
Span 2: 0.011 m/m^2

Figure 5.2: Crack map for MN-IC-LC-HPC-1 (Survey 4)

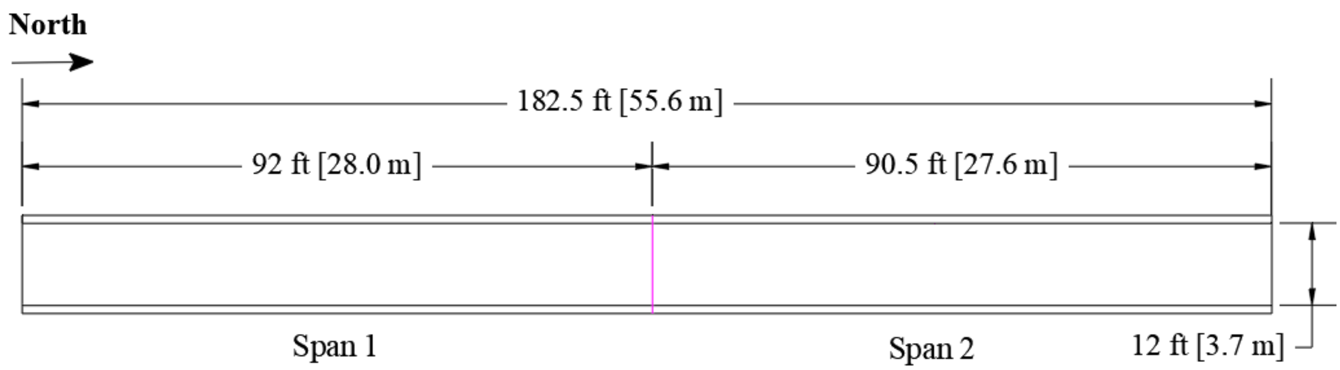


Bridge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94, St. Paul, MN
Construction Date: 9/22/2016
Crack Survey Date: 6/14/2021

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 56.8 months
Crack Density: 0.003 m/m^2
Span 1: 0.002 m/m^2
Span 2: 0.004 m/m^2

Figure 5.3: Crack map for MN-IC-LC-HPC-1 (Survey 5)



Bridge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94, St. Paul, MN
Construction Date: 9/22/2016
Crack Survey Date: 5/23/2022

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 68.0 months
Crack Density: 0.000 m/m^2
Span 1: 0.000 m/m^2
Span 2: 0.000 m/m^2

Figure 5.4: Crack map for MN-IC-LC-HPC-1 (Survey 6)

5.3.1.2 MN-Control-1

The associated control deck for MN-IC-LC-HPC-1, MN-Control-1, is a pedestrian bridge deck located at Grotto St. over I-94 in St. Paul. The deck was constructed in one placement on September 28, 2016. This deck has been surveyed six times, exhibiting low crack densities (below 0.05 m/m^2). MN-Control-1, in general, exhibited higher crack densities than MN-IC-LC-HPC-1 ages. The cracks were only observed near the contraction joint of the center pier, with crack lengths somewhat longer than MN-IC-LC-HPC-1. Survey 1 was performed at a deck age of 9 months with a crack density of 0.034 m/m^2. As with MN-IC-LC-HPC-1, the deck exhibited decreased crack densities within the six years after the construction. The deck had crack densities of 0.032, 0.029, 0.027, and 0.024 m/m^2 for Surveys 2, 3, 4, and 5, respectively; and 0.021 m/m^2 for Survey 6, with crack widths ranging from 0.013 to 0.020 in. (0.33 to 0.51 mm), with an average of 0.016 in. (0.41 mm). The specifications for high-performance concrete (HPC) followed in the construction of MN-Control decks in Minnesota are distinguished from those used in construction of Control decks in Kansas. MN-Control subdecks in this study contained a binary cementitious system with a 25 or 35% replacement of cement (by total weight of binder) with Class F fly ash and paste contents of only 26.7 or 26.9%, while Kansas Control subdecks had either portland cement as the only binder with paste contents between 25.6 and 27.1% (both low) or a 20% replacement of cement (by total weight of binder) with Class F fly ash, with a paste content of 29% (high). The effects of paste content on the cracking performance of bridge decks have been addressed in numerous studies (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2020, Khajehdehi et al. 2021). Schmitt and Darwin (1999) observed that concrete decks with a cement paste content greater than 27% (by concrete volume) exhibited significantly greater cracking compared to decks with lower paste contents. As a result, crack densities of MN-Control-1 (with a low paste content) are expected to be lower than that of the Kansas Control decks with higher paste contents. The most recent crack maps (Surveys 4, 5, and 6 performed at a deck age of 44.8, 56.6, and 67.9 months, respectively) are shown in Figures 5.5 to 5.7. Additional details associated with Surveys 1 to 3 of MN-Control-1 are documented by Lafikes et al. (2020).

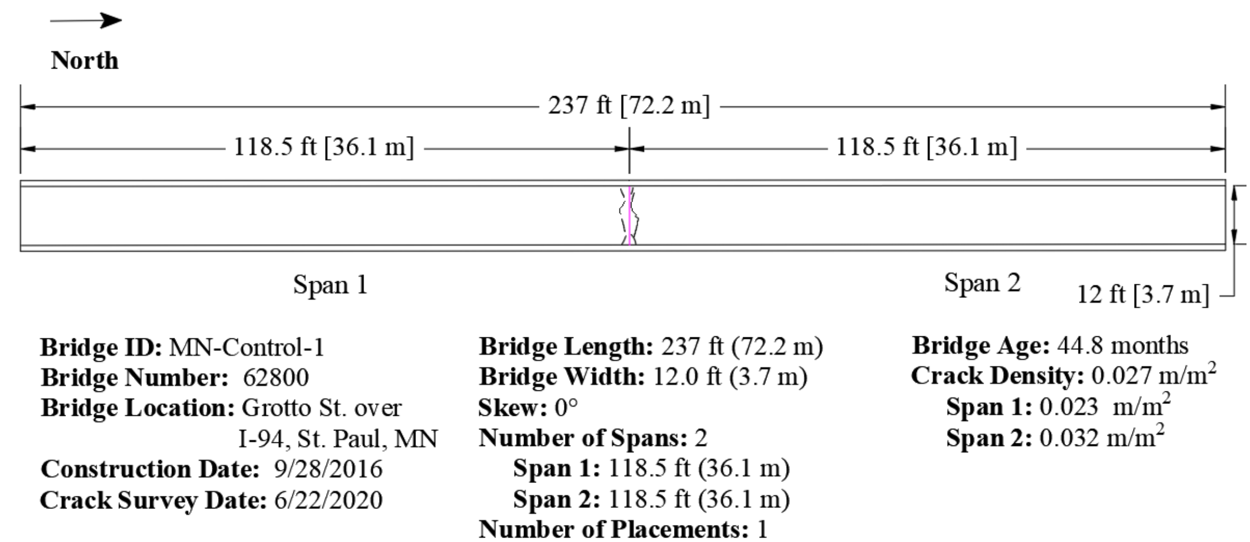


Figure 5.5: Crack map for MN-Control-1 (Survey 4)

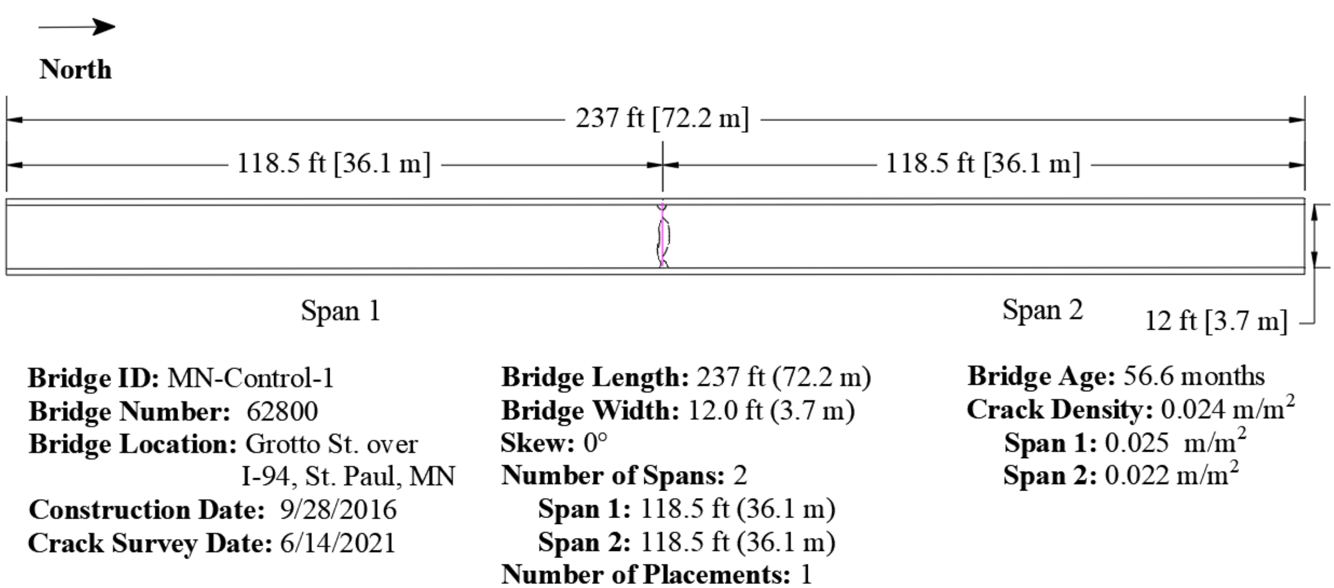
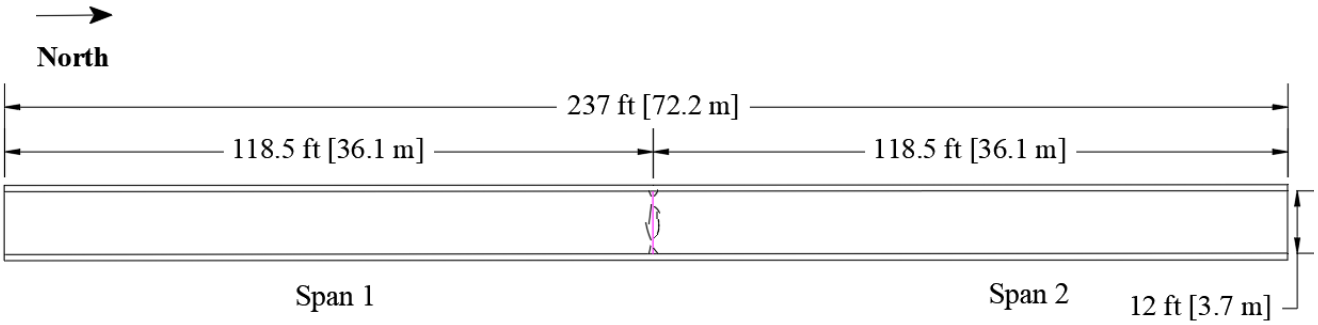


Figure 5.6: Crack map for MN-Control-1 (Survey 5)



Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94, St. Paul, MN
Construction Date: 9/28/2016
Crack Survey Date: 5/23/2022

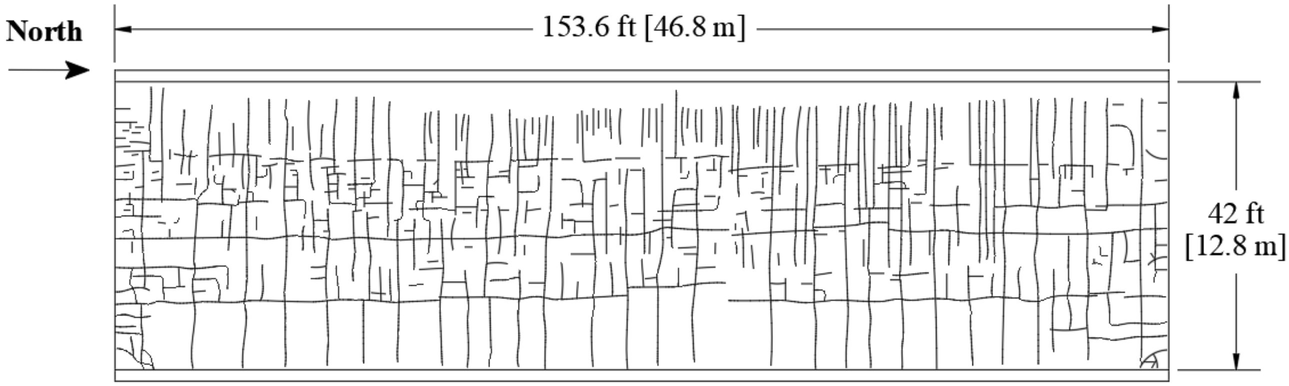
Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 67.9 months
Crack Density: 0.021 m/m^2
Span 1: 0.022 m/m^2
Span 2: 0.021 m/m^2

Figure 5.7: Crack map for MN-Control-1 (Survey 6)

5.3.1.3 MN-IC-LC-HPC-2

MN-IC-LC-HPC-2 is a two-lane bridge that carries southbound traffic on T.H. 52 over the Little Cannon River, near Cannon Falls. In this study, MN-IC-LC-HPC-2, MN-Control-2, and MN-IC-LC-HPC-3 are the only decks constructed with overlay placements. The substructure was constructed on July 6, 2017 and received a 2-in. (25-mm) wearing course (overlay) on July 21 and July 24, 2017, for the right lane and shoulder, and left lane and shoulder, respectively. This deck has been surveyed three times. With a crack density of 1.429 m/m^2, this bridge exhibited the highest crack density in this study. Survey 1 was performed at a deck age of 10.2 months after substructure construction or 9.6 months after overlay placement, with a crack density of 0.165 m/m^2. The cracks were mainly in the longitudinal direction and concentrated near the north and south abutments, possibly due to restraint from the abutments in the transverse direction (Schmitt and Darwin 1995, Miller and Darwin 2000). In Survey 2, performed at an age of 22.9 months after substructure construction, however, longitudinal and transverse cracks were observed along the full length of the deck, with a crack density of 0.896 m/m^2. In Survey 3, performed at an age of 36.6 months after substructure construction, significant longer transverse and longitudinal cracking was found throughout the deck. The transverse cracks extended across the entire surveyed width along the full length of the bridge. A number of longitudinal cracks were found mainly near the centerline of the deck, with cracks ranging in length from 1 to 90 ft (0.3 to 27.4 m), 5 to 10 ft (1.5 to 3.1 m) apart along the bridge width. Crack widths in Survey 3 ranged from 0.009 to 0.016 in. (0.23 to 0.41 mm), with an average of 0.012 in. (0.31 mm). The high crack density on MN-IC-LC-HPC-2 is likely the result of the overlay, as it has been addressed in a number of studies (Miller and Darwin 2000, Lindquist et al. 2005, Pendergrass and Darwin 2014, Lafikes et al. 2020). Miller and Darwin (2000) and Lindquist et al. (2005) reported greater cracking in decks with concrete overlays than for monolithic decks (one coarse) with similar characteristics. Additionally, the MN-IC-LC-HPC-2 overlay was placed in July 2017, and one possible contributor to the especially poor cracking performance of this deck could be that the restrained drying shrinkage of the overlay was exacerbated by high air temperatures. The most recent crack map (Survey 3) is shown in Figure 5.8. Additional details associated with Surveys 1 and 2 of MN-IC-LC-HPC-2 are documented by Lafikes et al. (2020).



Bridge ID: MN-IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over Little Cannon River, MN
Construction Date: 7/6/2017
Crack Survey Date: 7/23/2020

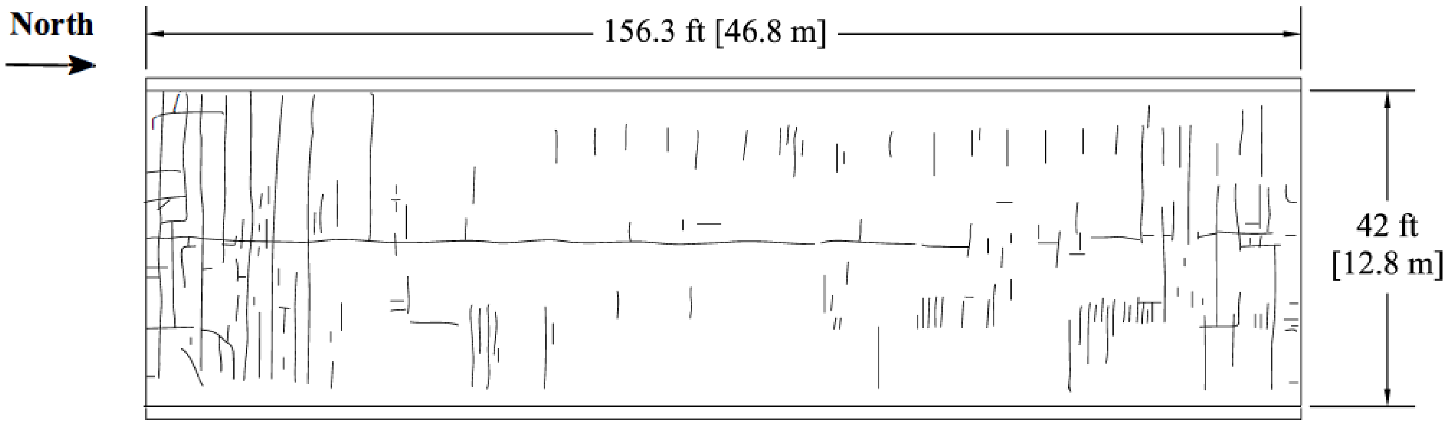
Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 36.6 months
Crack Density: 1.429 m/m^2

Figure 5.8: Crack map for MN-IC-LC-HPC-2 (Survey 3)

5.3.1.4 MN-Control-2

The associated control deck for MN-IC-LC-HPC-2, MN-Control-2, is a two-lane bridge that carries northbound traffic on T.H. 52 over the Little Cannon River, near Cannon Falls. The substructure was constructed on September 15, 2017 and received a 2-in. (25-mm) wearing course (overlay) on September 28 and September 30, 2017, for the right lane and shoulder and the left lane and shoulder, respectively. This deck has been surveyed three times. Survey 1 was performed at a deck age of 7.8 months after substructure construction or 7.3 months after overlay placement, with no observable cracks. Survey 2 was performed at a deck age of 20.6 months after substructure construction, with a crack density of 0.050 m/m^2. In Survey 2, the cracks were mainly concentrated near the north and south abutments. Some longitudinal cracks extended from the south abutment. One longer transverse crack, approximately 20 ft (6.1 m) in length, had developed approximately 5 ft (1.5 m) from the south abutment. Crack widths in Survey 2 ranged from 0.003 to 0.007 in. (0.08 to 0.18 mm), with an average of 0.005 in. (0.13 mm). Survey 3 was performed at a deck age of 34.3 months after substructure construction, with a crack density of 0.539 m/m^2. The crack density observed in Survey 3 was significant compared to 0.050 m/m^2 in Survey 2, but not unexpected since it often takes three years to establish the cracking performance of bridge decks – even decks that perform well during the first two years (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014). Longer transverse cracking was found throughout the deck. The transverse cracks extended across the entire surveyed width near the south end. A longer longitudinal crack, approximately 90 ft (27.4 m) in length, had developed from the south abutment near the centerline. Crack widths in Survey 3 ranged from 0.004 to 0.020 in. (0.10 to 0.51 mm), with an average of 0.011 in. (0.28 mm). One possible reason for the better cracking performance of this deck compared to its pair (MN-IC-LC-HPC-2) could be the placement of its overlay in a milder environmental condition. The MN-Control-2 overlay was placed in September when the cooler ambient temperatures would have helped reduce rapid drying shrinkage, exacerbated by higher temperatures for the MN-IC-LC-HPC-2 overlay placed in July. Due to the placement of overlay on MN-Control-2, the effects of fibers in the substructure could not be investigated. The most recent crack map (Survey 3) is shown in Figure 5.9. Additional details associated with Surveys 1 and 2 of MN-Control-2 are documented by Lafikes et al. (2020).



Bridge ID: MN-Control-2
Bridge Number: 25032
Bridge Location: S.B TH 52 over Little Cannon River, MN
Construction Date: 9/15/2017
Crack Survey Date: 7/23/2020

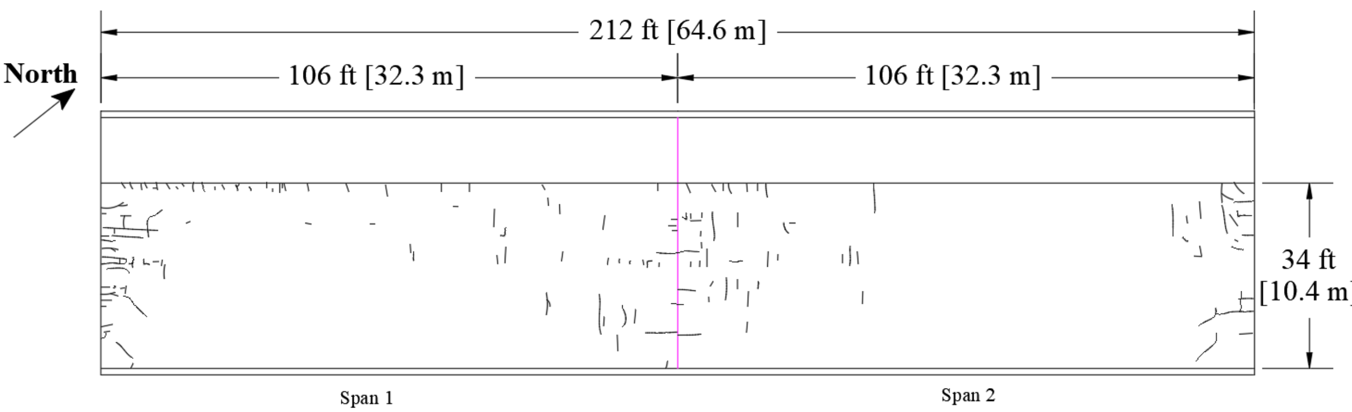
Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 34.3 months
Crack Density: 0.539 m/m^2

Figure 5.9: Crack map for MN-Control-2 (Survey 3)

5.3.1.5 MN-IC-LC-HPC-3

MN-IC-LC-HPC-3 is a two-way bridge that carries traffic on T.H. 58 over T.H. 52 in Zumbrota. The subdeck was constructed in one placement on June 29, 2017. The deck received a 2-in. (25-mm) wearing course (overlay) on September 7 and September 9, 2017. The 34-ft (10.4 m) wide roadway of the deck has been surveyed three times. Survey 1 was performed at a deck age of 10.4 months after substructure construction or 8.1 months after overlay placement, with no observable cracks. Survey 2 was performed at a deck age of 23.2 months after substructure construction, with a crack density of 0.042 m/m^2. In Survey 2, the cracks were mainly concentrated near the north and south abutments, as well as the center pier. Some longitudinal cracks extended from each abutment, with cracks ranging in length from 1 to 2.5 ft (0.3 to 0.8 m). Transverse cracks, between 1 and 8 ft (0.3 and 2.4 m) in length, also formed within 19 ft (5.8 m) on each side of the center pier. Crack widths in Survey 2 ranged from 0.003 to 0.006 in. (0.08 to 0.15 mm), with an average of 0.004 in. (0.10 mm). Survey 3 was performed at a deck age of 36.8 months after substructure construction, with a crack density of 0.161 m/m^2. In Survey 3, the extent and the number of transverse and longitudinal cracks increased. Several cracks were found in the shoulder area on the west side of the deck, mainly in span 1. A number of longitudinal cracks were also formed over the piers, with cracks ranging from 1 to 7 ft (0.3 to 2.1m) in length. Some diagonal cracks were observed near each abutment, with approximately 5 ft (1.5 m) in length. Crack widths in Survey 3 ranged from 0.005 to 0.007 in. (0.13 to 0.18 mm), with an average of 0.006 in. (0.15 mm). With the overlay placed in September and cured in cooler ambient temperatures as well as incorporating IC water, MN-IC-LC-HPC-3 exhibited the lowest crack density at a given deck age compared to other overlay decks in this study. The most recent crack map (Survey 3) is shown in Figure 5.10. Additional details associated with Surveys 1 and 2 of MN-IC-LC-HPC-3 are documented by Lafikes et al. (2020).



Bridge ID: MN-IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52, Zumbrota, MN
Construction Date: 6/29/2017
Crack Survey Date: 7/23/2020

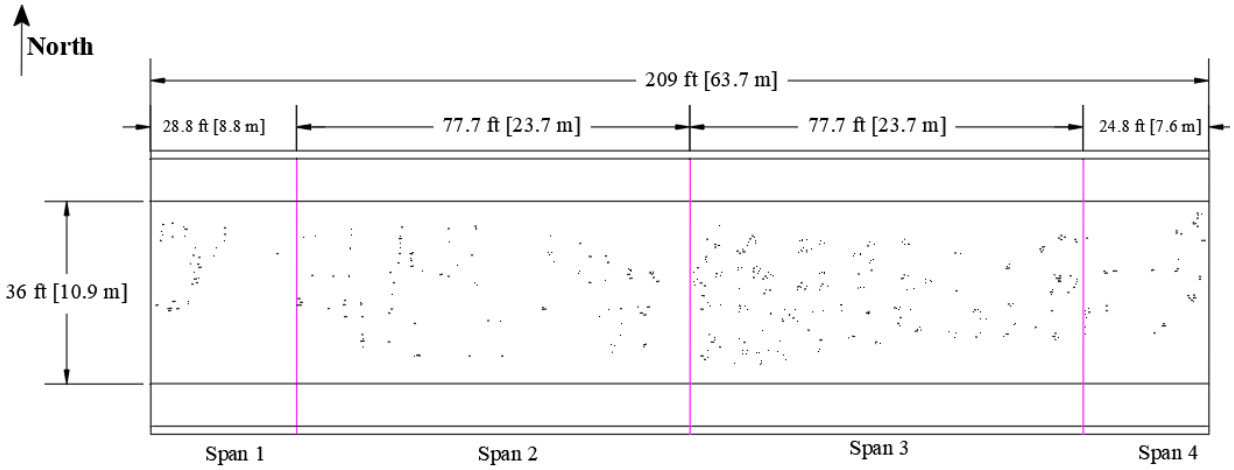
Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 36.8 months
Crack Density: 0.161 m/m^2
Span 1: 0.181 m/m^2
Span 2: 0.142 m/m^2

Figure 5.10: Crack map for MN-IC-LC-HPC-3 (Survey 3)

5.3.1.6 MN-IC-LC-HPC-4

MN-IC-LC-HPC-4 is a two-way bridge that carries traffic on 38th St. over I-35W in Minneapolis. The deck was constructed in one placement on May 15, 2018. The 36-ft (11-m) wide roadway has been surveyed three times and exhibited a crack density as low as 0.046 m/m^2 at a deck age of 48.3 months. Survey 1 was performed at a deck age of 16.0 months, with a crack density of 0.005 m/m^2. In Survey 1, the majority of cracks were in the transverse direction and were distributed over spans 1 and 3 of the deck. A few longitudinal cracks were located near the middle of spans 2 and 3. No cracking was observed in span 4. The bridge deck was not surveyed in the second year after the construction. Surveys 2 and 3 were performed at ages of 37.0 and 48.3 months, respectively. The overall crack density did not noticeably change in Surveys 2 and 3, with values of 0.045 and 0.046 m/m^2, respectively. The majority of cracks in Surveys 2 and 3 were short longitudinal and transverse cracks (crack lengths below 1 ft. [305 mm]) distributed over the entire deck area with crack widths ranging from 0.002 to 0.007 in. (0.05 to 0.18 mm) and an average of 0.003 in. (0.08 mm). One larger transverse crack was also observed in span 3 with a crack length of 2 ft (0.6 m). Some surface damage was observed due to poor tining of the deck, as reported by Lafikes et al. (2020). The most recent crack maps (Surveys 2 and 3) are shown in Figures 5.11 and 5.12. Additional details associated with Survey 1 of MN-IC-LC-HPC-4 are documented by Lafikes et al. (2020).



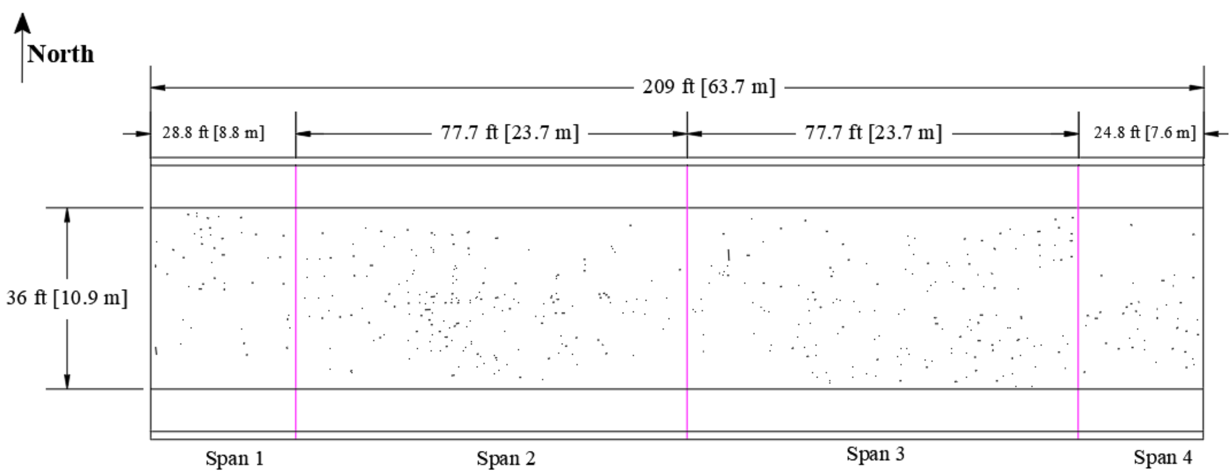
Bridge ID: MN-IC-LC-HPC-4
Bridge Number: 9619
Bridge Location: 38th St. over I-35W, Minneapolis, MN
Construction Date: 5/15/2018
Crack Survey Date: 6/15/2021

Bridge Length: 209 ft (63.7 m)
Bridge Width: 36 ft (10.9 m)
Skew: 0°
Number of Spans: 4
- **Span 1:** 28.8 ft (8.8 m)
- **Span 2:** 77.7 ft (23.7 m)
- **Span 3:** 77.7 ft (23.7 m)
- **Span 4:** 24.8 ft (7.6 m)

Number of Placements: 1

Bridge Age: 37.0 months
Crack Density: 0.045 m/m^2
- **Span 1:** 0.033 m/m^2
- **Span 2:** 0.034 m/m^2
- **Span 3:** 0.061 m/m^2
- **Span 4:** 0.046 m/m^2

Figure 5.11: Crack map for MN-IC-LC-HPC-4 (Survey 2)



Bridge ID: MN-IC-LC-HPC-4
Bridge Number: 9619
Bridge Location: 38th St. over I-35W, Minneapolis, MN
Construction Date: 5/15/2018
Crack Survey Date: 5/23/2022

Bridge Length: 209 ft (63.7 m)
Bridge Width: 36 ft (10.9 m)
Skew: 0°
Number of Spans: 4
- **Span 1:** 28.8 ft (8.8 m)
- **Span 2:** 77.7 ft (23.7 m)
- **Span 3:** 77.7 ft (23.7 m)
- **Span 4:** 24.8 ft (7.6 m)

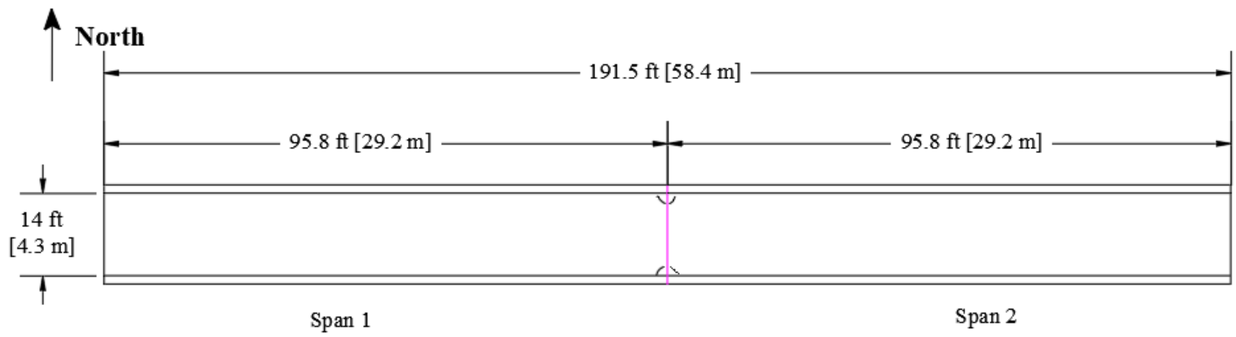
Number of Placements: 1

Bridge Age: 48.7 months
Crack Density: 0.046 m/m^2
- **Span 1:** 0.042 m/m^2
- **Span 2:** 0.049 m/m^2
- **Span 3:** 0.046 m/m^2
- **Span 4:** 0.043 m/m^2

Figure 5.12: Crack map for MN-IC-LC-HPC-4 (Survey 3)

5.3.1.7 MN-IC-LC-HPC-5

MN-IC-LC-HPC-5 is a pedestrian bridge located at 40th St. over I-35W in Minneapolis. The deck was constructed in one placement on July 23, 2019. This deck has been surveyed three times since 2019 and has exhibited the highest crack densities at a given age of the pedestrian bridge decks (MN-IC-LC-HPC-1 and MN-Control-1) constructed in this study. Survey 1 was performed at a deck age of 11.0 months, with a crack density of 0.009 m/m^2. In Survey 1, only a number of diagonal cracks were observed on either side of the contraction joint over the center pier, with crack lengths ranging from 1.5 to 2 ft (0.5 to 0.6 m). Survey 2 was performed at a deck age of 22.7 months, with a crack density of 0.091 m/m^2, an increase from the 0.009 m/m^2 density observed during Survey 1. Some long transverse cracks were observed over the entire deck, mainly with lengths of 3 to 6 ft (0.9 to 1.8 m). Crack widths in Survey 2 ranged from 0.004 to 0.007 in. (0.10 to 0.18 mm), with an average of 0.006 in. (0.152 mm). Survey 3 was conducted at a deck age of 34.1 months and had transverse cracks that extended almost one-third of the deck width, with a crack density of 0.153 m/m^2. Crack widths in Survey 3 ranged from 0.010 to 0.050 in. (0.25 to 1.27 mm), with an average of 0.019 in. (0.48 mm). The crack maps associated with Surveys 1 to 3 are shown in Figures 5.13 to 5.15, respectively. As discussed in Section 4.4.7, the cracking performance of the deck may have been affected due to inadequate consolidation, as observed during the construction. Construction personnel were observed walking through areas that had been previously vibrated, resulting in deconsolidation of the concrete. As demonstrated in multiple decks in Kansas, inadequate consolidation can result in a higher crack density (McLeod et al. 2009, Khajehdehi and Darwin 2018).

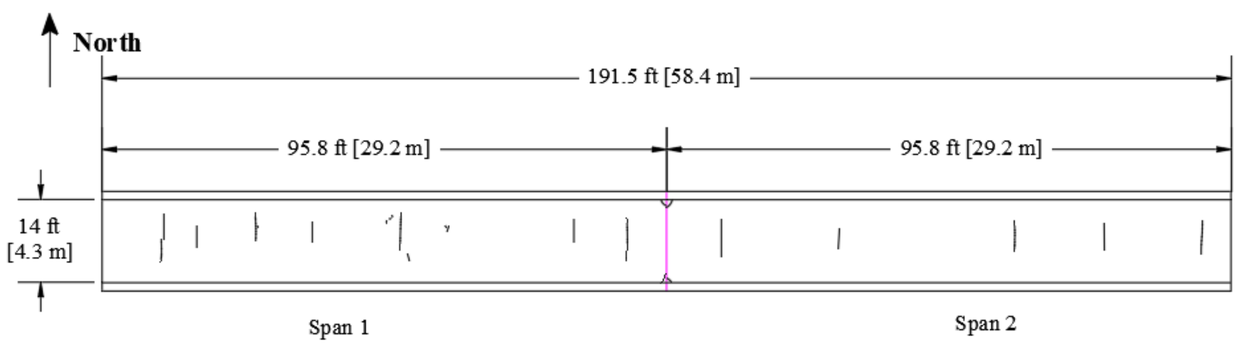


Bridge ID: MN-IC-LC-HPC-5
Bridge Number: 27700
Bridge Location: 40th St over I-35W, Minneapolis, MN
Construction Date: 7/22/2019
Crack Survey Date: 6/23/2020

Bridge Length: 191.5 ft (58.4 m)
Bridge Width: 14 ft (4.3 m)
Skew: 0°
Number of Spans: 2
Span 1: 95.8 ft (29.2 m)
Span 2: 95.8 ft (29.2 m)
Number of Placements: 1

Bridge Age: 11.0 months
Crack Density: 0.009 m/m^2
Span 1: 0.009 m/m^2
Span 2: 0.009 m/m^2

Figure 5.13: Crack map for MN-IC-LC-HPC-5 (Survey 1)

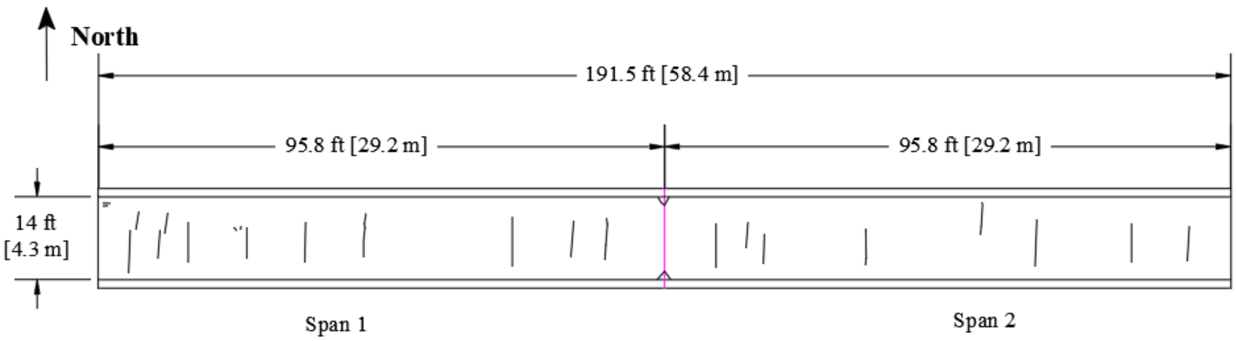


Bridge ID: MN-IC-LC-HPC-5
Bridge Number: 27700
Bridge Location: 40th St over I-35W, Minneapolis, MN
Construction Date: 7/22/2019
Crack Survey Date: 6/14/2021

Bridge Length: 191.5 ft (58.4 m)
Bridge Width: 14 ft (4.3 m)
Skew: 0°
Number of Spans: 2
Span 1: 95.8 ft (29.2 m)
Span 2: 95.8 ft (29.2 m)
Number of Placements: 1

Bridge Age: 22.7 months
Crack Density: 0.091 m/m^2
Span 1: 0.112 m/m^2
Span 2: 0.069 m/m^2

Figure 5.14: Crack map for MN-IC-LC-HPC-5 (Survey 2)



Bridge ID: MN-IC-LC-HPC-5
Bridge Number: 27700
Bridge Location: 40th St over I-35W, Minneapolis, MN
Construction Date: 7/22/2019
Crack Survey Date: 5/23/2022

Bridge Length: 191.5 ft (58.4 m)
Bridge Width: 14 ft (4.3 m)
Skew: 0°
Number of Spans: 2
Span 1: 95.8 ft (29.2 m)
Span 2: 95.8 ft (29.2 m)
Number of Placements: 1

Bridge Age: 34.1 months
Crack Density: 0.153 m/m^2
Span 1: 0.179 m/m^2
Span 2: 0.127 m/m^2

Figure 5.15: Crack map for MN-IC-LC-HPC-5 (Survey 3)

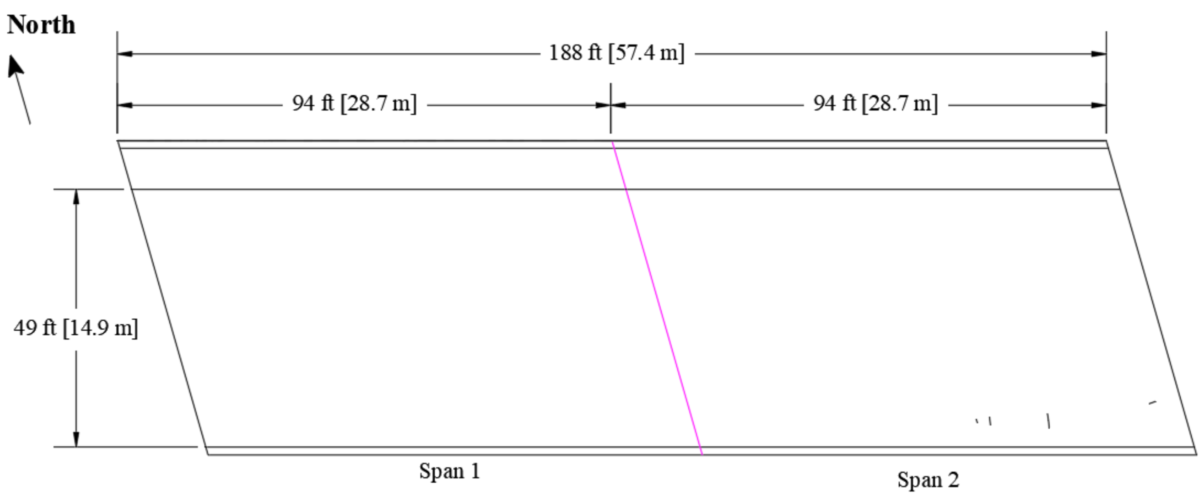
During Surveys 2 and 3, scaling was also observed at multiple locations on the surface of the deck (Figure 5.16). As discussed in Section 4.4.7, significant bleed water was observed on the deck during the construction, and the surface damage is possibly the result of the contractor overfinishing the deck in an attempt to remove excess bleed water. In the process, much of that bleed water was worked back into the surface, resulting in a thin paste layer with a high *w/cm*. Additionally, the bridge deck had two tests for air content that were below the minimum specified value of the specifications (6.5%), although retests showed slightly higher values and concrete placement continued. MN-IC-LC-HPC-5 clearly indicates that with poor construction practices, even decks with low paste content and internal curing water can exhibit increased cracking and the possibility of other durability problems.

(a) (b)

Figure 5.16: Scaling damage of MN-IC-LC-HPC-5 (a) near barriers; (b) a typical section for the remainder of the deck

5.3.1.8 MN-IC-LC-HPC-6

MN-IC-LC-HPC-6 is a two-lane bridge that carries traffic on C.S.A.H. 7 over I-35W near Pine City. The deck was constructed in one placement on September 19, 2019. This deck has been surveyed three times since 2019, exhibiting very low crack densities (below 0.02 m/m^2). The 49-ft (14.9-m) roadway, but not the sidewalk, was surveyed. Survey 1 was performed at a deck age of 10.8 months with a crack density of 0.002 m/m^2. In Survey 1, the majority of cracks were randomly positioned, distributed only over span 2. No cracks were observed in span 1. Crack widths in Survey 1 ranged from 0.004 to 0.007 in. (0.10 to 0.18 mm), with an average of 0.005 in. (0.13 mm). Survey 2 was performed at a deck age of 20.9 months with a crack density as low as 0.003 m/m^2. In Survey 2, some randomly positioned cracks were observed distributed over spans 1 and 2. One short crack was observed near the west end of the deck (crack length below 1 ft [305 mm]). One diagonal crack was extended from the central pier, with approximately 3.5 ft (1.1 m) in length. Survey 3 was performed at a deck age of 32.2 months with a crack density of 0.011 m/m^2. Both the number and the length of cracks increased compared to Survey 2, and similar to previous years, the cracks were short and scattered at discrete locations on the deck. A number of longitudinal cracks were found, mostly on the south side of span 1, with crack lengths ranging from 1 to 6 ft (0.3 to 1.8 m). Crack widths in Survey 3 ranged from 0.003 to 0.016 in. (0.08 to 0.41 mm), with an average of 0.010 in. (0.25 mm). The crack maps associated with Surveys 1 to 3 are shown in Figures 5.17 to 5.19, respectively.

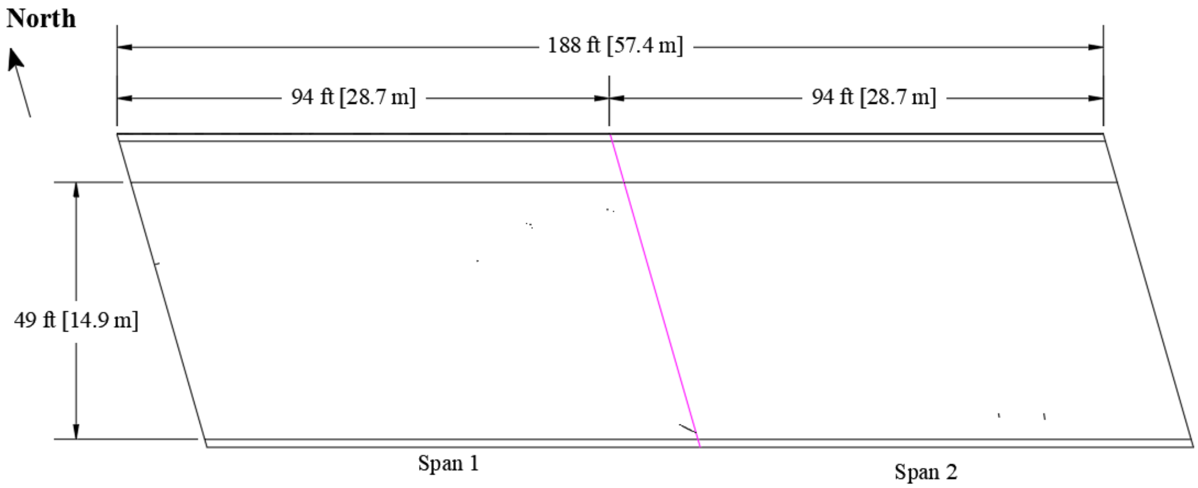


Bridge ID: MN-IC-LC-HPC-6
Bridge Number: 58826
Bridge Location: T.H.35 Under C.S.A.H 7, Pine City, MN
Construction Date: 9/19/2019
Crack Survey Date: 8/13/2020

Bridge Length: 188 ft (57.4 m)
Bridge Width: 49 ft (14.9 m)
Skew: 16º 2' 30"
Number of Spans: 2
Span 1: 94 ft (28.7 m)
Span 2: 94 ft (28.7 m)
Number of Placements: 1

Bridge Age: 10.8 months
Crack Density: 0.002 m/m^2
Span 1: 0.000 m/m^2
Span 2: 0.005 m/m^2

Figure 5.17: Crack map for MN-IC-LC-HPC-6 (Survey 1)

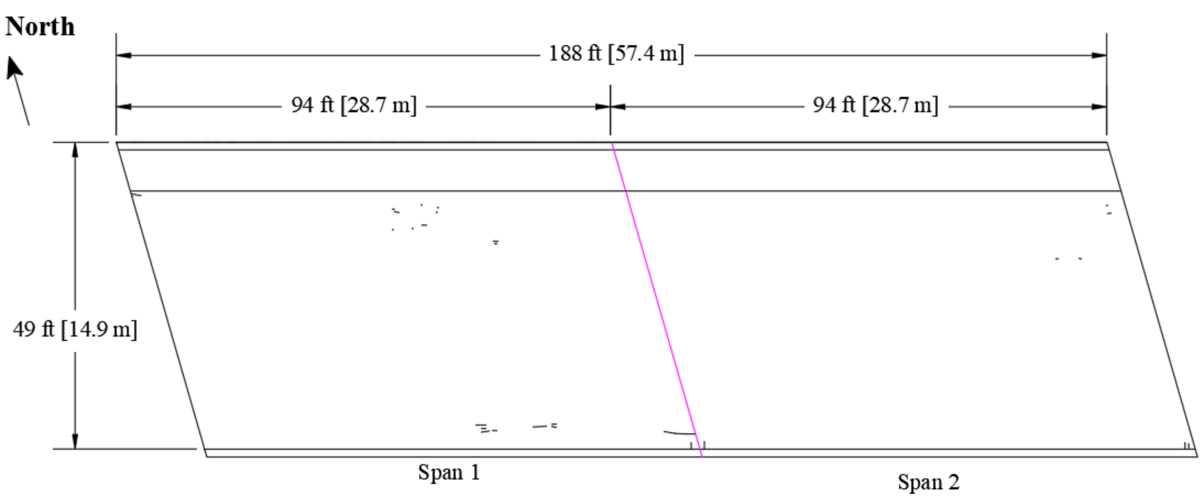


Bridge ID: MN-IC-LC-HPC-6
Bridge Number: 58826
Bridge Location: T.H.35 Under C.S.A.H 7, Pine City, MN
Construction Date: 9/19/2019
Crack Survey Date: 6/16/2021

Bridge Length: 188 ft (57.4 m)
Bridge Width: 49 ft (14.9 m)
Skew: 16º 2' 30"
Number of Spans: 2
Span 1: 94 ft (28.7 m)
Span 2: 94 ft (28.7 m)
Number of Placements: 1

Bridge Age: 20.9 months
Crack Density: 0.003 m/m^2
Span 1: 0.004 m/m^2
Span 2: 0.001 m/m^2

Figure 5.18: Crack map for MN-IC-LC-HPC-6 (Survey 2)



Bridge ID: MN-IC-LC-HPC-6
Bridge Number: 58826
Bridge Location: T.H.35 Under C.S.A.H 7, Pine City, MN
Construction Date: 9/19/2019
Crack Survey Date: 5/24/2022

Bridge Length: 188 ft (57.4 m)
Bridge Width: 49 ft (14.9 m)
Skew: 16º 2' 30"
Number of Spans: 2
Span 1: 94 ft (28.7 m)
Span 2: 94 ft (28.7 m)
Number of Placements: 1

Bridge Age: 32.2 months
Crack Density: 0.011 m/m^2
Span 1: 0.017 m/m^2
Span 2: 0.004 m/m^2

Figure 5.19: Crack map for MN-IC-LC-HPC-6 (Survey 3)

As with MN-IC-LC-HPC-4, MN-IC-LC-HPC-6 showed some surface damage during the crack surveys, as shown in Figure 5.20. As discussed in Section 4.4.8, the deck was heavily tined immediately after finishing and before application of the curing compound, resulting in varying groove widths and depths on the deck surface. During Surveys 2 and 3, some scaling was also observed near the barriers. One possible explanation could be that although the deck had an average air content of 7.9%, it was constructed in late September (and therefore cured at cold ambient temperatures), which increased the potential of concrete durability problems.

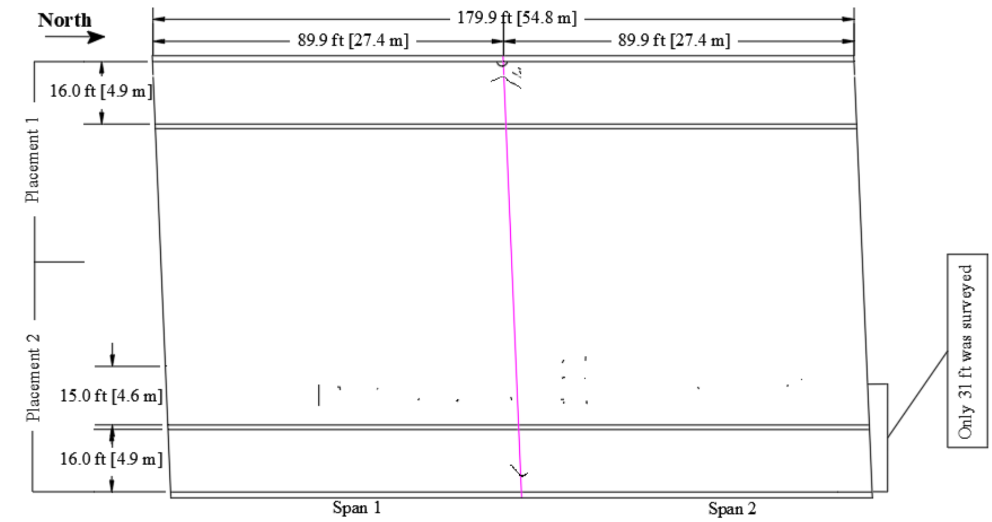
(a) (b)

Figure 5.20: Poorly tining of MN-IC-LC-HPC-6 (a) an overview; (b) a close-up view

5.3.1.9 MN-IC-LC-HPC-7

MN-IC-LC-HPC-7 is a two-way bridge that carries traffic on Dale St. over I-35 in St. Paul. The deck was constructed in two placements; each placement covered half of the total deck width, dividing the deck into east and west sides from the centerline of the roadway. The first placement (MN-IC-LC-HPC-7-P1) was constructed on June 24, 2020. The second placement (MN-IC-LC-

HPC-7-P2) was completed on September 22, 2020. The crack surveys covered only the sidewalks (incorporating IC water) and a portion of the roadway due to restrictions imposed by traffic control. For Survey 1, only one lane and the two sidewalks were surveyed. Survey 1 was performed at a deck age of 11.7 months for Placement 1 and 8.8 months for Placement 2. In Survey 1, the deck exhibited a low crack density (below 0.050 m/m^2), with cracks observed mainly on the sidewalks near the center pier. One single transverse crack was observed within 25 ft from the south end, with a length of about 5 ft (1.5 m). Crack widths in Survey 1 ranged from 0.002 to 0.006 in. (0.05 to 0.15 mm), with an average of 0.004 in. (0.10 mm). For Survey 2, the two sidewalks (incorporating IC water) but only one lane and a shoulder were surveyed. Survey 2 was performed at a deck age of 23.0 months for Placement 1 and 20.0 months for Placement 2. A number of diagonal cracks were observed on either side of the piers on the sidewalks. Some randomly oriented cracks were found at all spans. Two longitudinal cracks were observed near the north end, with approximately 7 ft (2.1 m) in length. Some short and narrow cracks (with crack lengths below 6 in. [152.4 mm]) were observed mostly on the roadway within 5 ft (1.5 m) from the barrier, possibly due to insufficient consolidation, observed in some locations during the construction. The crack densities for the entire deck (both placements) were 0.016 and 0.031 in Surveys 1 and 2, respectively, 0.018 and 0.037 for Placement 1; and 0.014 and 0.024 m/m^2 for Placement 2. Crack widths in Survey 2 ranged from 0.003 to 0.025 in. (0.08 to 0.64 mm), with an average of 0.007 in. (0.18 mm). The crack maps associated with Surveys 1 and 2 are shown in Figures 5.21 and 5.22, respectively.

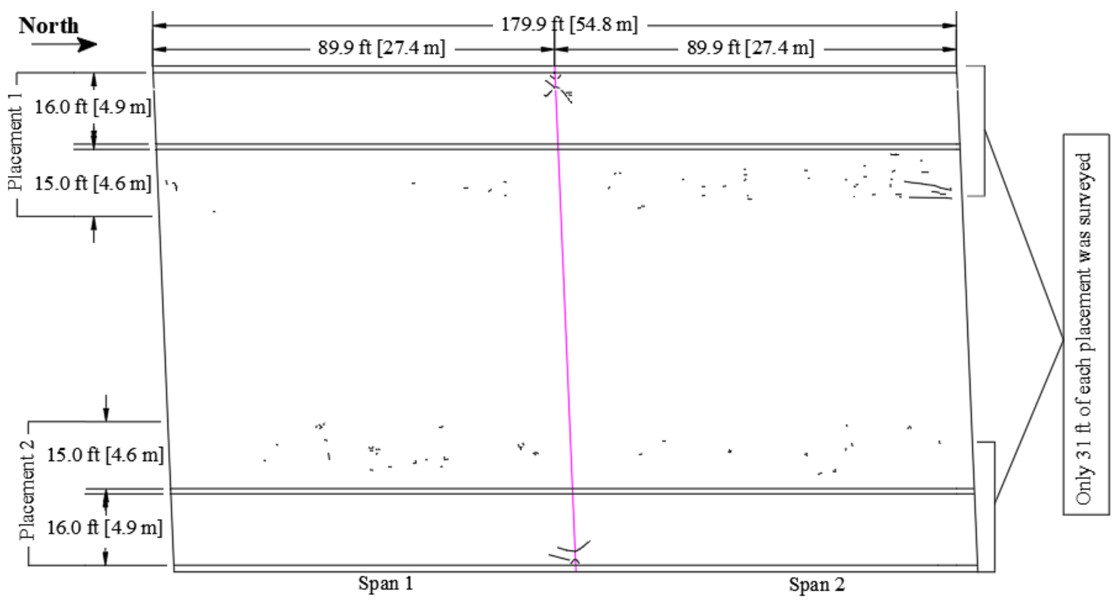


Bridge IC: MN-IC-LC-HPC-7
Bridge Number: 62735
Bridge Location: Dale St. over T.H.94, St Paul, MN
Construction Date:
Placement 1(West): 6/24/2020
Placement 2(East): 9/23/2020
Crack Survey Date: 6/14/2021

Bridge Length: 179.9 ft (54.8 m)
Bridge Width: Only one sidewalk, lane, and shoulder of each placement were surveyed
Skew: 87º 35' 22"
Number of Spans: 2
Span 1: 89.9 ft (27.4 m)
Span 2: 89.9 ft (27.4 m)
Number of Placements: 2

Bridge Age:
Placement 1 (West): 11.7 months
Placement 2 (East): 8.8 months
Crack Density: 0.016 m/m^2
Placement 1 (West): 0.018 m/m^2
Placement 2 (East): 0.014 m/m^2
Span 1: 0.016 m/m^2
Span 2: 0.015 m/m^2

Figure 5.21: Crack map for MN-IC-LC-HPC-7 (Survey 1)



Bridge IC: MN-IC-LC-HPC-7
Bridge Number: 62735
Bridge Location: Dale St. over T.H.94, St Paul, MN
Construction Date:
Placement 1(West): 6/24/2020
Placement 2(East): 9/23/2020
Crack Survey Date: 5/24/2022

Bridge Length: 179.9 ft (54.8 m)
Bridge Width: Only one sidewalk, lane, and shoulder of each placement were surveyed
Skew: 87º 35' 22"
Number of Spans: 2
Span 1: 89.9 ft (27.4 m)
Span 2: 89.9 ft (27.4 m)
Number of Placements: 2

Bridge Age:
Placement 1 (West): 23 months
Placement 2 (East): 20 months
Crack Density: 0.031 m/m^2
Placement 1 (West): 0.037 m/m^2
Placement 2 (East): 0.024 m/m^2
Span 1: 0.024 m/m^2
Span 2: 0.037 m/m^2

Figure 5.22: Crack map for MN-IC-LC-HPC-7 (Survey 2)

5.3.1.10 MN-IC-LC-HPC-8

MN-IC-LC-HPC-8 is a two-lane bridge that carries traffic on C.S.A.H. 12 over I-90 in Winona. The deck was constructed in one placement on August 20, 2020. As discussed in Chapter 4, MN-IC-LC-HPC-8 is another example of a bridge deck constructed with poor construction practices. This deck has been surveyed two times, with Survey 2 exhibiting one of the highest crack densities for an IC deck placed without overlay in this study. Survey 1 was performed at a deck age of 9.9 months with a crack density of 0.013 m/m^2. In Survey 1, the majority of cracks were longitudinal cracks extending from both abutments. Some transverse cracks, approximately 3 ft (0.9 m) in length, had developed near the center pier of the bridge. Crack widths in Survey 1 ranged from 0.004 to 0.025 in. (0.10 to 0.64 mm), with an average of 0.009 in. (0.23 mm). Due to high crack density, in Survey 2 only one lane and a shoulder of MN-IC-LC-HPC-8 were surveyed (18 ft (5.5) of the west side). Survey 2 was performed at a deck age of 21.2 months with a crack density of 0.671 m/m^2, considerably higher than Survey 1. As shown in Figure 5.23, a notable amount of map cracking was found during Survey 2, especially near the center pier and in the middle of Spans 1 and 2. The crack maps associated with Surveys 1 and 2 are shown in Figures 5.24 and 5.25, respectively. As discussed in Section 5.2.1, map cracking is not totally clear in Figure 5.24 due to the scale of the image. As discussed in Section 4.4.10, one possible cause of the poor cracking performance of decks is non-uniform distribution of curing compound applied during construction, leading to plastic shrinkage. It was also indicated by MnDOT personnel that the cracking may have resulted from increased traffic from heavy vehicles from a truck parking lot located 0.3 miles (0.482 km) south of the bridge, which could have increased tensile stresses in the deck. While most cracks were longitudinal and distributed over the entire deck area, several larger longitudinal and transverse cracks were found near the abutments and center pier, respectively. Crack widths in Survey 2 ranged from 0.003 to 0.060 in. (0.08 to 1.52 mm), with an average of 0.018 in. (0.46 mm).

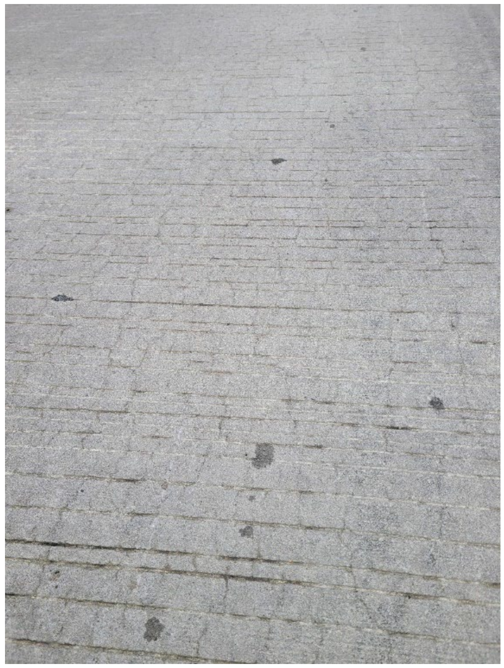


Figure 5.23: Map cracking on a typical section of MN-IC-LC-HPC-8

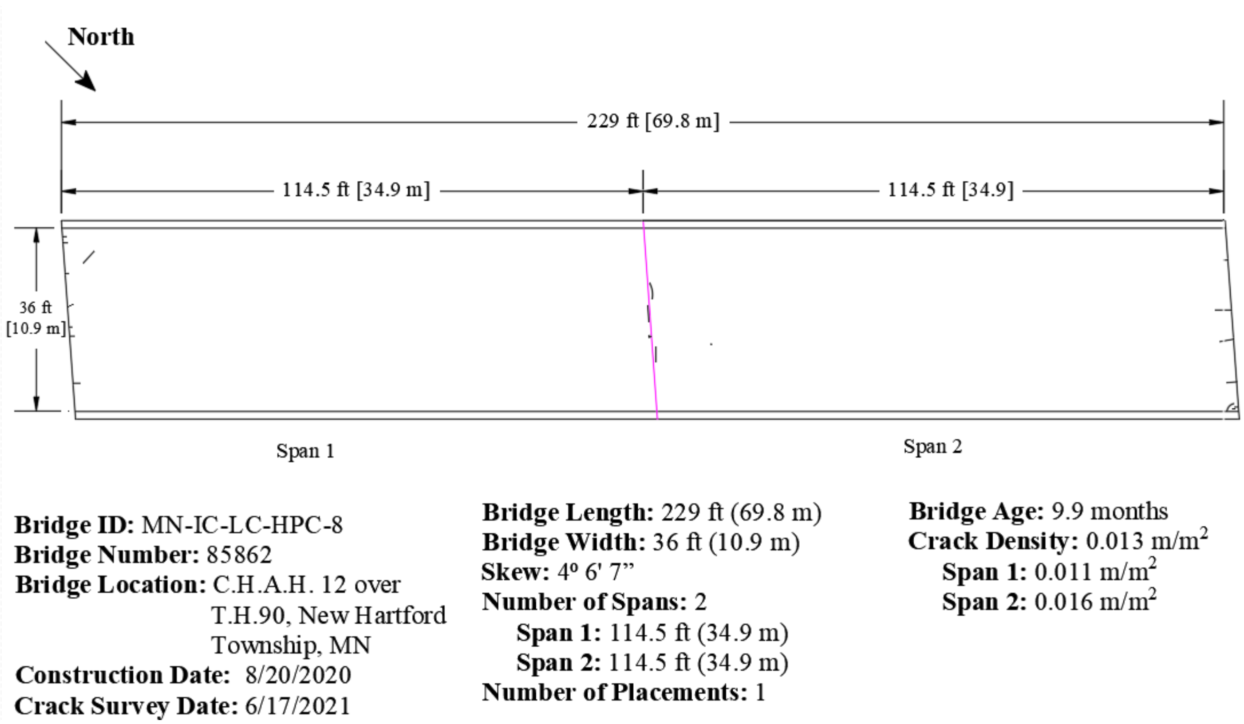
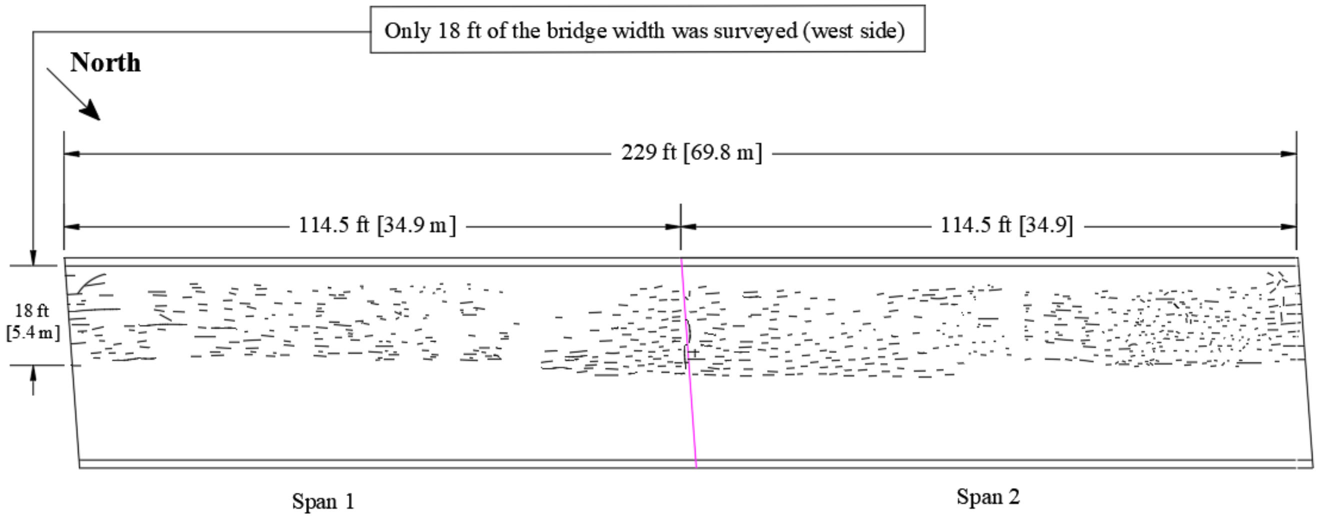


Figure 5.24: Crack map for MN-IC-LC-HPC-8 (Survey 1)



Bridge ID: MN-IC-LC-HPC-8
Bridge Number: 85862
Bridge Location: C.H.A.H. 12 over T.H.90, New Hartford Township, MN
Construction Date: 8/20/2020
Crack Survey Date: 5/26/2022

Bridge Length: 229 ft (69.8 m)
Bridge Width: 36 ft (10.9 m)-only 18 ft was surveyed
Skew: 4º 6' 7”
Number of Spans: 2
Span 1: 114.5 ft (34.9 m)
Span 2: 114.5 ft (34.9 m)
Number of Placements: 1

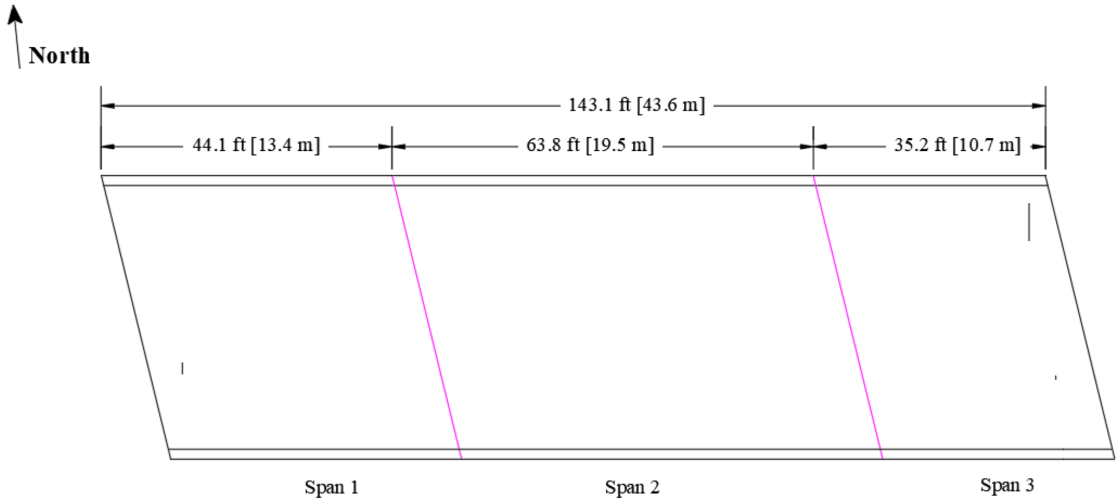
Bridge Age: 21.2 months
Crack Density: 0.671 m/m^2
Span 1: 0.641 m/m^2
Span 2: 0.700 m/m^2

Figure 5.25: Crack map for MN-IC-LC-HPC-8 (Survey 2)

5.3.1.11 MN-IC-LC-HPC-9

MN-IC-LC-HPC-9 carries eastbound traffic on I-90 over Dakota Valley in Winona. The deck was constructed in one placement on September 4, 2020. The concrete supplier and the contractor were the same as MN-IC-LC-HPC-8 and, as with MN-IC-LC-HPC-8, MN-IC-LC-HPC-9, is another example of a bridge deck constructed with poor construction practices. This deck has been surveyed two times, with Survey 2 exhibiting the highest crack densities for an IC deck placed without overlay in this study. Survey 1 was performed at a deck age of 9.5 months with a crack density of 0.004 m/m^2. In Survey 1, the majority of cracks were transverse cracks within 5 ft (1.5 m) of the abutments. No cracks were observed in span 2. Crack widths in Survey 1 ranged from 0.002 to 0.004 in. (0.05 to 0.10 mm), with an average of 0.003 in. (0.08 mm). Due to high crack density, in Survey 2, only one lane and a shoulder of MN-IC-LC-HPC-9 were surveyed (20 ft (6.1 m) of the south side). Survey 2 was performed at a deck age of 20.6 months with a crack density of 0.788 m/m^2, considerably higher than Survey 1. As shown in Figure 5.26, a notable amount of map cracking was found during Survey 2, especially in the middle of spans 1 and 3. The crack maps associated with Surveys 1 and 2 are shown in Figures 5.27 and 5.28, respectively. Again, as discussed in Section 5.2.1, map cracking is not totally clear in Figure 5.28 due to the scale of the image. The majority of cracks were longitudinal (lengths of 2 ft [0.6 m] or less) distributed over the entire deck area. The underside of the deck, however, did not appear to reflect these cracks, as shown in Figure 5.29. Some longitudinal cracks extended from the east abutment. Two longer longitudinal cracks, approximately 9 ft (2.7 m) in length, had developed from the pier between spans 2 and 3. A number of transverse cracks were observed within 15 ft (4.6 m) of the west abutment and within 5 ft (1.5 m) of the east abutment. Crack widths in Survey 2 ranged from 0.007 to 0.025 in. (0.18 to 0.64 mm), with an average of 0.011 in. (0.28 mm). The reason for the poor cracking performance of the deck of MN-IC-LC-HPC-9 is similar to that discussed for MN-IC-LC-HPC-8, including non-uniform distribution of curing compound.

Figure 5.26: Map cracking on a typical section of MN-IC-LC-HPC-9

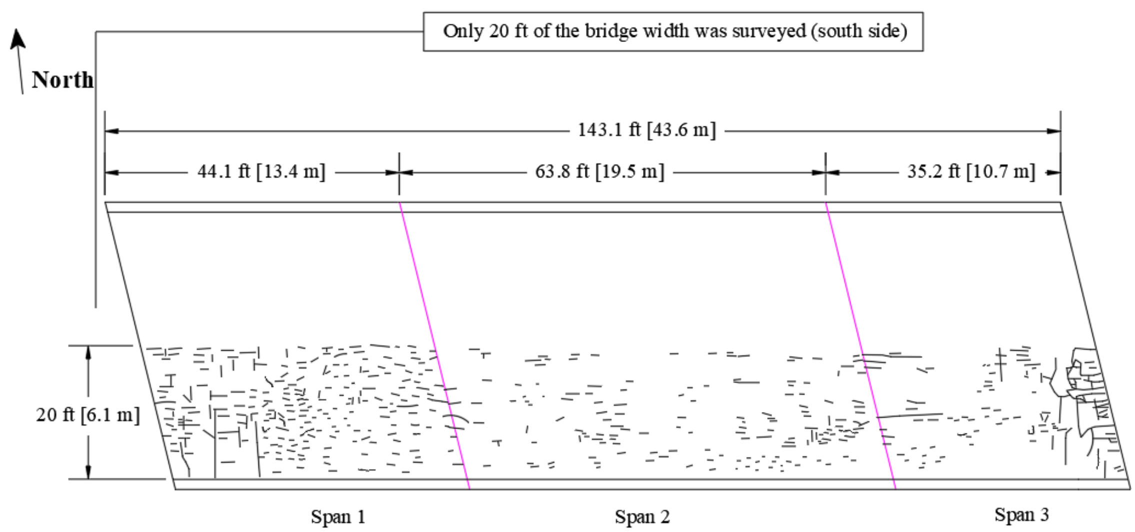


Bridge ID: MN-IC-LC-HPC-9
Bridge Number: 85863
Bridge Location: T.H.90 over TWP Rd 231, New Hartford Township, MN
Construction Date: 9/4/2020
Crack Survey Date: 6/17/2021

Bridge Length: 143.1 ft (43.6 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 13º 45' 24"
Number of Spans: 3
Span 1: 44.1 ft (13.4 m)
Span 2: 63.8 ft (19.5 m)
Span 3: 35.2 ft (10.7 m)
Number of Placements: 1

Bridge Age: 9.5 months
Crack Density: 0.004 m/m^2
Span 1: 0.003 m/m^2
Span 2: 0.000 m/m^2
Span 3: 0.008 m/m^2

Figure 5.27: Crack map for MN-IC-LC-HPC-9 (Survey 1)



Bridge ID: MN-IC-LC-HPC-9
Bridge Number: 85863
Bridge Location: T.H.90 over TWP Rd 231, New Hartford Township, MN
Construction Date: 9/4/2020
Crack Survey Date: 5/23/2022

Bridge Length: 143.1 ft (43.6 m)
Bridge Width: Only 20 ft (6.1 m) was surveyed
Skew: 13º 45' 24"
Number of Spans: 3
Span 1: 44.1 ft (13.4 m)
Span 2: 63.8 ft (19.5 m)
Span 3: 35.2 ft (10.7 m)
Number of Placements: 1

Bridge Age: 20.6 months
Crack Density: 0.788 m/m^2
Span 1: 1.110 m/m^2
Span 2: 0.451 m/m^2
Span 3: 0.991 m/m^2

Figure 5.28: Crack map for MN-IC-LC-HPC-9 (Survey 2)

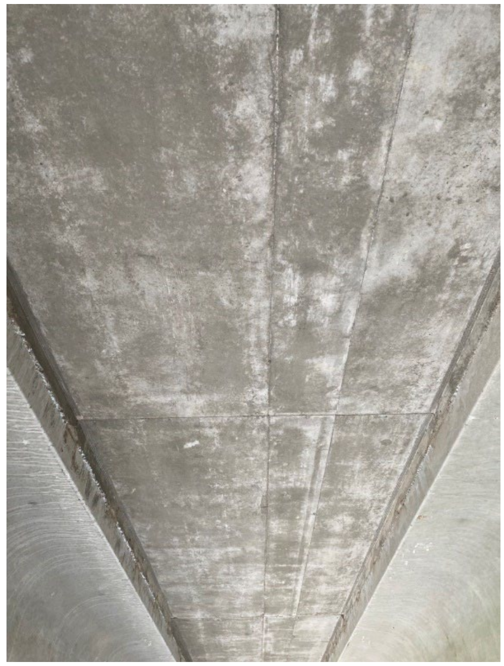


Figure 5.29: Underside of MN-IC-LC-HPC-9 bridge deck

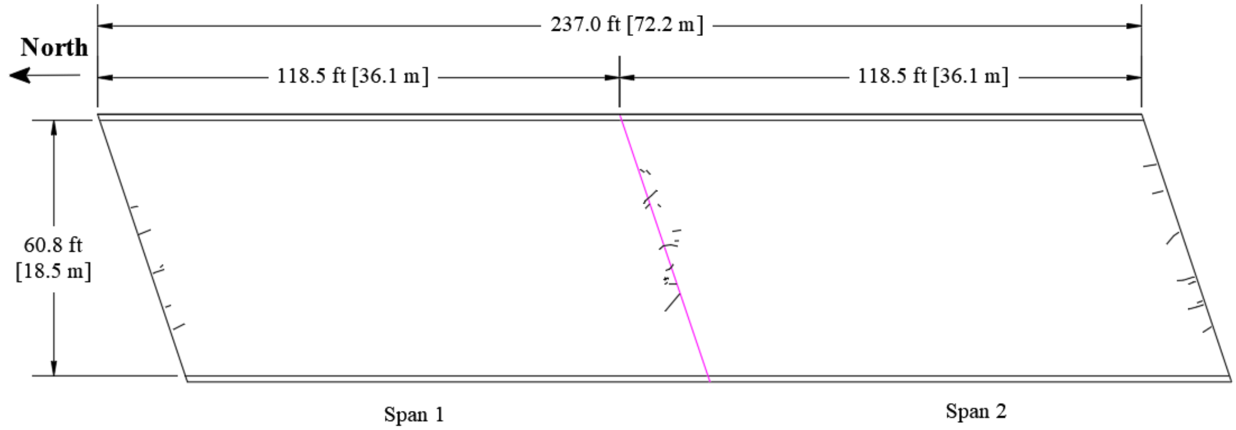
5.3.2 Kansas Bridge Deck Crack Survey Results

Three IC-LC-HPC bridge decks have, to date, been constructed in Kansas, one each in 2019, 2020, and 2021. Crack surveys on the deck constructed in 2019, KS-IC-LC-HPC-1, were performed in July 2021 (approximately 20 months after construction) and June 2022 (approximately 31 months after construction). Crack surveys on the deck constructed in 2020 (KS-IC-LC-HPC-2), which involved two placements, were performed in July 2021 (approximately 8.5 months for both placements) and June 2022 (approximately 19.5 months for both placements). A crack survey on the deck constructed in 2021, KS-IC-LC-HPC-3, was performed in June 2022 (approximately 9 months after construction).

5.3.2.1 KS-IC-LC-HPC-1

KS-IC-LC-HPC-1 is a two-lane bridge that carries traffic on Sunflower Rd. over I-35 in Edgerton, Kansas, with a skew of 18º 32'. The deck was constructed in one placement on

November 26, 2019. This deck has been surveyed two times and exhibited a crack density of 0.019 m/m^2 at a deck age of 30.9 months. The deck was not surveyed in the first year after the construction. Survey 1 was performed at a deck age of 19.8 months, with a crack density of 0.015 m/m^2. In Survey 1, the majority of cracks were located on either side of the piers, normal to the end of the deck. Some cracks were also observed perpendicular to the skew of the deck at both abutments. Crack widths in Survey 1 ranged from 0.003 to 0.025 in. (0.08 to 0.64 mm), with an average of 0.015 in. (0.38 mm). Survey 2 was performed at a deck age of 30.9 months, with a crack density of 0.019 m/m^2. In Survey 2, the number and length of cracks increased compared to Survey 1, mostly observed near the same locations. Crack widths in Survey 2 ranged from 0.013 to 0.020 in. (0.33 to 0.51 mm), with an average of 0.016 in. (0.41 mm). The crack maps associated with Surveys 1 and 2 are shown in Figures 5.30 and 5.31, respectively. During the crack surveys, some scaling was also observed, mainly near the shoulders, as shown in Figure 5.32. The scaling may have occurred because the concrete had air contents as low as 5.5%, as discussed in Section 4.7.1. Overall, air contents ranged from 5.5 to 7.6%, with an average of 6.3%, which compares with the LC-HPC specifications that require individual air content reading to be between 6.5 and 9.5%. Lafikes et al. (2020) recommended requiring air contents above 7% to improve freeze-thaw durability and scaling resistance of concrete mixtures incorporating IC water. KS-IC-LC-HPC-1 (Sunflower Rd.) bridge deck was constructed in late November (and therefore cured in cold ambient temperatures). Furthermore, on the day of placement the air temperature ranged from 38 to 49 °F with an average of 43 °F, which may have also increased the potential of concrete durability problems.

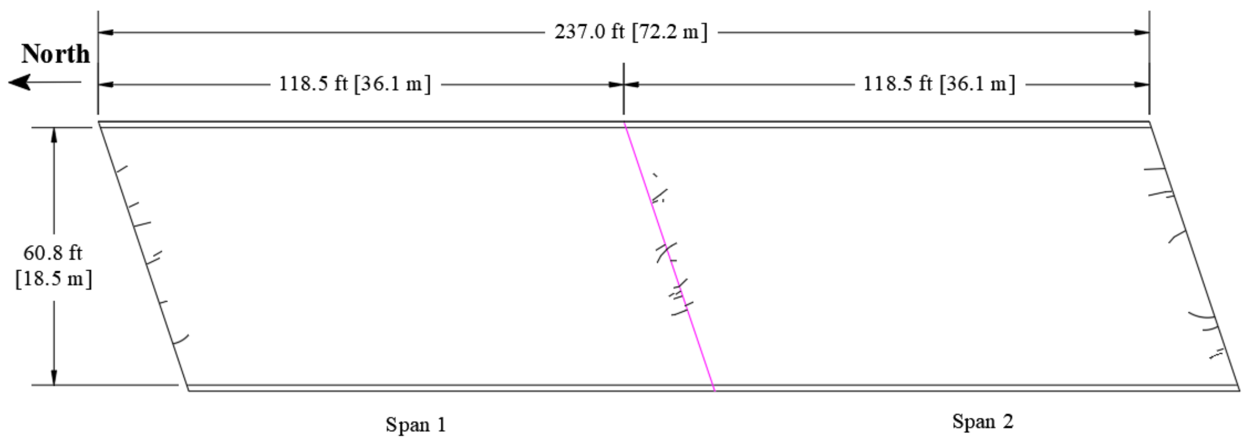


Bridge ID: KS-IC-LC-HPC-1
Bridge Number: 35-46 KA 3083-01
Bridge Location: Sunflower Rd over I-35, KS
Construction Date: 11/26/2019
Crack Survey Date: 7/19/2021

Bridge Length: 237.0 ft (72.2 m)
Bridge Width: 60.8 ft (18.5 m)
Skew: 18º 32' 0"
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 19.8 months
Crack Density: 0.015 m/m^2
Span 1: 0.011 m/m^2
Span 2: 0.018 m/m^2

Figure 5.30: Crack map for KS-IC-LC-HPC-1 (Survey 1)



Bridge ID: KS-IC-LC-HPC-1
Bridge Number: 35-46 KA 3083-01
Bridge Location: Sunflower Rd over I-35, KS
Construction Date: 11/26/2019
Crack Survey Date: 6/22/2022

Bridge Length: 237.0 ft (72.2 m)
Bridge Width: 60.8 ft (18.5 m)
Skew: 18º 32' 0"
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 30.9 months
Crack Density: 0.019 m/m^2
Span 1: 0.017 m/m^2
Span 2: 0.022 m/m^2

Figure 5.31: Crack map for KS-IC-LC-HPC-1 (Survey 2)

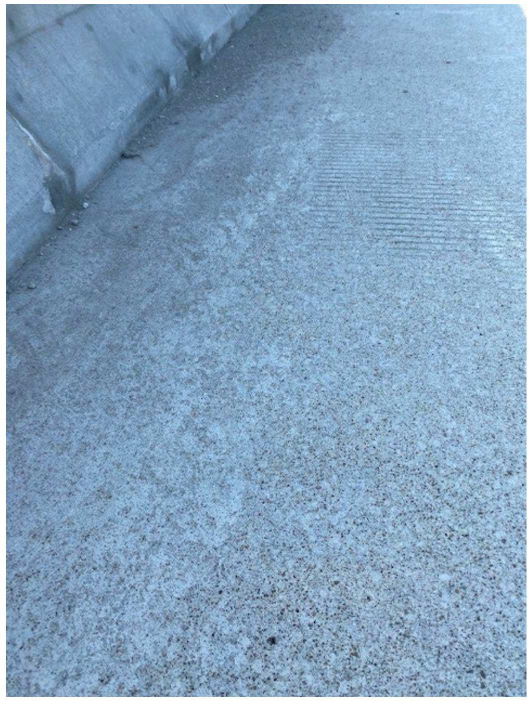


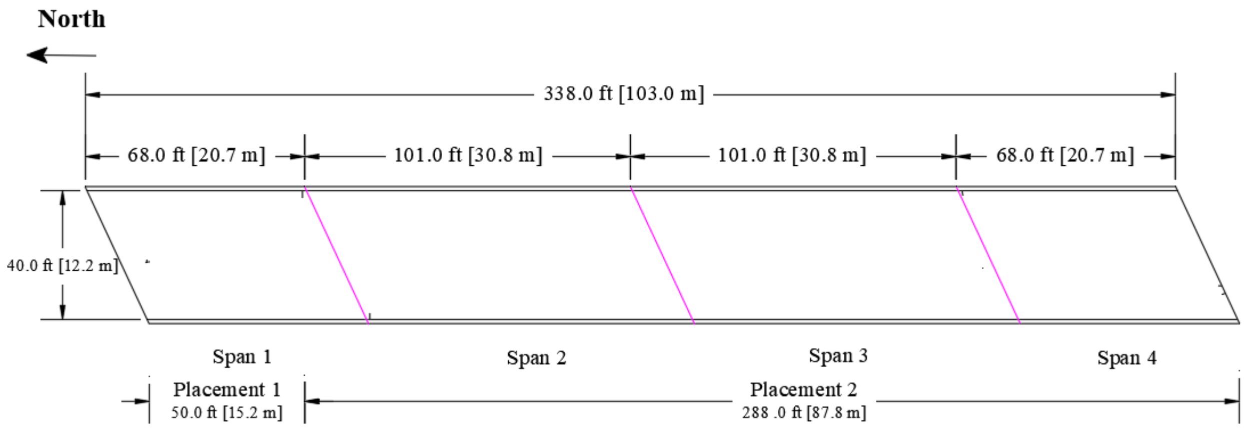
Figure 5.32: Scaling damage observed near the shoulders of KS-IC-LC-HPC-1

5.3.2.2 KS-IC-LC-HPC-2

KS-IC-LC-HPC-2 is a two-lane bridge that carries traffic on Montana Rd over I-35 in Ottawa, Kansas. The deck was constructed in two placements. The first placement (KS-IC-LC-HPC-2-P1) was constructed on November 3, 2020 and the second placement (KS-IC-LC-HPC-2-P2) was completed on November 11, 2020. This deck has been surveyed two times. Survey 1 was performed at a deck age of 8.6 months for Placement 1 and 8.4 months for Placement 2, and exhibited very low crack densities (below 0.02 m/m^2). Some randomly oriented cracks were found in spans 1, 2, and 4. A few cracks were observed perpendicular to the south abutment. Crack widths in Survey 1 ranged from 0.002 to 0.007 in. (0.05 to 0.18 mm), with an average of 0.004 in. (0.10 mm). During Survey 1, an area with surface damage (Figure 5.33) was observed approximately 15 ft (4.6 m) from the north abutment in Placement 1, possibly caused by the direct spraying of water by the contractor (almost perpendicular to the deck surface) from a work bridge on the surface (Figure 4.57(b)) in an attempt to wet the burlap.

Figure 5.33: Surface damage observed on KS-IC-LC-HPC-2-P1

Survey 2 was performed at a deck age of 19.7 months for Placement 1 and 19.4 months for Placement 2, also exhibiting very low crack densities (below 0.02 m/m^2). Some randomly oriented cracks were found at all spans. A few cracks were observed near the pier between spans 1 and 2, and near the pier between spans 3 and 4. Crack widths in Survey 2 ranged from 0.002 to 0.005 in. (0.05 to 0.13 mm), with an average of 0.003 in. (0.08 mm). The crack densities for the entire deck (both placements) were 0.002 and 0.003 in Surveys 1 and 2, respectively, 0.004 and 0.004 for Placement 1; and 0.002 and 0.003 m/m^2 for Placement 2. The crack maps associated with Surveys 1 and 2 are shown in Figures 5.34 and 5.35, respectively.

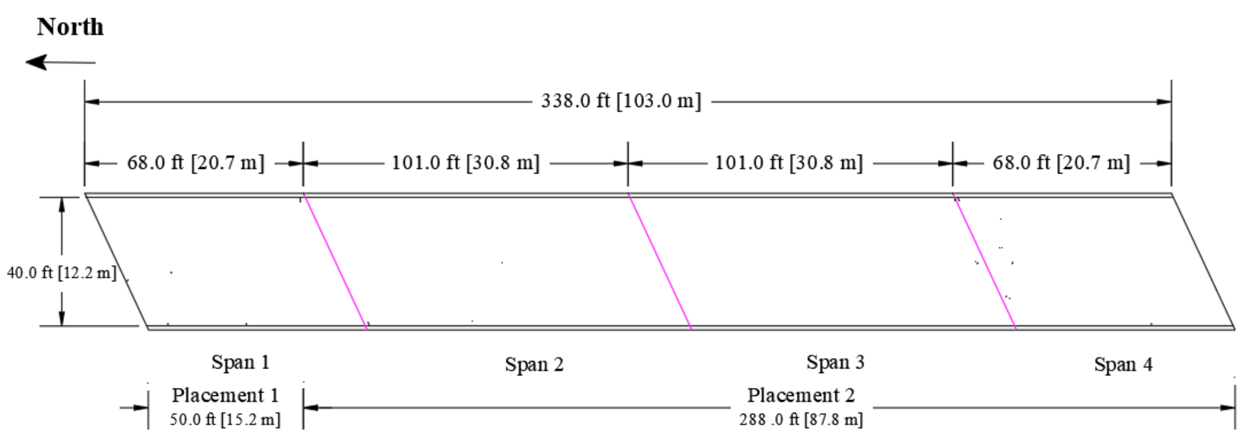


Bridge ID: KS-IC-LC-HPC-2
Bridge Number: 35-30 KA-3102-01
Bridge Location: Montana Rd over I-35, Ottawa, KS
Construction Date:
Placement 1:11/3/2020
Placement 2:11/11/2020
Crack Survey Date: 7/21/2021

Bridge Length: 338.0 ft (103.0 m)
Bridge Width: 40.0 ft (12.2 m)
Skew: 25°
Number of Spans: 4
Span 1: 68.0 ft (20.7 m)
Span 2: 101.0 ft (30.8 m)
Span 3: 101.0 ft (30.8 m)
Span 4: 68.0 ft (20.7 m)
Number of Placements: 2

Bridge Age:
Placement 1: 8.6 months
Placement 2: 8.4 months
Crack Density: 0.002 m/m^2
Span 1: 0.005 m/m^2
Span 2: 0.001 m/m^2
Span 3: 0.000 m/m^2
Span 4: 0.003 m/m^2
Placement 1:0.004 m/m^2
Placement 2:0.002 m/m^2

Figure 5.34: Crack map for KS-IC-LC-HPC-2 (Survey 1)



Bridge ID: KS-IC-LC-HPC-2
Bridge Number: 35-30 KA-3102-01
Bridge Location: Montana Rd over I-35, Ottawa, KS
Construction Date:
Placement 1:11/3/2020
Placement 2:11/11/2020
Crack Survey Date: 6/23/2022

Bridge Length: 338.0 ft (103.0 m)
Bridge Width: 40.0 ft (12.2 m)
Skew: 25°
Number of Spans: 4
Span 1: 68.0 ft (20.7 m)
Span 2: 101.0 ft (30.8 m)
Span 3: 101.0 ft (30.8 m)
Span 4: 68.0 ft (20.7 m)
Number of Placements: 2

Bridge Age:
Placement 1: 19.7 months
Placement 2: 19.4 months
Crack Density: 0.003 m/m^2
Span 1: 0.005 m/m^2
Span 2: 0.002 m/m^2
Span 3: 0.002 m/m^2
Span 4: 0.001 m/m^2
Placement 1:0.004 m/m^2
Placement 2:0.003 m/m^2

Figure 5.35: Crack map for KS-IC-LC-HPC-2 (Survey 2)

Similar to KS-IC-LC-HPC-1 (Sunflower Rd. bridge deck), scaling damage was observed in multiple spots on the surface of KS-IC-LC-HPC-2 (Montana Rd. deck), as shown in Figure 5.36. The surface damage on this deck could be the result of multiple issues. As discussed in Section 4.7.2, during construction, workers made repeated bullfloat passes while bleed water was visible on the surface. Much of that excess water was worked back into the surface. Overfinishing the deck in the presence of bleed water, leads to a thin paste layer with a high *w/cm* at the concrete surface, which can result in scaling damage. Moreover, according to IC-LC-HPC specifications, no finishing aids are permitted. In spite of this, the contractor applied a finishing aid on the concrete for the entire deck. The use of the finishing aid increases the *w/cm* ratio at the surface, which may also contribute to increased scaling damage. This shortcoming was pointed out to the contract (non-KDOT) inspector who said that this was *"not a big deal at this point."* Additionally, it was observed that the fogging system deposited excessive water on the bridge deck.

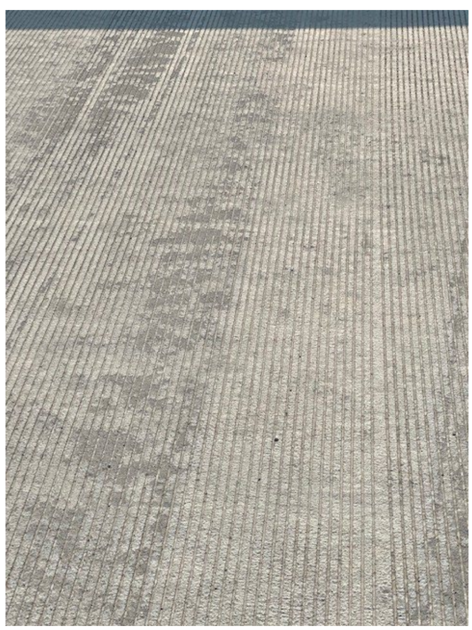
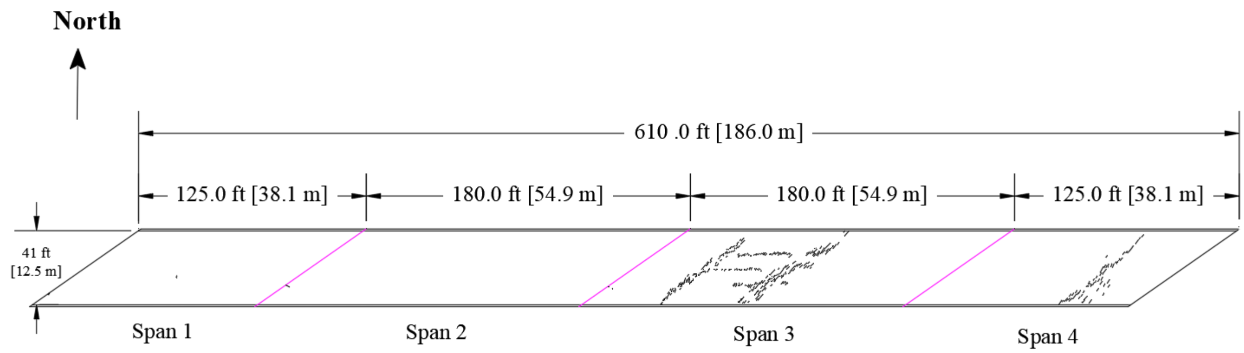


Figure 5.36: Scaling damage observed on some portions of KS-IC-LC-HPC-2

5.3.2.3 KS-IC-LC-HPC-3

KS-IC-LC-HPC-3 is a two-lane bridge that carries traffic on 199th St. over I-35 in Edgerton, Kansas. The deck was constructed in one placement on September 16, 2021. The deck has been surveyed one time. The survey showed a crack density of 0.061 m/m^2. The cracks were primarily located 60 ft (18.3) and 200 ft (70 m) from the east end of the deck, as shown in the crack map in Figure 5.37. Some scaling damage was also observed on the deck. Crack widths ranged from 0.003 to 0.020 in. (0.08 to 0.51 mm), with an average of 0.013 in. (0.33 mm). The cracks and scaling damage observed in those portions of the deck could be the result of multiple factors that occurred during the construction, as discussed in Section 4.7.3. Malfunctioning fogging equipment was observed spraying excess water directly onto the deck surface, especially in spans 3 and 4. The excess water was later worked back into the surface by the contractors when bullfloating the deck, which resulted in a thin paste layer with a high *w/cm* at the concrete surface, causing high cracks in those areas. Although not permitted by the IC-LC-HPC specifications, a finishing aid was also used on the first half of the deck. The finishing aid increases the *w/cm* ratio at the surface, which may contribute to increased scaling damage. The use of the finishing aid, however, was discontinued after it was pointed out to KDOT and contractor personnel. Additionally, a bullfloat was repeatedly used in the longitudinal direction while the excess water was visible on the surface. The scaling damage is shown in Figure 5.38.



Bridge ID: KS-IC-LC-HPC-3
Bridge Number: 35-46-4.20
Bridge Location: 199th St, Edgerton, KS
Construction Date: 9/16/2021
Crack Survey Date: 6/21/2022

Bridge Length: 610.0 ft (186.0 m)
Bridge Width: 41.0 ft (12.5 m)
Skew: -55°8'2"
Number of Spans: 4
Span 1: 125.0 ft (38.1 m)
Span 2: 180.0 ft (54.9 m)
Span 3: 180.0 ft (54.9 m)
Span 4: 125.0 ft (38.1 m)
Number of Placements: 1

Bridge Age: 9.2 months
Crack Density: 0.061 m/m^2
Span 1: 0.002 m/m^2
Span 2: 0.001 m/m^2
Span 3: 0.160 m/m^2
Span 4: 0.066 m/m^2

Figure 5.37: Crack map for KS-IC-LC-HPC-3 (Survey 1)

Figure 5.38: Scaling damage observed on some portions of KS-IC-LC-HPC-3

5.4 CRACKING PERFORMANCE OF IC-LC-HPC DECKS

Figure 5.39 shows crack density as a function of age for IC-LC-HPC and Control decks surveyed from 2017 to 2022 in Minnesota and Kansas.

The crack surveys have shown that the majority of the IC-LC-HPC decks constructed in Minnesota and Kansas exhibited low crack densities (below 0.05 m/m^2, shown in green) during the first two or three years (and longer for some decks) after the construction. For decks without overlays, the use of IC and SCMs reduced bridge deck cracking compared to Control decks. No improvement, however, was noted for the two IC bridge decks with an overlay where higher amounts of cracking were observed. The use of overlays can increase bridge deck cracking and decks with concrete overlays are also susceptible to map cracking (Miller and Darwin 2000, Lindquist et al. 2005). The construction issues during placement of MN-IC-LC-HPC-5, -8, and -9 likely contributed to increased crack densities. When proper construction practices are not followed–as was the case for the three MN decks, where overfinishing, excess water worked into the surface, and inadequate curing were observed–bridge decks can exhibit noticeable cracking. To date, the Kansas IC-LC-HPC decks have exhibited low crack densities. The tendency to exhibit cracking over the long term, however, usually becomes apparent only after 36 months (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014). Therefore, future surveys will provide a better indicator of long-term cracking performance. Factors that affect bridge deck cracking, including internal curing, paste content, and construction procedures, are discussed in Chapter 6.

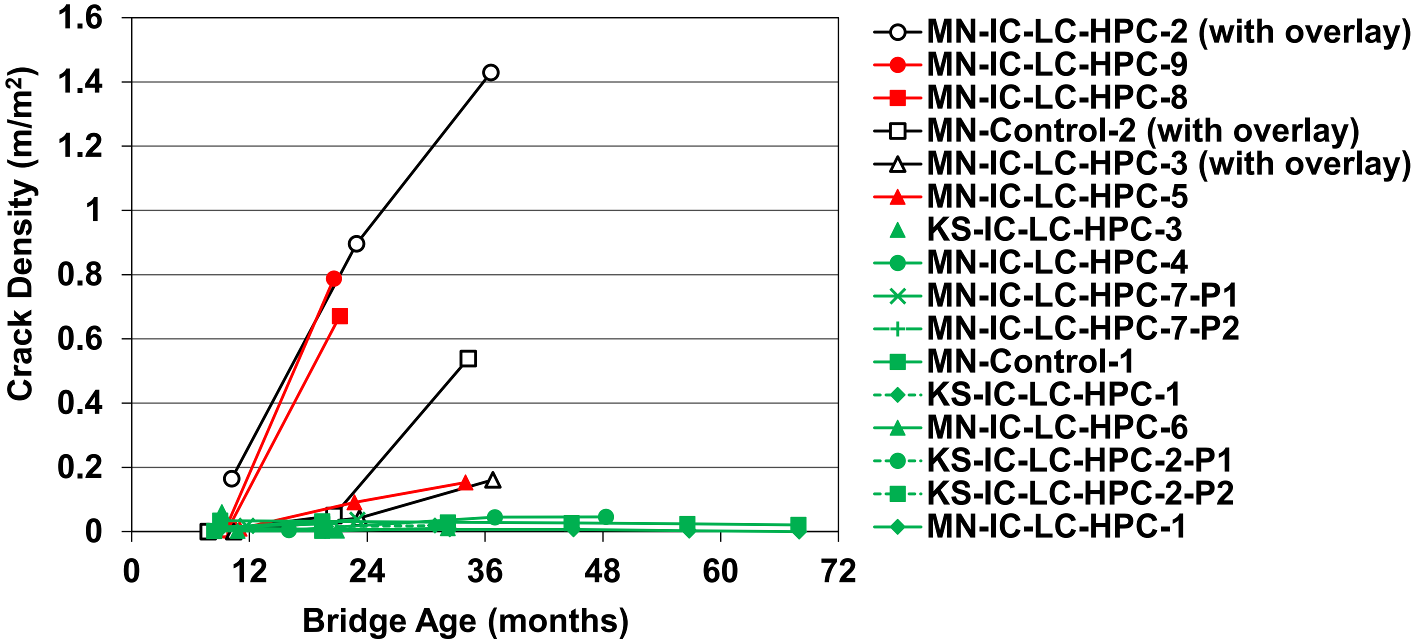


Figure 5.39: Crack density as a function of age for IC-LC-HPC and Control decks

5.4.1 Comparison with Kansas LC-HPC Decks

Figure 5.40 compares the cracking performance of the IC-LC-HPC monolithic decks with cracking in LC-HPC bridge decks in Kansas (Darwin et al. 2016). Bridge decks for which the contractor followed poor construction practices and decks with overlays are excluded from the figures. A single monolithic deck in Minnesota without internal curing water (MN-Control-1) is not shown in the figure because the study focuses on the effects of internal curing and SCMs on bridge deck cracking. As described in Chapter 1, LC-HPC decks were constructed between 2005 and 2011 in Kansas. LC-HPC mixtures have low paste contents (below 24.6%) to reduce shrinkage and all had crack densities below 0.4 m/m^2 through 48 months. Annual crack surveys performed on the LC-HPC decks demonstrated their improved cracking performance in comparison with Control decks (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Alhmood et al. 2015, Darwin et al. 2016).

As described in Chapter 4, both the Minnesota and Kansas IC-LC-HPC decks had low paste content; the Minnesota IC-LC-HPC decks contained a binary cementitious system that included 27 to 30% mass replacement of cement with slag cement and a paste content ranging from 25.4 to 26%; the Kansas IC-LC-HPC decks contained either a binary cementitious system that included a 30% mass replacement of cement with slag cement and a paste content of 24.2%, or a ternary cementitious system that included 30% mass replacement of cement with slag cement and 2 or 3% mass replacement of cement with silica fume and a paste content of either 24.4 or 24.6%. As described in Chapter 1, given that decks with low paste contents exhibit low cracking, the low cracking of the IC-LC-HPC decks is not unexpected. As shown in Figure 5.40, the IC-LC-HPC decks exhibited better cracking performance (below 0.07 m/m^2 between 9 and 68 months after placement) than the LC-HPC decks.

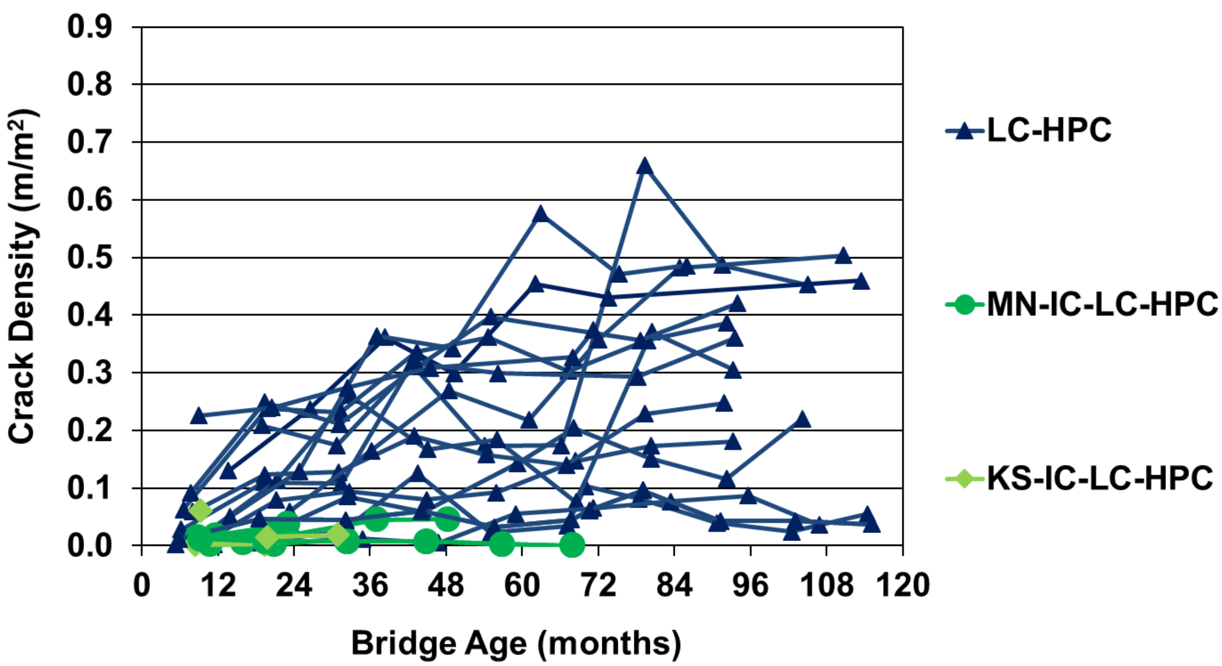


Figure 5.40: Crack densities versus deck age for monolithic LC-HPC decks, Minnesota, and Kansas IC-LC-HPC decks with good construction practices. All had paste contents of 26% or less

5.4.2 Comparison with Utah and Indiana Decks

Figure 5.41 compares the cracking performance of the IC-LC-HPC decks surveyed in this study (MN-IC-LC-HPC and KS-IC-LC-HPC) with cracking in internally-cured decks in Utah and Indiana. As described in Chapter 1, the results of two crack surveys are available for two IC decks in Utah (identified here as UT-IC), supported by prestressed girders with partial-depth precast concrete deck panels. The concrete for the decks had a *w/cm* ratio of 0.44 and a binary cementitious material system (with partial replacements of portland cement with fly ash), but the paste content was 28%. The concrete for the UT-IC decks was proportioned to provide a nominal IC water content of 7% by the weight of binder (Bitnoff 2014). Additionally, one IC deck containing portland cement as the only binder (identified as IN-IC) was constructed in 2010 in Indiana. This deck had a *w/cm* ratio of 0.39 and a paste content of 27.6%. The nominal quantity of IC water was 7.2% by the cement weight (Di Bella et al. 2012). In addition to these decks, four IC decks containing a ternary binder system (identified as IN-IC-HPC, with partial replacements of portland cement with either slag cement and silica fume or fly ash and silica fume) were constructed between 2013 and 2015 in Indiana. These decks had *w/cm* ratios ranging from 0.40 to 0.43 and lower paste contents than IN-IC, between 24.6 and 26.0%. They had IC water contents ranging from 8.5 to 12.0% by total weight of binder (Barrett et al. 2015). As shown in Figure 5.41, the IC-LC-HPC decks, all with paste contents below 27.2%, exhibited noticeably less cracking at similar ages than the internally-cured Utah and Indiana decks (UT-IC and IN-IC) with paste contents greater than 27.2%.

In most cases, the IC-LC-HPC decks in this study, that had IC water contents ranging from 5.2 to 8% (by the weight of binder), exhibited lower crack densities at 36 months than the IN-IC-HPC decks (0.000 to 0.046 vs. 0.000 to 0.214 m/m^2) at similar ages. These observations suggest that there is no apparent reduction in cracking when IC water is increased above 8% (by total weight of binder). Based on Figures 5.40 and 5.41, it can be concluded that IC and SCMs contributed noticeably to a reduction in cracking when the paste content is below 27.2%; for decks with paste contents greater than 27.2%, the addition of IC and SCMs cannot overcome the negative effects of high paste contents, resulting in high crack densities as is the case for UT-IC and IN-IC decks at similar ages to IN-IC-LC-HPC, MN-IC-LC-HPC, and KS-IC-LC-HPC decks.

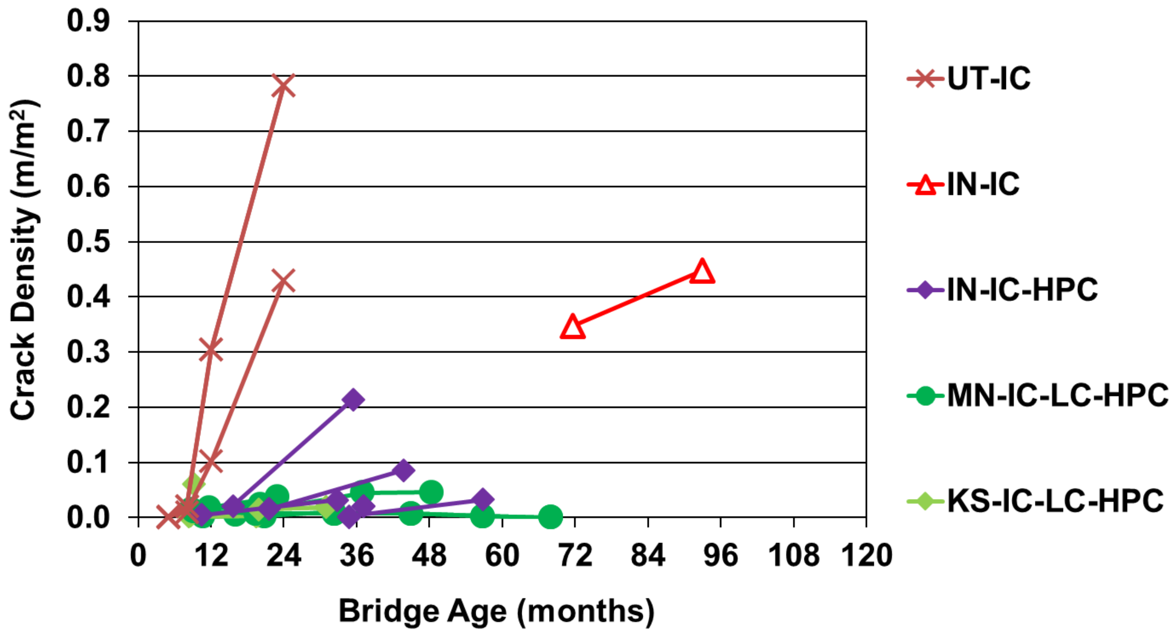


Figure 5.41: Crack densities versus deck age for Utah, Indiana, Minnesota, and Kansas IC decks

5.5 SUMMARY AND CONCLUSION

Between 2017 and 2022, crack surveys were performed on 12 bridge decks containing internal curing water (IC) with supplementary cementitious materials (SCMs), following IC-LC-HPC specifications (of Minnesota or Kansas) and two associate Control decks without IC (MN-Control). Of the 12 decks, nine (identified as MN-IC-LC-HPC-1 to -9) were constructed in Minnesota between 2016 and 2020, and three (identified as KS-IC-LC-HPC-1 to -3) were constructed in Kansas between 2019 and 2021. The decks were supported by either steel or precast-prestressed concrete girders.

For the Minnesota IC-LC-HPC decks, the design paste content ranged from 25.4 to 26% (of the concrete volume), with a design IC water content of either 7 or 8% by the weight of binder. Three bridge decks contained a 2-in. (51-mm) thick overlay (two MN-IC-LC-HPC and one MN-Control decks). The paste content of the overlays was 34.3% and did not contain IC. For Kansas IC-LC-HPC decks, the design paste contents ranged from 24.2 to 24.6%, with a design IC water content of 7% by the weight of binder.

The following conclusions are based on the crack density results (expressed in m/m^2) presented in this chapter.

1. The combination of IC and SCMs in Minnesota and Kansas monolithic decks resulted in decreased cracking in bridge decks.
2. The placement of overlays on internally-cured subdecks does not result in low cracking; the two IC bridge decks with an overlay exhibited much greater cracking than the IC decks without an overlay.
3. Low-cracking bridge decks require concrete with a low paste content (27.2% and below). For decks with paste contents greater than 27.2%, the addition of IC and SCMs cannot overcome the negative effects of high paste contents.
4. When poor construction practices are used, even decks with low paste content and internal curing can exhibit high cracking. Poor construction practices also increase the likelihood of durability-related damage to IC-LC-HPC decks.

CHAPTER 6 – FACTORS AFFECTING BRIDGE DECK CRACKING: PASTE CONTENT, INTERNAL CURING, AND CONSTRUCTION PRACTICES

6.1 GENERAL

The crack density of bridge decks increases over time. While the IC-LC-HPC monolithic decks surveyed in this study were constructed between 2016 and 2021, a fair comparison is not possible unless the crack densities are compared at the same deck age. In studies that have been performed over many years, estimating a crack density for a given bridge deck at a given age usually involves simple interpolation. The procedure, described in Appendix I, is used to estimate the crack densities of the bridge decks surveyed in this study at an age of 36 months; the results of this interpolation or extrapolation are shown in Table 6.1.

Additionally, crack survey results from 74 monolithic (one-coarse) bridge deck placements in Kansas, Virginia, and Indiana are used as a means of comparison against the IC-LC-HPC monolithic decks surveyed in this study. The comparison survey results are based on research at the University of Kansas (KU) dating back to the early 1990s. Over that period, more than 679 field surveys on nearly 227 bridge deck placements have been performed by KU personnel. Previous studies have shown that although many factors are involved in bridge deck cracking, the primary factors are a function of the concrete material properties and construction practices.

6.2 CRACK DENSITY AT 36 MONTHS OF IC-LC-HPC DECKS

As discussed in Chapter 1, stresses in a bridge deck can be influenced by the degree of restraint and the composite action between the deck, girders, and abutments. A composite deck is externally restrained by the girders and abutments, which can result in transverse cracks (Schmitt and Darwin 1995, Krauss and Rogalla 1996). Decks supported by steel girders are more prone to cracking than decks supported by prestressed precast concrete girders (PCA 1970, Schmitt and

Darwin 1995, Krauss and Rogalla 1996, Frosch et al. 2003, Hopper et al. 2015, Darwin et al. 2016, Khajehdehi and Darwin 2018). This observation can be attributed to differences between the thermal expansion coefficient of steel and concrete girders, as well as the fact that the steel girders do not creep or shrink while concrete girders do (Pendergrass and Darwin 2014).

Considering that the IC-LC-HPC monolithic decks constructed in this study were supported by either prestressed precast concrete girders or steel girders, these bridge decks have been categorized into two groups: those supported by prestressed precast concrete girders incorporating internal curing (IC) and supplementary cementitious materials (SCMs) are labeled as PS-IC-LC-PC; and those supported by steel girders incorporating internal curing (IC) and supplementary cementitious materials (SCMs) are labeled as S-IC-LC-HPC. Although each IC-LC-HPC deck introduced in Chapter 4 has its designated bridge ID, in this chapter, these decks are identified as PS-IC-LC-HPC or S-IC-LC-HPC for analysis. Each placement is treated as a different deck and analyzed separately. One PS-IC-LC-HPC monolithic deck (KS-IC-LC-HPC-3) has been removed from the analysis because the survey data is inadequate to estimate 36-month crack density. Two PS-IC-LC-HPC decks with overlays, MN-IC-LC-HPC-2 and -3 with overlays, are also excluded from the analysis.

The 36-month crack density is linearly extrapolated for two PS-IC-LC-HPC and two S-IC-LC-HPC deck placements (MN-IC-LC-HPC-7-P1, -P2 and KS-IC-LC-HPC-2-P1, -P2, respectively) based on the two available surveys. MN-IC-LC-HPC-7-P1, -P2 and KS-IC-LC-HPC-2-P1 and -P2 are "young" decks with ages between 19.4 and 23 months. The extrapolation approach used for these four decks is not guaranteed to give a good prediction for 36-month crack density. While previous research has shown that the 36-month crack density of the decks constructed with good construction procedures can be estimated reliably using the previous year's crack survey data, the negative effects of poor construction practices on cracking may not appear until two and usually three years after the construction. As will be shown in Section 6.4.2, three Minnesota IC-LC-HPC decks (MN-IC-LC-HPC-5, -8, and -9) exhibited low cracking within the first year after the construction, but showed high cracking after just 20 months. Given that some issues (inadequate consolidation and overfinishing) were observed during the construction of MN-IC-LC-HPC-7-P1, -P2 and KS-IC-LC-HPC-2-P1 and -P2, 36-month crack densities greater than those estimated based on extrapolating the earlier crack survey results would not be unexpected. Nevertheless, considering that these decks exhibited very low crack densities at the latest surveys (below 0.04 m/m^2 within 24 months), the 36-month crack density for these decks was estimated using the previous survey data. One more survey, however, is required to obtain more data to calculate the 36-month crack density for these four decks.

As illustrated in Table 6.1, the 36-month estimated crack densities range from 0.007 to 0.788 m/m^2 for the PS-IC-LC-HPC decks, and either 0.004 or 0.005 m/m^2 for the S-IC-LC-HPC decks. The low cracking of the IC-LC-HPC decks is not unexpected considering that this performance is likely related to the fact that these decks had low paste contents ($\leq$ 27.2%), as discussed in Chapter 5. An increase in cracking has also been correlated with poor construction practices (Khajehdehi and Darwin 2018, Feng and Darwin 2020, Lafikes et al. 2020). This may be the case for the decks of MN-IC-LC-HPC-8 and -9, the only two IC-LC-HPC decks with crack densities above 0.2 m/m^2.

Table 6.1: Crack densities at an age of 36 months for monolithic decks surveyed in this study

Bridge ID	Technology	Category[a]	Design Paste Content (%)	36-Month Crack Density (m/m^2)
MN-IC-LC-HPC-1	IC-LC-HPC	PS-IC-LC-HPC	25.4	0.007
MN-IC-LC-HPC-4		PS-IC-LC-HPC	26.0	0.045
MN-IC-LC-HPC-5[b]		PS-IC-LC-HPC	26.0	0.153
MN-IC-LC-HPC-6		PS-IC-LC-HPC	26.0	0.011
MN-IC-LC-HPC-7-P1		PS-IC-LC-HPC	25.9	0.059
MN-IC-LC-HPC-7-P2		PS-IC-LC-HPC	25.9	0.038
MN-IC-LC-HPC-8[b]		PS-IC-LC-HPC	25.6	0.671
MN-IC-LC-HPC-9[b]		PS-IC-LC-HPC	25.6	0.788
KS-IC-LC-HPC-1		PS-IC-LC-HPC	24.6	0.019
KS-IC-LC-HPC-2-P1		S-IC-LC-HPC	24.2	0.004
KS-IC-LC-HPC-2-P2		S-IC-LC-HPC	24.2	0.005
KS-IC-LC-HPC-3[c]		S-IC-LC-HPC	24.4	-[b]

[a] PS-IC-LC-HPC = prestressed precast concrete girders with IC and SCMs; S-IC-LC-HPC = steel girders with IC and SCMs

[b] Decks for which the contractor followed poor construction practices

[c] Removed from the analysis due to inadequate survey data

6.3 BRIDGE DECKS USED FOR COMPARISON WITH SURVEYED DECKS

Although the primary contributors to bridge deck cracking are restrained shrinkage and thermal stresses, previous studies have shown that a number of other factors are involved in bridge deck cracking. These factors are mainly a function of the concrete material properties and construction practices, all of which can influence the cracking performance of bridge decks (Durability of Concrete Bridge Decks 1970, Schmitt and Darwin 1995, Pendergrass and Darwin 2014). The primary variables considered for analysis include paste content, ranging from 22.8 to 29.4%, the use of a crack-reducing technology, such as low-cracking high-performance concrete (LC-HPC) specifications, internal curing (IC), fiber reinforcement (FRC), shrinkage-reducing admixtures (SRA), girder type (steel, prestressed precast concrete, or prestressed box girders), and construction practices (of the 74 decks, 62 were constructed with good construction practices and 12 with poor construction practices). The terms "good" or "bad" construction practices, as described in the following sections, refer to the extent to which concrete suppliers and contractors adhered to the specifications designated for constructing each IC-LC-HPC deck, as observed and recorded by KU personnel during construction. In this study, as shown in Appendix J, an evaluation spreadsheet containing the most common concerns about the construction of IC-LC-HPC decks can be used to record the quality of construction. The procedure described in Appendix I is used to estimate the crack densities of the 74 monolithic bridge decks included in this chapter at an age of 36 months. The bridge decks have been categorized into nine groups, as described in the following sections.

6.3.1 Bridge Decks With Good Construction Practices

The 62 bridge deck placements with no construction issues are organized into seven groups. Each group includes decks with at least two surveys at different ages. The decks in each group have the same type of deck, girders, and, where applicable, the same crack-reducing technologies.

Group 1 (G1) includes 43 bridge deck placements with the decks supported by steel girders without the use of a crack-reducing technology other than following low-cracking high-performance concrete (LC-HPC) specifications and are labeled S. Surveys of 24 placements are reported by Schmitt and Darwin (1995), Miller and Darwin (2000), and Lindquist et al. (2005) for decks constructed following Standard Kansas Department of Transportation (KDOT) specifications. Surveys of 12 placements are reported by Lindquist et al. (2008), McLeod et al. (2009), Yuan et al. (2011), Pendergrass and Darwin (2014), Bohaty et al. (2013), and Alhmood et al. (2015) on decks constructed in Kansas as part of a 13-year two-phase Pooled-Fund study at KU following low-cracking high-performance concrete specifications. Surveys on two of the decks are reported by Harley et al. (2011) and Shrestha et al. (2013). These bridges are located on highway US-59 south of Lawrence, Kansas and are referred to as the US-59 decks. Surveys on three of the decks, referred to as Control, are reported by Feng and Darwin (2020). These bridges are located on highway K-10 south of Lawrence, Kansas. Surveys on one deck, referred to as VA Control (S), constructed near Fredericksburg, Virginia, are reported by Polley et al. (2015) and Feng and Darwin (2020), and surveys on one deck, referred to as Extra Control (S), constructed in 2005 in Kansas, is described Khajehdehi and Darwin (2018). The decks in this group had paste contents ranging from 23.4 to 29.4% of the concrete volume, as shown in Table 6.2.

Table 6.2: Paste contents of the bridge decks in Group 1, (S)

Bridge Deck Placement	Paste Content (%)	Bridge Deck Placement	Paste Content (%)
Conv*. 3-046 Ctr. Deck (S)	25.7	Conv. 99-076 North (West Ln.) (S)	28.7
Conv. 3-045 E. Ctr. Deck (S)	26.4	Conv. 99-076-P4 (S)	28.7
Conv. 70-095 Deck (S)	27.2	LC-HPC 1-P1 (S)	24.6
Conv. 70-104 Deck (S)	27.2	LC-HPC 1-P2 (S)	24.6
Conv. 70-103 Left (S)	27.2	LC-HPC 2 (S)	24.6
Conv. 70-103 Right (S)	27.2	LC-HPC 4-P2 (S)	23.4
Conv. 3-045 East Deck (S)	26.4	LC-HPC 5 (S)	23.9
Conv. 3-045 Ctr. Deck (S)	26.4	LC-HPC 6 (S)	24.4
Conv. 3-046 East Deck (S)	26.4	LC-HPC 7 (S)	24.6
Conv. 99-076 North (East Ln.) (S)	28.7	LC-HPC 9 (S)	24.2
Conv. 56-148 Deck (S)	27.2	LC-HPC 11 (North Ln.) (S)	23.4
Conv. 75-044 Deck (S)	27.9	LC-HPC 15 (S)	22.8
Conv. 3-045 West Deck (S)	26.4	LC-HPC 16 (S)	22.8
Conv. 3-045 W. Ctr. Deck (S)	26.4	LC-HPC 17 (S)	24.6
Conv. 3-046 West Deck (S)	26.4	US 59 1 (S)	24.0
Conv. 70-107 Deck (S)	27.2	US 59 2 (S)	24.0
Conv. 56-142 N. Pier (S)	26.5	Control 5 (Eastbound) (S)	24.7
Conv. 56-142 + Moment (S)	26.5	Control 6 (Eastbound) (S)	24.6
Conv. 89-208 Deck (S)	27.1	Control 7 (Eastbound) (S)	24.6
Conv. 89-204 Deck (S)	28.8	VA Control (S)	29.4
Conv. 99-076-P3** (S)	27.9	Extra Control (S)	25.7
Conv. 99-076-P5 (S)	28.7		

* Conv. = Conventional deck
** P = placement

Group 2 (G2) consists of six monolithic bridge deck placements incorporating fibers supported by steel girders (Feng and Darwin 2020) and are labeled S-F. The bridges are located in Wyandotte, Shawnee, and Douglas Counties in Kansas. The paste contents of these decks ranged from just 23.8 to 24.7% of the concrete volume, as shown in Table 6.3.

Table 6.3: Paste contents of the bridge decks in Group 2, (S-F)

Bridge Deck Placement	Paste Content (%)
Fiber 1 NB-P1* (S-F)	23.8
Fiber 1 NB-P2 (S-F)	23.8
Fiber 2 SB-P1 (S-F)	23.8
Fiber 5 WB (S-F)	24.7
Fiber 6 WB (S-F)	24.6
Fiber 7 WB (S-F)	24.6

* P = placement

Group 3 (G3) consists of four monolithic bridge deck placements incorporating internal curing (IC) technology supported by steel girders and are labeled S-IC. The bridge deck placements (identified as IN-IC-HPC) are located in two districts, Seymour and Vincennes, in Indiana (Lafikes et al. 2020). The paste contents and quantities of IC water of these decks ranged from 25.3 to 26.0% of the concrete volume and from 9.2 to 12.0% (by the weight of binder), respectively, as shown in Table 6.4.

Table 6.4: Paste contents of the bridge decks in Group 3, (S-IC)

Bridge Deck Placement	Paste Content (%)	Actual IC water (% of binder weight)
IN-IC-HPC-2 (S-IC)	25.3	9.2
IN-IC-HPC-3 (S-IC)	25.9	11.6
IN-IC-HPC-4-P1* (S-IC)	25.7	12.0
IN-IC-HPC-4-P2 (S-IC)	26.0	11.2

* P = placement

Group 4 (G4) consists of two monolithic bridge deck placements incorporating shrinkage-reducing admixtures (SRAs) supported by steel girders and are labeled S-SRA. The bridge decks (VA-SRA) are located in Staunton and Fredericksburg, Virginia (Polley et al. 2015, Feng and Darwin 2020). The paste contents of these decks were 27.0 or 27.3%, as shown in Table 6.5.

Table 6.5: Paste contents of the bridge decks in Group 4, (S-SRA)

Bridge Deck Placement	Paste Content (%)
VA-SRA 4 (S-SRA)	27.0
VA-SRA 8 (S-SRA)	27.3

Group 5 (G5) consists of three monolithic bridge deck placements without a crack-reducing technology supported by prestressed precast concrete girders and are labeled PS. The decks were constructed as part of a 13-year Pooled-Fund program at KU, two following (LC-HPC) specifications and one deck (Control 8/10) constructed following KDOT specifications (Lindquist et al. 2008, McLeod et al. 2009, Yuan et al. 2011, Pendergrass and Darwin 2014, Bohaty et al. 2013, Alhmood et al. 2015). The paste contents of these decks ranged from 23.4 to 26.0%, as shown in Table 6.6.

Table 6.6: Paste contents of the bridge decks in Group 5, (PS)

Bridge Deck Placement	Paste Content (%)
LC-HPC 8 (PS)	23.4
LC-HPC 10 (PS)	23.4
Control 8/10 (PS)	26.0

Group 6 (G6) consists of two monolithic bridge deck placements incorporating fibers supported by prestressed precast concrete girders located on US-59 south of Lawrence, Kansas (Harley et al. 2011, Shrestha et al. 2013) and are labeled as PS-F. Both decks had a paste content of 26.4% by volume of concrete, as shown in Table 6.7.

Table 6.7: Paste contents of the bridge decks in Group 6, (PS-F)

Bridge Deck Placement	Paste Content (%)
US-59 10 (PS-F)	26.4
US-59 12 (PS-F)	26.4

Group 7 (G7) consists of two monolithic bridge deck placements supported by prestressed box girders. The bridges are located near Seymour, Indiana. One deck (IN-Control) incorporated no crack-reducing technology and the other (IN-IC) incorporated internal curing (Lafikes et al. 2020). The decks are labeled as PS Box and PS Box-IC, respectively. Both decks had a paste content of 27.6% by volume of concrete. Placement IN-IC had an IC water content of 7.2% by the weight of binder (Table 6.8).

Table 6.8: Paste contents of the bridge decks in Group 7, (PS Box/PS Box-IC)

Bridge Deck Placement	Paste Content (%)	Actual IC water (% of binder weight)
IN-Control (PS Box)	27.6	0
IN-IC (PS Box-IC)	27.6	7.2

The 36-month crack densities of the bridge decks in groups G1 through G7 are shown in Table 6.9. The detailed crack survey results are documented by Lindquist et al. (2006) and Khajehdehi and Darwin (2018) for the Conventional decks and the extra control deck constructed in Kansas; by Darwin et al. (2016) for the LC-HPC decks constructed in Kansas; by Shrestha et al. (2013) for the decks on US-59 the south of Lawrence, Kansas; by Polley et al. (2015) for the decks in Virginia containing SRAs, Feng and Darwin (2020) for the decks in Kansas containing fiber reinforcement, and by Lafikes et al. (2020) for the Indiana decks with and without IC technology.

Table 6.9: Crack density of bridge decks used for comparison at 36 months of age

Bridge Deck Placement	Group	Crack Density (m/m^2)	Bridge Deck Placement	Group	Crack Density (m/m^2)
*Conv. 3-046 Ctr. Deck (S)	G1***	0.042	LC-HPC 9 (S)	G1	0.325
Conv. 3-045 E. Ctr. Deck (S)	G1	0.043	LC-HPC 11 (North Ln.) (S)	G1	0.163
Conv. 70-095 Deck (S)	G1	0.025	LC-HPC 15 (S)	G1	0.227
Conv. 70-104 Deck (S)	G1	0.069	LC-HPC 16 (S)	G1	0.250
Conv. 70-103 Left (S)	G1	0.391	LC-HPC 17 (S)	G1	0.283
Conv. 70-103 Right (S)	G1	0.253	US 59 1 (S)	G1	0.391
Conv. 3-045 East Deck (S)	G1	0.078	US 59 2 (S)	G1	0.242
Conv. 3-045 Ctr. Deck (S)	G1	0.174	Control 5 (Eastbound) (S)	G1	0.052
Conv. 3-046 East Deck (S)	G1	0.392	Control 6 (Eastbound) (S)	G1	0.011
Conv. 99-076 North (East Ln.) (S)	G1	0.412	Control 7 (Eastbound) (S)	G1	0.033
Conv. 56-148 Deck (S)	G1	0.259	VA Control (S)	G1	0.232
Conv. 75-044 Deck (S)	G1	0.165	Extra Control (S)	G1	0.215
Conv. 3-045 West Deck (S)	G1	0.074	Fiber 1 NB-P1 (S-F)	G2	0.112
Conv. 3-045 W. Ctr. Deck (S)	G1	0.178	Fiber 1 NB-P2 (S-F)	G2	0.220
Conv. 3-046 West Deck (S)	G1	0.254	Fiber 2 SB-P1 (S-F)	G2	0.127
Conv. 70-107 Deck (S)	G1	0.322	Fiber 5 WB (S-F)	G2	0.061
Conv. 56-142 N. Pier (S)	G1	0.064	Fiber 6 WB (S-F)	G2	0.011
Conv. 56-142 + Moment (S)	G1	0.071	Fiber 7 WB (S-F)	G2	0.004
Conv. 89-208 Deck (S)	G1	0.009	IN-IC-HPC-2 (S-IC)	G3	0.003
Conv. 89-204 Deck (S)	G1	0.736	IN-IC-HPC-3 (S-IC)	G3	0.061
Conv. 99-076-P3 (S)	G1	0.739	IN-IC-HPC-4-P1 (S-IC)	G3	0.214
Conv. 99-076-P5 (S)	G1	0.861	IN-IC-HPC-4-P2 (S-IC)	G3	0.032
Conv. 99-076 North (West Ln.) (S)	G1	0.801	VA-SRA 4 (S-SRA)	G4	0.083
Conv. 99-076-P4 (S)	G1	0.872	VA-SRA 8 (S-SRA)	G4	0.056
LC-HPC 1-P1** (S)	G1	0.049	LC-HPC 8 (PS)	G5	0.358
LC-HPC 1-P2 (S)	G1	0.024	LC-HPC 10 (PS)	G5	0.029
LC-HPC 2 (S)	G1	0.048	Control 8/10 (PS)	G5	0.136
LC-HPC 4-P2 (S)	G1	0.090	US 59 10 (PS-F)	G6	0.178
LC-HPC 5 (S)	G1	0.154	US 59 12 (PS-F)	G6	0.047
LC-HPC 6 (S)	G1	0.271	IN-IC (PS Box-IC)	G7	0.181
LC-HPC 7 (S)	G1	0.012	IN-Control (PS Box)	G7	0.236

* Conv. = Conventional deck; ** P = placement; ***G# = group No.

6.3.2 Bridge Decks With Poor Construction Practices

The 12 bridge deck placements constructed with documented poor construction practices were supported by steel girders - eight with no crack-reducing technology placed in Group 8 and identified as S and four contained fibers placed in Group 9 and identified as S-F. Comparing the cracking on these decks with that of the decks surveyed in this study is done to help identify the effects of construction practices. The 36-month crack densities and concrete properties of the 12 bridge decks with poor construction practices are provided in Table 6.10.

The main issue associated with the construction of eight of the placements, LC-HPC 12-P1 (S) and LC-HPC 12-P2 (S), LC-HPC 13 (S), Topeka Control-P1 (S-F) and Topeka Control-P2 (S-F), Topeka Fiber 1 (S-F), and Topeka Fiber 2-P1 and-P2 (S-F), was the loss of consolidation caused by workers walking through fresh concrete that had been previously consolidated. The contractor failed to re-consolidate the concrete prior to striking off and finishing the deck, which increased the likelihood of settlement cracking.

Poor practices were also observed during the construction of LC-HPC14-P1 (S), LC-HPC 14-P2 (S), LC-HPC 14-P3 (S), and Fiber 2 SB-P2 (S-F). A variety of issues were observed in the construction of LC-HPC 14-P1 (S), LC-HPC 14-P2 (S), and LC-HPC14-P3 (S), including insufficient consolidation, overfinishing of the deck, and late delivery of concrete. As a result, the three placements on LC-HPC 14-P1 (S), LC-HPC 14-P2 (S), LC-HPC 14-P3 (S) exhibited the highest crack density among the LC-HPC decks. Additional details associated with the construction of LC-HPC-12 (S), LC-HPC-13 (S), LC-HPC14-P1 (S), LC-HPC 14-P2 (S), and LC-HPC 14-P3 (S) are provided by McLeod et al. (2009), Pendergrass and Darwin (2014), and Khajehdehi and Darwin (2018). In addition, based on on-site observation, the contractor of Fiber 2 SB-P2 (S-F) did not follow many aspects of the specifications, such as insufficient consolidation and disturbance of the concrete after consolidation, resulting in a highly cracked bridge deck.

Table 6.10: 36-month crack density and concrete properties of decks with construction issues

Bridge Deck Placement	Group	36-month Crack Density (m/m^2)	Cement Paste (%)	Air Content (%)	Slump (in.)	28-day Strength (psi)
LC-HPC 12-P1 (S)	G8	0.301	24.3	7.4	2¾	4600
LC-HPC 12-P2 (S)	G8	0.332	24.2	7.8	4¼	4380
LC-HPC 13 (S)	G8	0.344	24.1	8.1	3	4280
LC-HPC 14-P1 (S)	G8	0.543	24.4	8.7	3¾	4440
LC-HPC 14-P2 (S)	G8	1.223	24.4	9.8	4¼	3710
LC-HPC 14-P3 (S)	G8	0.695	24.4	9.9	5¼	3830
Topeka Control-P1 (S)	G8	0.766	22.2	5.5	3¼	-[a]
Topeka Control-P2 (S)	G8	0.393	22.2	5.7	3¼	5700
Topeka Fiber 1-(S-F)	G9	0.284	22.2	6.5	3¼	5230
Topeka Fiber 2-P1 (S-F)	G9	0.709	22.2	6.5	3	5330
Topeka Fiber 2-P2 (S-F)	G9	0.431	22.2	6.7	3¼	5530
Fiber 2 SB-P2 (S-F)	G9	0.456	23.8	5.3	5	5950

[a] Data is not available

6.4 ANALYSIS

The effects of material properties, crack-reducing technology (IC), and construction practices on cracking of IC-LC-HPC monolithic bridge decks surveyed in Minnesota and Kansas are evaluated by comparison with the survey results for the 74 bridge deck placements summarized in Section 6.3. IC-LC-HPC decks with overlays are excluded from the analysis. As discussed in Section 3.1.1, Student's t-test is used to determine if the difference between the means of two small data sets, drawn from two normally distributed populations, with unknown means and standard deviations, is due to random variation or represents an actual difference in the populations. A p-value greater than 0.05 would indicate that the difference between the two means is likely to have been due to chance. Values of $p \leq 0.05$ are usually taken as indicating that the difference between two means is statistically significant.

6.4.1 Effects of Paste Content and Internal Curing (Deck with Good Construction)

As discussed in Chapters 1 and 5, numerous studies have shown that concrete material properties play a crucial role in the durability and cracking of bridge decks. Cement paste content is the most dominant factor in concrete shrinkage and, consequently, cracking in bridge decks. The effects of paste content on the cracking performance of bridge decks have been addressed in numerous studies (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2019).

Researchers have also demonstrated that low cement paste content has greater importance than the incorporation of crack-reducing technologies alone, such as the use of fiber-reinforced concrete (FRC), SRAs, or IC water in the construction of bridge decks (Feng and Darwin 2020, Lafikes et al. 2020). Lafikes et al. (2020) reported that the incorporation of IC water in decks with a paste content higher than 27%, with or without SCMs, does not result in lower cracking than in decks constructed with lower paste contents. With this as background, the IC-LC-HPC monolithic bridge decks surveyed in this study are categorized into two groups: decks without construction issues (eight decks) and decks involving poor construction practices (three decks: MN-IC-LC-HPC-5, -8, and -9, as described in Chapter 5) are analyzed in Section 6.4.2.

Figure 6.1 shows the 36-month crack density of the six PS-IC-LC-HPC and two S-IC-LC-HPC bridge decks (with good construction practices in Table 6.1) surveyed in this study and those with good construction practices that are used for comparison (in Tables 6.2 to 6.8), as a function of the paste content. As shown in the figure, 35 of the decks with paste contents below 27.2% had crack densities below 0.2 m/m^2 and 18 decks had crack densities between 0.3 to 0.4 m/m^2 at 36 months. The PS-IC-LC-HPC and S-IC-LC-HPC decks surveyed in this study, with paste contents ranging from 24.2 to 26%, had crack densities ranging from just 0.004 to 0.059 m/m^2 at 36 months, well below 0.2 m/m^2. As a general observation, the cracking of bridge decks incorporating crack-reducing technologies such as fibers, SRAs, or IC are comparable to those of the decks without crack-reducing technologies. Once the paste content exceeds 27.2%, cracking tends to increase. Of the nine decks with a paste content greater than 27.2%, seven decks have crack densities above 0.2 m/m^2 at 36 months.

Among the six PS-IC-LC-HPC decks (with good construction) included in Figure 6.1 (Table 6.1) deck MN-IC-LC-HPC-7-P1, with a paste content of 25.9%, exhibited the highest crack density, with a value of 0.059 m/m^2 and deck KS-IC-LC-HPC-2 with a paste content of 24.2%, exhibited the lowest crack density, with a value of 0.004 m/m^2, at an age of 36 months.

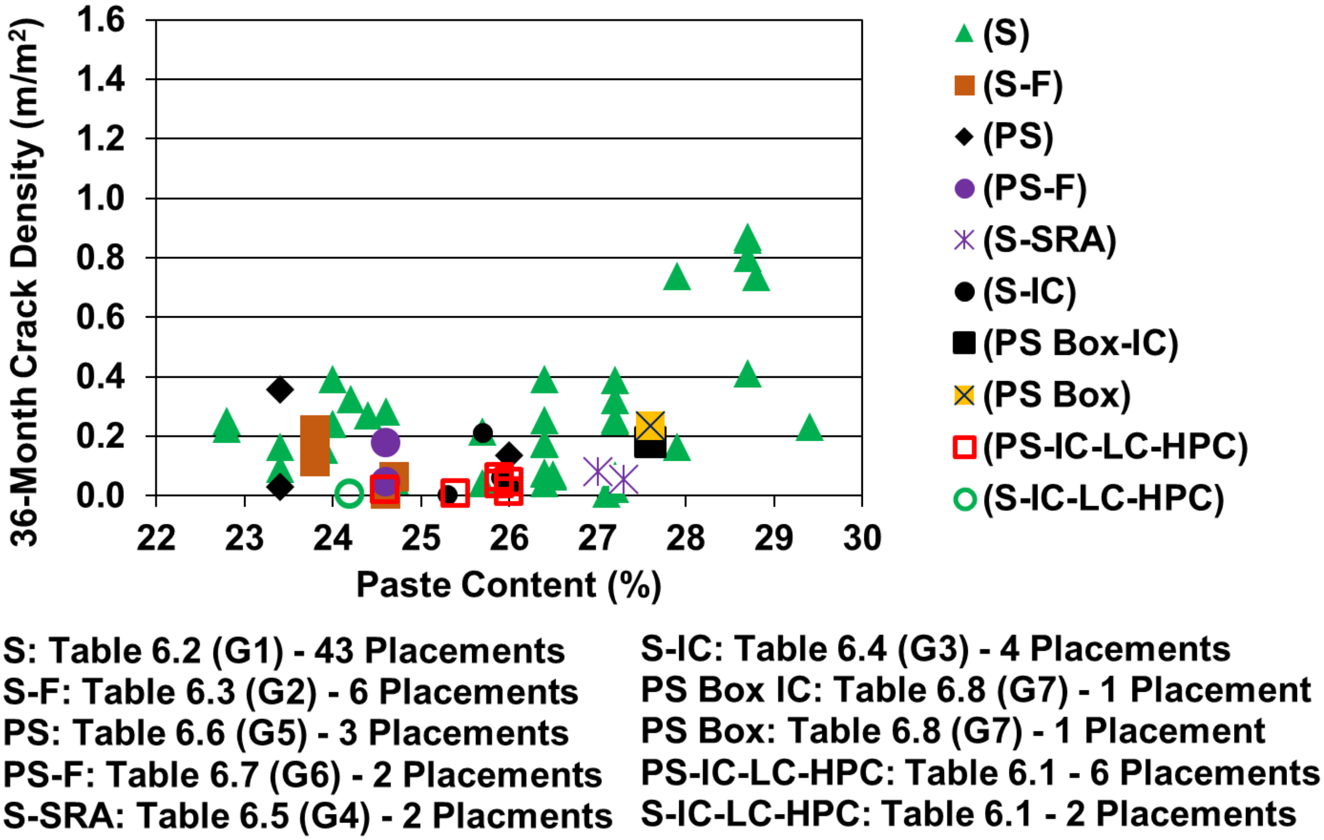


Figure 6.1: Paste content versus 36-month crack density for decks with good construction practices-Decks described in Tables 6.1 to 6.8

Using the results shown in Tables 6.1 and 6.9, the average 36-month crack densities of bridge decks with and without IC for decks supported by steel (S), prestressed precast concrete (PS) girders and prestressed box girders (PS Box) are compared in Figures 6.2 and 6.3, respectively.

In a study that included 40 monolithic bridge decks, Khajehdehi and Darwin (2018) and Khajehdehi et al. (2021) reported that cracking of bridge decks containing more than 26.4% paste at 96 months was higher than that of decks with less than 26.4% paste content, but that reductions below 26.4% provided no additional advantage. The 96-month crack densities of the decks with paste contents ranging from 22.8 to 26.4% were not influenced by differences in paste content. The 96-month crack densities of decks with paste contents greater than 26.4%, however, increased almost linearly as the paste content increased. For the current study, where comparisons of crack density are made at 36 months, the threshold value for paste content is chosen as 27.2%. Decks with paste contents of 27.2% or less are categorized as "Low Paste," and decks with paste contents greater than 27.2% are categorized as "High Paste." Error bars show the ranges of crack density for each deck type. The decks supported by steel girders, designated as "(S)," with "Low Paste," contents include 35 placements, with paste contents ranging from 22.8 to 27.2%; decks designated as "(S)" with "High Paste" contents include eight placements, with paste contents ranging from 27.9 to 28.8%; decks designated as "(S-IC)" with "Low Paste" contents include four placements, with paste contents ranging from 25.3 to 26%; and decks designated as "(S-IC-LC-HPC)," with "Low Paste" contents include two placements, both with a paste content of 24.2%. Similarly, decks supported by prestressed precast concrete girders, designated as "(PS)," with "Low Paste" contents include three placements, with paste contents ranging from 23.4 to 26.0%; decks designated as "(PS-IC-LC-HPC)," with "Low Paste" contents include six placements, with paste contents ranging from 24.6 to 26%; and decks supported by prestressed box girders, designated as "(PS Box)," with "High Paste" contents include two placements, one with IC and one without, both with a paste content of 27.6%.

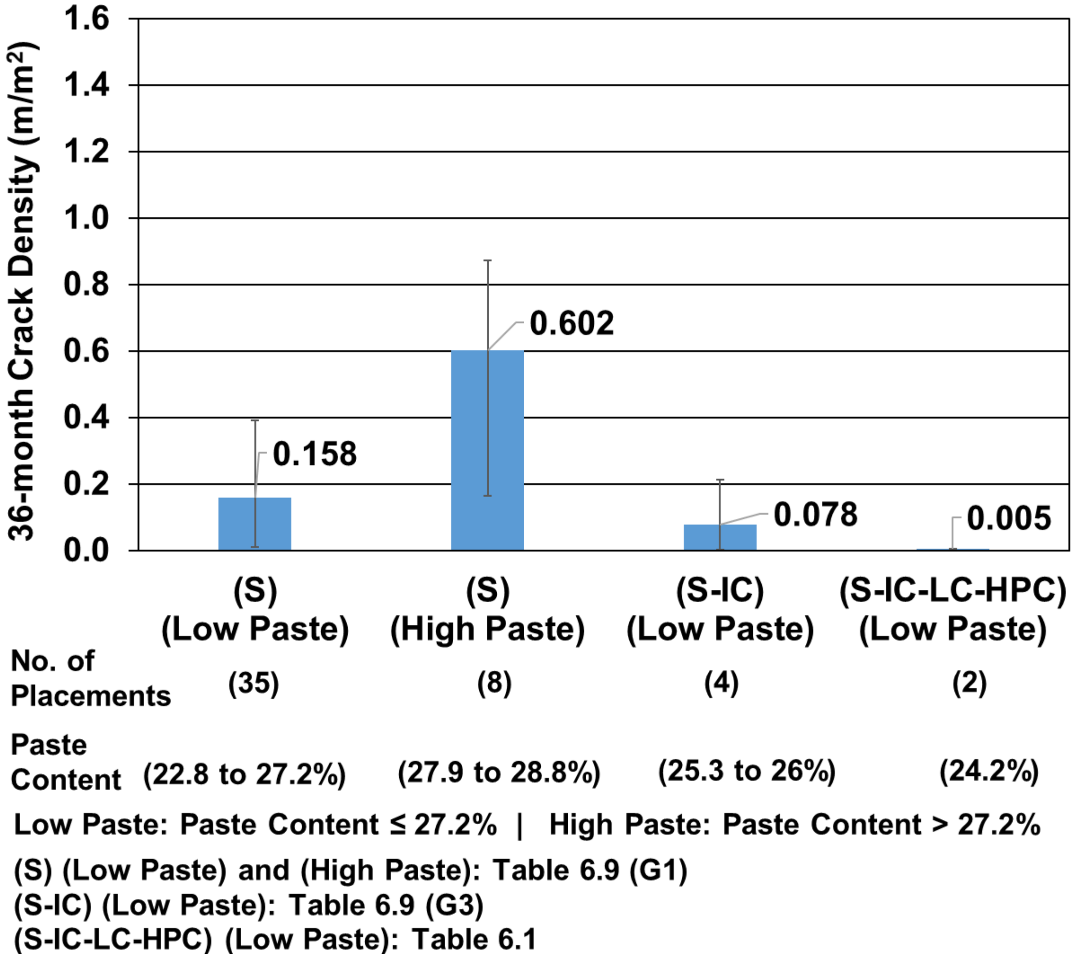


Figure 6.2: Average 36-month crack densities of decks supported by steel girders with and without IC

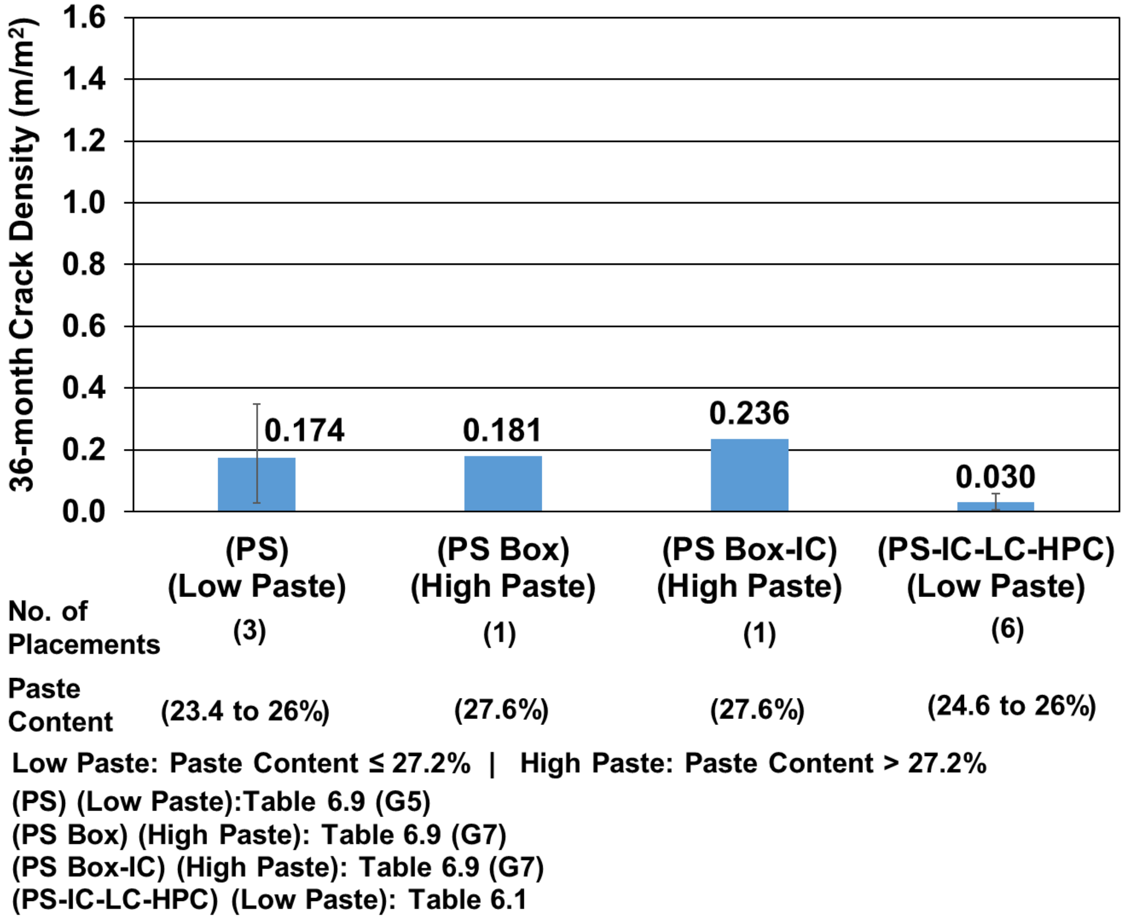


Figure 6.3: Average 36-month crack densities of decks supported by prestressed precast concrete and prestressed box girders with and without IC

Tables 6.11 and 6.12 show the Student's t-test results comparing the cracking of these decks. To perform such an analysis, at least two data points are needed for each data set. Thus, single deck placements supported by prestressed box girders with high paste contents with and without IC are excluded from the tables.

Table 6.11: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported steel girders with and without IC*

Bridges	**Group**	**(S) Low Paste (35 placements)**	**(S) High Paste (8 placements)**	**(S-IC) Low Paste (4 placements)**	**(S-IC-LC-HPC) Low Paste (2 placements)**
Group	**Avg. of 36-month crack density (m/m^2)**	(0.158)	(0.602)	(0.078)	(0.005)
(S) Low Paste (35 placements)	(0.158)		**2.2×10^{-8}**	0.216	0.091
(S) High Paste (8 placements)	(0.602)			**0.006**	**0.023**
(S-IC) Low Paste (4 placements)	(0.078)				0.358

**p* values ≤ 0.05 are shown in bold.

Table 6.12: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by prestressed precast concrete girders with IC

Bridges	**Group**	**(PS) Low Paste (3 placements)**	**(PS-IC-LC-HPC) Low Paste (6 placements)**
Group	**Avg. of 36-month crack density (m/m^2)**	(0.174)	(0.030)
(PS) Low Paste (3 placements)	(0.174)		0.060

Figure 6.2 and Table 6.11 show that on average, the bridge decks with high paste contents (> 27.2%) supported by steel girders exhibit noticeably higher crack densities at 36 months than those with paste contents ≤ 27.2%, with differences that are statistically significant. In decks supported by steel girders, the average 36-month crack densities of decks with low paste contents range from 0.005 for the two S-IC-LC-HPC placements to 0.158 m/m^2 for the 35 S placements, while the average 36-month crack density for the eight S placements with high paste content is 0.602 m/m^2. The difference between the average crack density of decks with high paste contents (average of 0.602 m/m^2) and that of the decks with low paste contents with (0.078 and 0.005 m/m^2)

or without (0.158 m/m^2) IC is statistically significant (p = 0.006 and 0.023 or 2.2×10^{-8}, respectively). In decks supported by steel girders, the difference between the average crack density of decks with low paste contents with or without IC, however, is not statistically significant (p = 0.216 and 0.091).

As shown in Figure 6.3, in decks supported by either prestressed precast concrete girders or prestressed box girders, the average 36-month crack densities of decks with low paste contents ranged from 0.030 for the six PS-IC-LC-HPC placements to 0.174 m/m^2 for the three PS placements (without IC), while the average 36-month crack density for the two PS Box placements (with or without IC) with high paste content is either 0.181 or 0.236 m/m^2. The p-value obtained in Student's t-test indicates that in decks supported by prestressed precast concrete girders with low paste contents, the difference between the cracking of decks with IC and that of the deck without IC, is not statistically significant. (p = 0.060).

Despite the fact that p values for S-IC and S-IC-LC-HPC placements compared to decks without internal curing are greater than 0.05 (0.216 and 0.091, respectively), the S-IC and S-IC-LC-HPC decks consistently exhibited lower cracking than the 35 S placements. As shown in Tables 6.1 and 6.9, only 1 out of 6 decks with IC had a crack density greater than 0.1 m/m^2 versus 18 out of 35 S placements. The scatter of crack density values for the S placements is much greater than for S-IC and S-IC-LC-HPC placements (standard deviations: 0.122, 0.081, and 0.001 m/m^2 for S, S-IC, and S-IC-LC-HPC placements, respectively). Additionally, the sample size of the two categories of decks with internal curing (S-IC and S-IC-LC-HPC) is small. If those decks are grouped (total of six placements) to increase the sample size, the difference between the mean crack density for the IC decks on steel girders, 0.054 m/m^2, and the mean crack density of the 35 S placements with low paste content, 0.158 m/m^2, is statically significant (p = 0.050).

Similar observations can be made for the effects of IC on cracking of decks supported by prestressed precast concrete girders. Although the difference between the average 36-month crack density for the three PS and the six PS-IC-LC-HPC deck placements is not significant ($p = 0.060$), the PS-IC-LC-HPC decks also consistently exhibited lower cracking than the three PS deck placements (mean value of 0.030 vs. 0.174 m/m^2). The range of crack densities for the PS placements (without IC) is much greater in data for PS-IC-LC-HPC placements (between 0.029 to 0.358 m/m^2 vs. 0.007 to 0.059 m/m^2). Therefore, the results shown in Figures 6.2 and 6.3, indicate that the combination of low paste, internal curing, and good construction procedures can provide for a reduction in crack density; the high consistency of lower cracking on the low paste IC-LC-HPC deck placements indicates that the differences shown in Tables 6.11 and 6.12 can be statistically significant and is deserving of further study.

As a general observation, in bridge decks with similar paste contents, the decks with internal curing in conjunction with Minnesota and Kansas IC-LC-HPC specifications (the six PS-IC-LC-HPC and the two S-IC-LC-HPC decks with average 36-month crack densities of 0.030 and 0.005 m/m^2, respectively) had lower average 36-month crack densities than those without IC (35 S and three PS placements with average 36-month crack densities of 0.154 and 0.174 m/m^2, respectively) or those IC Indiana decks (four S-IC placements) that followed specifications for IC-HPC (with an average 36-month crack density of 0.078 m/m^2).

Using the results shown in Tables 4.7, 4.38, 6.4, and 6.8, a comparison in terms of 36-month crack density can also be made as a function of the IC water content, using three ranges of IC water content: 5 to 7%, 7 to 8%, and 8 to 12%. All the decks, except for one (IN-IC), had low paste contents (below 27.2%). As shown in Figure 6.4, the average 36-month crack densities of decks with IC water contents from 5 to 12% (by the weight of binder) range from 0.009 to 0.093

m/m^2, well below 0.4 m/m^2. Table 6.13 shows the Student's t-test results comparing the average 36-month crack densities of IC monolithic decks shown in Figure 6.4. Given that decks with high quantities of IC water typically exhibit lower crack densities, higher cracking of the decks with 7 to 8% or 8 to 12% IC water contents (average of 0.093 and 0.071 m/m^2, respectively) compared to the decks with 5 to 7% IC water contents (with an average crack density of 0.009 m/m^2), is not expected, even though the difference is statistically significant (p = 0.044). Further research is required to obtain more data detailing the impact of IC water quantities on crack density across a variety of ranges.

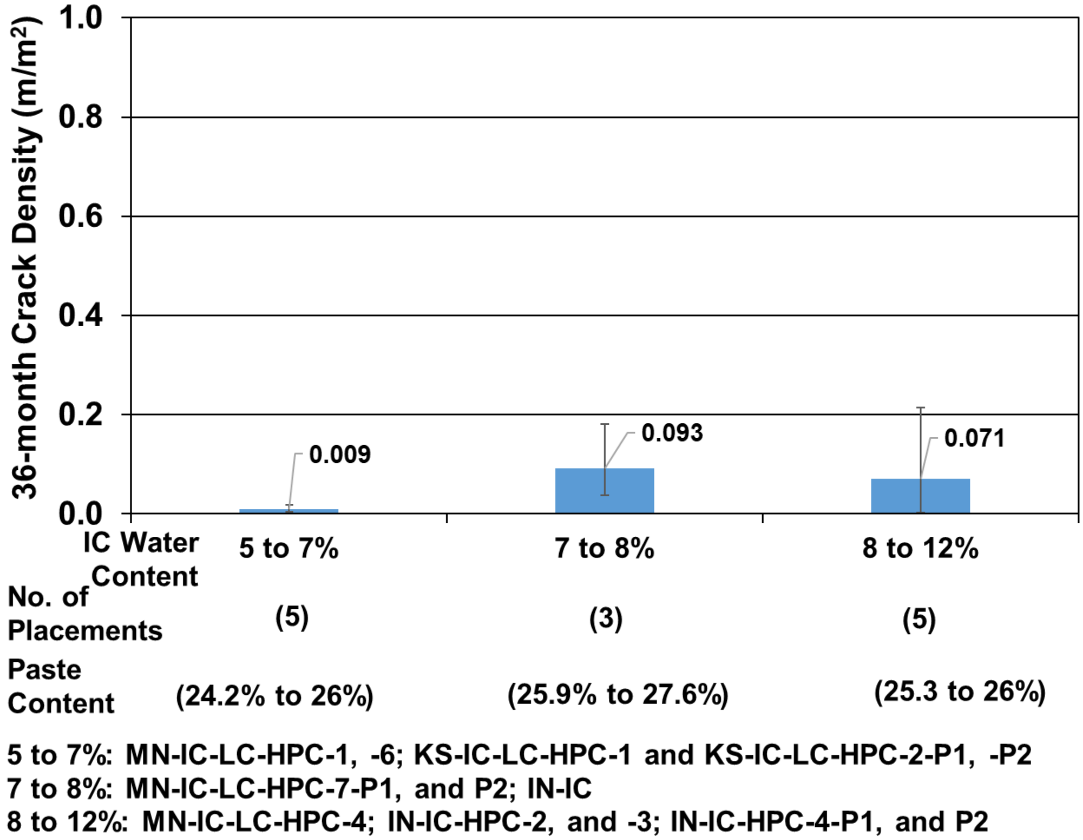


Figure 6.4: 36-month crack densities of IC decks versus IC water contents

Table 6.13: *p* values obtained from Student's t-test for the differences in cracking performance of IC decks*

IC quantities (%, by the weight of binder)	**Group**	**5 to 7%**	**7 to 8%**	**8 to 12%**
Group	**Avg. of 36-month crack density (m/m^2)**	(0.009)	(0.093)	(0.071)
5 to 7%	(0.009)		**0.044**	0.134
7 to 8%	(0.093)			0.726

*p values ≤ 0.05 are shown in bold.

The five decks with 8 to 12% IC water content exhibited lower crack density on average than the three decks with 7 to 8% IC water contents, with a difference that is not statistically significant (p = 0.726). Similar observations were made by Lafikes et al. (2020) who reported that increasing the quantity of IC beyond 7 or 8% (by total weight of binder) does not appear to mitigate cracking significantly.

Although internal curing technology has been demonstrated to be beneficial in mitigating early-age and long-term shrinkage, concerns exist as to the freeze-thaw durability and scaling resistance of IC mixtures. Therefore, the decision to use IC in bridge decks should not be made solely based on positive performance in reducing cracking. In spite of the fact that the durability issues observed on bridge decks appear to be the result of an interaction between multiple factors, it is not clear from the evidence what is the primary contributor factor. Previous studies have recommended providing air contents above 7% to improve freeze-thaw durability and scaling resistance of concrete mixtures incorporating IC water (Feng and Darwin 2020, Lafikes et al. 2020). Lafikes et al. (2020) indicated that increasing the quantity of IC might cause durability issues tied to freezing and thawing, a conclusion that is supported by findings in Chapter 3 (laboratory test results), where increasing the quantity of IC water from 8.2 to 13.0% by weight of cementitious material decreased the freeze-thaw durability of concrete mixtures, regardless of the paste content or quantity of absorbed water in LWA.

In this study, as indicated in Chapters 4 and 5, a number of IC decks exhibited freeze-thaw damage in the form of scaling or aggregate pop-outs or both. It is possible, however, that poor construction practices are the main contributor. The best construction procedures involve adequate and thorough consolidation, minimum finishing, and immediate and extended curing. Accordingly, poor construction practices involve poor consolidation and disturbance of concrete after consolidation, overfinishing, and delayed wet curing.

As discussed in Chapter 1, inadequate consolidation and disturbing freshly consolidated increase the risk of settlement cracking in decks (five out of 11 IC decks had inadequate consolidation). Overfinishing concrete through excessive screeding or bullfloating tends to bring excessive cement paste to the surface while pushing coarse aggregate to lower depths, which can result in increased cracking. Moreover, overfinishing the deck in the presence of bleed water, leads to a thin paste layer with a high *w/cm* at the concrete surface, which can result in scaling damage (four out of 11 IC decks had overfinishing). Delay in curing also reduces hydration at the surface (allowing less water to be tied up permanently through hydration and, thus, permitting more water to evaporate), which can result in increased shrinkage (six out of 11 IC decks had delays in curing). Also, tining can prevent the early application of curing and disrupt the aggregates near the surface (two out of 11). To obtain a rough surface, it is better to grind and groove instead of tining (Lafikes et al. 2020). It is also important to note that curing compounds do not mitigate cracking to the extent provided by wet curing (provided by wet burlap), as they slow down but do not stop drying.

In this study, seven out of the 11 IC-LC-HPC deck placements constructed in Minnesota and Kansas (MN-IC-LC-HPC-1, -4, -5, and -6; KS-IC-LC-HPC-1, -2, and -3) exhibited durability or surface damage, and three out of the 11 (MN-IC-LC-HPC-5, -8, and -9) exhibited high cracking, all of which tied to either poor construction practices, time of placement (curing at cold ambient temperatures), or low air content (below specifications limit, 6.5%), as briefly summarized below:

No significant issues arose during placement, finishing, and consolidation of MN-IC-LC-HPC-1, except for some long delays in curing. The deck had a 36-month crack density of 0.007 m/m^2 with some observable scaling damage near the barriers. MN-IC-LC-HPC-2 and -3 had a 2-in. (50.8 mm) overlay and are, therefore, excluded from the discussion.

Cracking and surface damage of MN-IC-LC-HPC-4 were mainly due to disturbance of the concrete after consolidation and long delays in curing observed during construction; at some locations, construction personnel were observed stepping in concrete that had been previously vibrated, resulting in the formation of a number of narrow longitudinal and transverse cracks (with an average crack width of 0.003 in. [0.08 mm]) over the entire deck area. The majority of the cracks, however, were short with crack lengths below 1 ft (305 mm), resulting in a 36-month crack density of 0.045 m/m^2. The deck was also heavily tined immediately after finishing and before application of the curing compound, resulting in varying groove widths and depths and delays in curing.

High cracking and scaling damage observed on MN-IC-LC-HPC-5 were mainly due to inadequate consolidation and overfinishing of the deck. As discussed in Section 4.4.7, contractor personnel were observed stepping on areas that had been recently vibrated, thus, disturbing the concrete after consolidation. Additionally, the contractor over finished the deck in an attempt to remove excess bleed water, leading to a thin paste layer with a high *w/cm* at the concrete surface. The deck had a 36-month crack density of 0.153 m/m^2 with transverse cracks that extended almost one-third of the deck width. Significant scaling was also observed at multiple locations on the surface of the deck.

No significant issues arose during placement and finishing of MN-IC-LC-HPC-6, although on some occasions, contractor personnel walked through areas that had been previously vibrated, resulting in deconsolidation of the concrete. The deck was also heavily tined immediately after finishing and before application of the curing compound, resulting in varying groove widths and depths on the deck surface. In addition, the deck was constructed in late September (cured at cold ambient temperatures). The deck had a 36-month crack density of just 0.011 m/m^2 but exhibited some scaling and surface damage.

As discussed in Section 4.4.9, disturbance of concrete after consolidation and overfinishing were observed on some occasions during the construction of MN-IC-LC-HPC-7-P1 and -P2. The deck had a low crack density (below 0.050 m/m^2 within two years of the deck age) with no observable durability damage on the surface.

High cracking observed on MN-IC-LC-HPC-8 and -9 was likely due to delays in curing and also non-uniform distribution of curing compound applied during construction. MN-IC-LC-HPC-8 and -9 had especially high crack densities, 0.671 and 0.788 m/m^2, respectively, at an age of just 21 months after construction. No noticeable durability damage was observed on either deck.

As discussed in Section 4.7.1, during construction of KS-IC-LC-HPC-1, contractor personnel were observed walking through areas that had been previously vibrated; it was also observed that the vibrators were quickly extracted from the concrete, leaving a series of holes on the surface, resulting in deconsolidation and inadequate consolidation of the concrete. The deck was constructed in late November (cured in cold ambient temperature), where on the day of placement, the air temperature ranged from 38 to 49 °F with an average of 43 °F. The air contents for this deck ranged from 5.5 to 7.6%, with an average of 6.3%, which were below 6.5% the lower limit of the Kansas IC-LC-HPC specifications. In spite of these shortcomings, the deck has an estimated 36-month crack density of 0.019 m/m^2. Some freeze-thaw damage was observed, mainly near the shoulders.

Scaling damage was observed on KS-IC-LC-HPC-2-P1 and P2. This damage was likely due to a combination of overfinishing and long delays in curing. Contractor personnel made repeated bullfloat passes while bleed water was visible on the surface. Much of that excess water was worked back into the surface. Moreover, according to the Kansas IC-LC-HPC specifications, no finishing aids are permitted. In spite of this, the contractor applied a finishing aid on the concrete for the entire deck. The use of the finishing aid increases the *w/cm* ratio at the surface. Additionally, it was observed that the fogging system deposited excessive water on the bridge deck. In some locations, the contractor was observed spraying water directly from a work bridge on the surface in an attempt to wet the burlap. The deck also had issues with inadequate consolidation, As discussed in Section 4.7.2, contractor personnel were observed walking through areas that had been previously vibrated, resulting in deconsolidation of the concrete. The deck had a crack density below 0.050 m/m^2 at an age of approximately 19 months after construction for both placements (low, but too early to evaluate the long-term cracking performance of the deck), with significant scaling damage in multiple spots on the surface.

As with KS-IC-LC-HPC-2, scaling damage was observed on KS-IC-LC-HPC-3, likely related to the adverse effects of the use of finishing aid and overfinishing the deck in the presence of bleed water. The deck had a crack density of 0.061 m/m^2 at an age of 9.2 months.

These examples clearly indicate that poor construction practices, time of placement (curing at cold ambient temperatures), and low air content (below specifications limit, 6.5%) can affect the freeze-thaw durability and scaling resistance of IC mixtures.

As discussed in Chapter 3, freeze-thaw damage can also be associated with excess quantities of IC water (probably better described as too much total internal water, which includes moisture in all aggregates), especially in decks with low air contents, which is the case for a number of IC decks constructed in Indiana, as documented by Lafikes et al. (2020). Some aggregate pop-outs were observed on IN-IC-HPC-2, possibly caused by freeze-thaw damage exacerbated by low air content (6.4%), excess IC water content (9.2% by the weight of binder), and late placement of the deck (October, cured at cold ambient temperatures). Poor tining was also observed on the deck, which would have also delayed the application of curing. Similarly, freeze-thaw damage and aggregate pop-outs were observed on IN-IC-HPC-3. IN-IC-HPC-3 contained 11.6% IC water content (17.0% total internal water), and it was constructed in November (cured at cold ambient temperatures), which increased the potential for concrete durability problems. IN-IC-HPC-4-P1 and -P2 also exhibited freeze-thaw and scaling damage. IN-IC-HPC-4-P1 and -P2 had air contents of 6.2 and 5.5%, respectively, with IC water contents of greater than 11% by weight of cementitious material (16.6% total internal water), possibly the main causes for poor scaling and freeze-thaw resistance. Poor tining was also noticed in both placements, which would have also delayed the application of curing. Three IN-IC-HPC decks exhibited low 36-month crack densities, with values of 0.003, 0.061, and 0.032 m/m^2 for IN-IC-HPC-2, -3, and -4-P2 decks, respectively. IN-IC-HPC-4-P1,0.214 had a 36-month crack density of 0.214.

6.4.2 Effects of Poor Construction Practices

In this section, the 36-month crack densities of bridge decks with poor construction practices are compared with those of the decks with or without crack-reducing technologies following good construction practices. As discussed in Section 6.4.1, three Minnesota IC-LC-HPC decks (MN-IC-LC-HPC-5, -8, and -9) exhibited significant construction issues. Two decks (MN-

IC-LC-HPC-8 and -9) had crack densities much greater than 0.4 m/m^2. Although MN-IC-LC-HPC-5, a pedestrian bridge deck, had a crack density of 0.153 m/m^2 at an age of 34.1 months, the deck exhibited significant cracking and durability issues compared to similar pedestrian bridge decks surveyed in this study, with crack densities no higher than 0.034 m/m^2. Figure 6.5 compares the 36-month crack densities of these three decks with those with poor construction practices that are used for comparison (Section 6.3.2). All has paste contents below 27.2%. Results for decks with fibers (S-F) also are shown to investigate the effectiveness of this crack-reducing technology when poor construction practices are followed.

As shown in Figure 6.5, the average 36-month crack densities of the three PS-IC-LC-HPC decks (Table 6.1) surveyed in this study are similar to most of the decks (eight S placements and four S-F placements shown in Table 6.10) that had poor construction practices (such as insufficient consolidation or overfinishing). As shown in the figure, the average 36-month crack densities of decks with construction issues were 0.470 m/m^2 and above, even when low paste content concretes were used; the average 36-month crack density of the three PS-IC-LC-HPC decks (MN-IC-LC-HPC-5, -8, and -9) containing IC water, shown in Figure 6.5, is 0.537 m/m^2, and that of the decks without crack reducing technology or with fibers is either 0.577 or 0.470 m/m^2, respectively. The results of Student's t-test results provided in Table 6.14 show that with the paste contents ranging from 22.2 to 26%, the differences in crack density of the poorly constructed decks documented in Section 6.3.2 with fibers or without crack-reducing technology (averages of 0.470 or 0.577 m/m^2, respectively) and the three PS-IC-LC-HPC decks (0.537 m/m^2) are not statistically significant (p = 0.743 and 0.856, respectively).

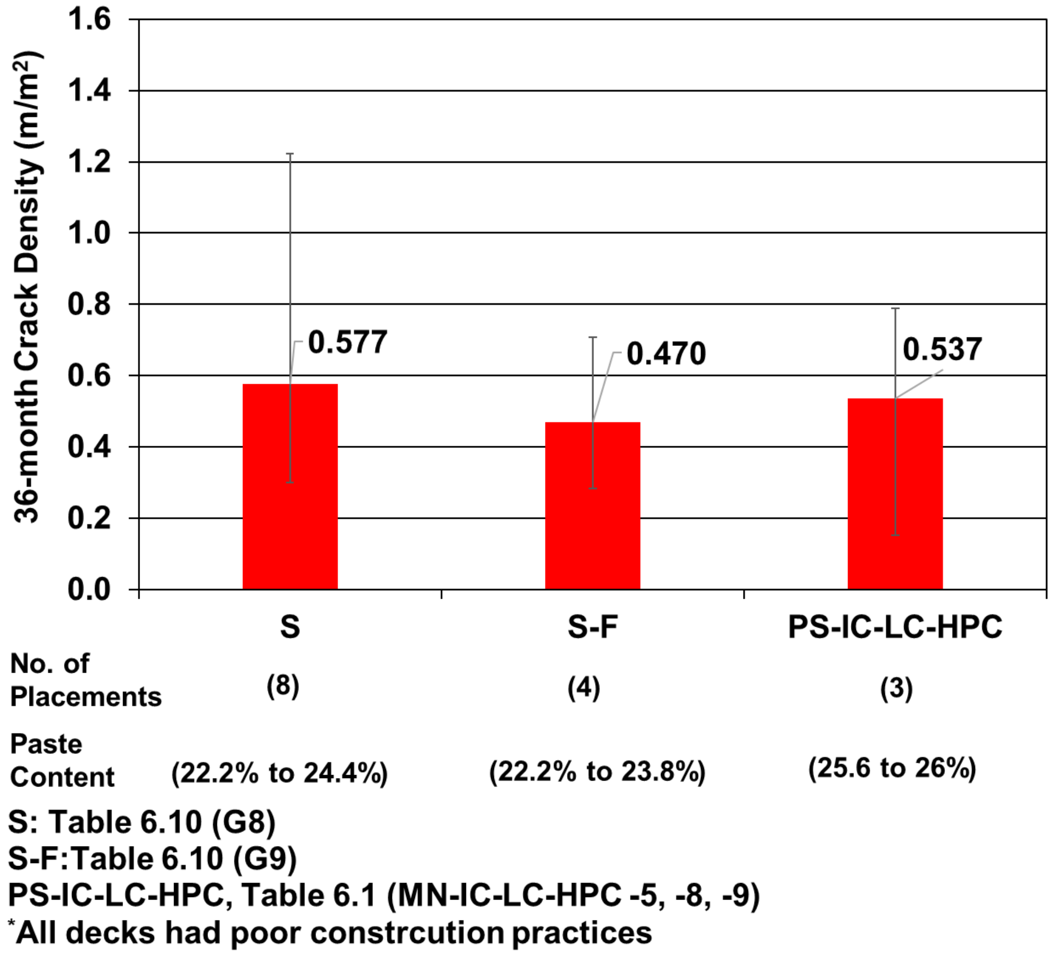


Figure 6.5: Comparing the 36-month crack densities of decks with construction issues

Table 6.14: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by steel and prestressed concrete girders, poorly constructed, with and without crack-reducing technology

Bridges	Group	(S)	(S-F)	(PS-IC-LC-HPC)
Group	Avg. of 36-month crack density (m/m^2)	(0.577)	(0.470)	(0.537)
(S)	(0.577)		0.543	0.856
(S-F)	(0.470)			0.743

The adverse effects of poor construction practices in bridge deck cracking are illustrated in Figure 6.6 by a comparison between poor construction practices and good construction practices in low paste (22.2 to 27.2%) concrete decks supported by prestressed precast concrete and steel girders with or without crack-reducing technologies. The results of Student's t-test results are provided in Table 6.15. As shown in the figure, the average 36-month crack densities of decks that followed poor construction practices, which range from 0.470 to 0.577 m/m^2, are at least three times higher than those that followed good construction practices, which range from 0.030 to 0.158 m/m^2, with differences that are statistically significant (p values ranging 1.9×10^{-7} to 0.045). Additionally, although the use of crack-reducing technologies such as fibers and IC-LC-HPC resulted in a reduction in cracking (0.089 and 0.030 vs. 0.158 m/m^2) their use cannot overcome the negative effects of poor construction practices (0.470 and 0.537 vs. 0.158 m/m^2).

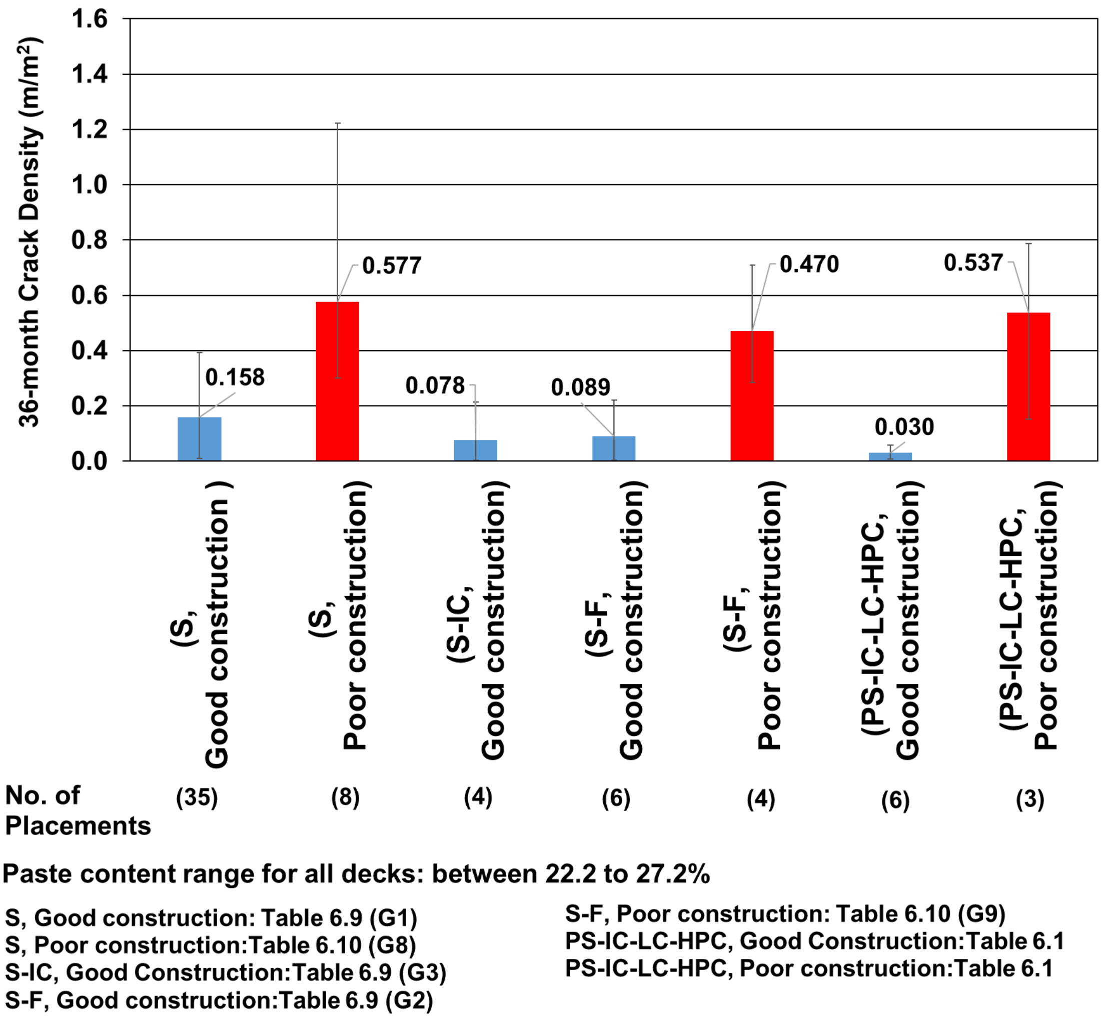


Figure 6.6: Comparing the 36-month crack densities of decks with good vs. poor construction practices

Table 6.15: *p* values obtained from Student's t-test for the differences in cracking performance of decks supported by steel and prestressed concrete girders, poorly or well-constructed, with and without crack-reducing technology*

Bridges	Group	(S, Good construction)	(S, Poor construction	(S-IC, Good construction)	(S-F, Good construction)	(S-F, Poor construction)	(PS-IC-LC-HPC, Good construction)	(PS-IC-LC-HPC, Poor construction
Group	Avg. of 36-month crack density (m/m^2)	(0.158)	(0.577)	(0.078)	(0.089)	(0.470)	(0.030)	(0.537)
(S, Good construction)	(0.158)		**1.9×10^{-7}**	0.216	**0.197**	**5.0×10^{-7}**	**0.019**	**1.0×10^{-4}**
(S, Poor construction	(0.577)			**0.012**	**0.003**	0.543	**0.001**	0.856
(S-IC, Good construction)	(0.078)				0.841	**0.008**	0.251	**0.045**
(S-F, Good construction)	(0.089)					**0.002**	0.115	**0.014**
(S-F, Poor construction)	(0.470)						**2.5×10^{-4}**	0.743
(PS-IC-LC-HPC, Good construction)	(0.030)							**0.005**

**p* values ≤ 0.05 are shown in bold.

6.5 CONCLUSIONS

In this chapter, the crack survey results are converted to equivalent crack densities at 36 months of age to provide a consistent comparison between decks. The effects of paste content, internal curing, and construction practices on cracking performance of the Minnesota and Kansas IC-LC-HPC monolithic bridge decks surveyed in this study at 36 months were investigated in comparison with crack surveys of 74 other bridge deck placements with paste contents between 22.8 and 29.4%.

The following conclusions are based on the results and analyses presented in this chapter.

1. When the paste content is less than or equal to 27.2% of the concrete volume, IC decks

constructed in conjunction with the Minnesota and Kansas IC-LC-HPC (MN-IC-LC-HPC and KS-IC-LC-HPC) or Indiana HPC (IN-IC-HPC) specifications exhibited lower average 36-month crack densities than those without IC, although the differences are not statistically significant ($p > 0.05$). This indicates that the combination of low paste, internal curing, and good construction procedures offer the potential to reduce cracking, but because the number of bridges is small and the differences in crack density between non-IC and IC decks are not statistically significant, the use of internal curing requires further study.

2. Poor construction practices, including poor consolidation and disturbance of concrete after consolidation, overfinishing, delayed application of wet curing, and tining as one of the potential causes for delayed curing can lead to durability problems.
3. Paste contents above 27.2% of the concrete volume correlate with increased cracking.
4. Good construction practices are needed for low-cracking decks. If poor construction practices are employed, even decks with low paste content and IC can exhibit high cracking.

CHAPTER 7 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY

The laboratory portion of this study investigates the effects of internal curing (IC) water in pre-wetted lightweight aggregates ranging between 8.2 and 9.0% and between 12.0 to 13.1% by weight of binder and total internal water (TI water) in all aggregates between 3.4 and 12.5% by weight of binder on freeze-thaw durability, scaling resistance, shrinkage, and ion transport properties of concrete mixtures with different binder compositions, paste contents, and water-to-cementitious material ratios (*w/cm*). Normalweight aggregates consisted of three types of coarse aggregates (granite [with absorptions between 0.6 and 0.86%], low absorption limestone [with absorptions of 0.73 and 0.89%], and high absorption limestone [with an absorption of 2.2%]) and river sand.

The mixtures were evaluated for freeze-thaw durability in accordance with ASTM C666-Procedure A (34 mixtures) and ASTM C666-Procedure B (12 mixtures), the latter following the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22, *Resistance of Concrete to Rapid Freezing and Thawing*, scaling resistance in accordance with ASTM C672 (16 mixtures) and Canadian test BNQ NQ 2621-900 (8 mixtures), free shrinkage in accordance with a modified version of ASTM C157 (8 mixtures, readings begin just after final set), rapid chloride permeability (RCP) in accordance with ASTM C1202 (8 mixtures), and surface resistivity measurement (SRM) results per AASHTO TP-95 and Louisiana Department of Transportation and Development (8 mixtures, LA DOTD TR 233-11). The mixtures had binders consisting of portland cement alone or a ternary composition including 30% slag cement and 3% silica fume as partial replacements for portland cement (by total weight of cementitious materials), paste contents of 23.7, 24.6, 26.7, or 33.7%, and water-to-cementitious material ratios of 0.41 or 0.45.

The second portion of the study, field work, involved the construction, crack surveys, and evaluation of 12 bridge decks containing IC water and supplementary cementitious materials (SCMs) that were constructed following IC-LC-HPC specifications (of Minnesota or Kansas) and two associated Control decks without IC (MN-Control). The decks were monolithic with the exception of three of the Minnesota decks, which had an overlay. Of the 12 IC decks, nine (identified as MN-IC-LC-HPC-1 to -9) were constructed in Minnesota between 2016 and 2020, and three (identified as KS-IC-LC-HPC-1 to -3) were constructed in Kansas between 2019 and 2021. The crack survey results are expressed in terms of crack densities at 36 months of age to provide a consistent comparison between decks. The effects of paste content, internal curing, and construction practices on cracking performance of the monolithic bridge decks surveyed in this study are compared with those of 74 earlier bridge deck placements with paste contents between 22.8 and 29.4%. The effects of construction practices on the durability of IC-LC-HPC decks are discussed.

7.2 CONCLUSIONS

The following conclusions are based on the results and analyses presented in this study.

7.2.1 Laboratory Evaluations

1. The freeze-thaw durability of internally-cured concrete mixtures is a function of the percentage of IC water by the weight of binder, rather than the absorbed water in the lightweight aggregate per unit volume of concrete.

2. Reducing the *w/cm* ratio from 0.45 to 0.41 for all the mixtures with a paste content of 23.7%, and for some mixtures with paste contents of either 26.7 or 33.7% improved the freeze-thaw durability of the concrete.
3. At *w/cm* ratios of 0.45 or 0.41, all the IC mixtures assessed for freeze-thaw durability in accordance with ASTM C666-Procedure A exhibited durability factors below 90% and failed the freeze-thaw test and would not be considered acceptable under MnDOT specifications.
4. At a *w/c* ratio of 0.45, mixtures with IC water contents (by the weight of binder) of 8.2 (with a paste content of 23.7%) and 8.8% (with a paste content of 26.7%) and tested in accordance with ASTM C666-Procedure B and KTMR-22 exhibited durability factors above 95%, passing the test and are considered acceptable under KDOT specifications.
5. At a *w/c* ratio of 0.41, all mixtures tested (IC water contents ranging from 8.6 to 13.0 and paste contents ranging from 23.7 to 33.7%) satisfied the requirements of ASTM C666-Procedure B and KTMR-22 and are considered acceptable under KDOT specifications.
6. The freeze-thaw resistance of the mixtures decreased markedly when the total internal water (provided by all aggregates) exceeded 12.0% by the weight of binder.
7. The ternary mixtures (consisting of 30% slag cement and 3% silica fume as partial replacements for portland cement [by total weight of cementitious materials]) with granite as the coarse aggregate exhibited better freeze-thaw resistance than the paired ternary mixtures with low-absorption limestone. Additionally, the mixtures containing portland cement as the only binder with TI water contents equal to 3.4 or 8.7% (by the weight of binder) exhibited considerably higher freeze-thaw resistance than the ternary mixtures with the same TI water content.

8. As the paste content increased from 23.7 to 33.7%, scaling resistance decreased.
9. As observed in the freeze-thaw tests, reducing the *w/cm* ratio from 0.45 to 0.41 improved scaling resistance. Mixtures tested in accordance with BNQ NQ 2621-900 (exposed to NaCl) had lower mass losses (by 32 to 47%) than the paired mixtures tested in accordance with ASTM C672 (exposed to $CaCl_2$). The reaction between calcium hydroxide ($Ca(OH)_2$) produced during the hydration of portland cement and calcium chloride can result in the formation of calcium oxychloride, which is expansive and causes tensile stresses and deterioration in concrete. The scaling tests performed in accordance with ASTM C672 result in increased damage.
10. When tested in accordance BNQ NQ 2621-900 (exposed to NaCl), for a given *w/cm* and paste content, as the quantity of IC water increased, the scaling damage increased. At a *w/cm* ratio of 0.45 and a paste content of 23.7%, mixtures with an IC water content of 8.8% passed the test; while those with IC water content above 12.0% did not; at a *w/cm* ratio of 0.41 and a paste content of 23.7%, mixtures with IC water contents of less than or equal to 13% passed the test. None of the mixtures with *w/cm* ratios of 0.45 and 0.41 and a paste content of 33.7% passed the test.
11. Except for two mixtures with IC water contents of 8.8 or 9.0% and *w/cm* ratios of 0.45 and 0.41, respectively, mixtures tested in accordance with ASTM C672 exhibited a visual rating of (2) or (3). MN-IC-LC-HPC specifications limit visual rating of concrete specimens to (0) or (1), representing minimal damage, when tested in accordance with ASTM C672.
12. In contrast to findings in the freeze-thaw test, increased TI water content did not negatively affect scaling resistance. At the same time, the type of coarse aggregate did. The ternary

mixtures with granite as the coarse aggregate, with 3.0 or 8.7% of TI water (0 or 5.9% of IC water), had lower mass losses than the ternary mixtures with low-absorption limestone and similar quantities of TI water.

13. For similar quantities of total internal water, mixtures containing slag cement and silica fume as partial replacements for portland cement exhibited lower shrinkage than mixtures containing portland cement as the only binder. As the total internal water increased, shrinkage of concrete decreased for a given binder composition.
14. All specimens expanded (swelling) during the 14-day curing period, regardless of binder compositions or quantity of IC water. Mixtures with IC water (8.7 to 12.5% TI water) exhibited somewhat greater expansion at the end of the curing period than mixtures with no IC water (3.0 and 3.4% TI water) with values for mixtures without IC water ranging from 20 to 30 microstrain compared to mixtures with IC water that exhibited expansions ranging from 37 to 90 microstrain.
15. For a given binder composition, mixtures with no IC water exhibited greater shrinkage and lower scaling resistance than mixtures with IC water. All the mixtures with no IC water exhibited satisfactory freeze-thaw resistance while three mixtures with IC water (T-9.0-L, T-12.0-L, and T-12.5-H) failed the freeze-thaw test in accordance with ASTM C666-Procedure A.
16. Increases in TI water did not affect rapid chloride permeability (RCP) or the surface resistivity measurement (SRM). The effect of binder compositions, however, was more pronounced, with the ternary mixtures, on average, showing higher and lower SRM and RCP values, respectively, than mixtures with 100% portland cement.

17. A comparison between mixtures with similar TI water but different IC water contents, or more specifically mixtures with low and high absorption limestone, respectively, indicates that mixture with low absorption limestone, T-12.0-L, exhibited better performance than the mixture with high absorption limestone, T-12.5-H with lower shrinkage, higher freeze-thaw and scaling resistance, lower RCP and higher SRM values, with differences that are statistically significant.

7.2.1 Field Work Evaluations

1. As demonstrated in earlier studies, the placement of overlays on bridge decks is not beneficial in mitigating cracking; the two IC bridge decks with an overlay exhibited much greater cracking than the IC decks without an overlay. The use of overlays on bridge decks is not recommended and should be avoided.
2. Low-cracking bridge decks require concrete with a paste content of 27.2% or less of the concrete volume. Paste contents above 27.2% correlate with increased cracking. For decks with paste contents greater than 27.2%, the addition of IC and SCMs does not overcome the negative effects of high paste content.
3. When the paste content is less than or equal to 27.2% of the concrete volume, IC decks constructed in conjunction with the Minnesota and Kansas IC-LC-HPC (MN-IC-LC-HPC and KS-IC-LC-HPC) or Indiana HPC (IN-IC-HPC) specifications exhibited lower average 36-month crack densities than those without IC, although the differences were not statistically significant ($p > 0.05$). This indicates that the combination of low paste, internal curing, and good construction procedures offer the potential to reduce cracking, but because the number of bridges was small, it deserves further study.
4. Good construction practices are needed for low-cracking decks. If poor construction

practices, including poor consolidation and disturbance of concrete after consolidation, overfinishing, delayed application of wet curing, and tining as one of the potential causes for delayed curing, are employed, even decks with low paste content and IC can exhibit high cracking.

5. Poor construction practices can, also, result in scaling damage on bridge decks.

7.3 RECOMMENDATIONS

1. Further research is recommended to study, with greater scope, how the freeze-thaw resistance of IC mixtures changes with a broader range for *w/c* ratio and binder composition, including supplementary cementitious materials, following the regime specified in the KTMR-22 test procedure.
2. Further research is recommended to evaluate the scaling resistance of concrete mixtures with quantities of IC water between 7 and 8.8% (by the weight of binder) and paste contents between 23.7 and 27.2%.
3. Further evaluation is recommended as to the effects of total internal water (provided by all aggregates) on the freeze-thaw durability and scaling resistance of internally-cured concrete mixtures containing granite or low absorption limestone (<1%, OD basis) and high absorption limestone (>1% , OD basis) as the coarse aggregate.
4. To provide the correct quantity of IC water, the final mixture proportions of the IC-LC-HPC mixtures should be based on the LWA absorption measured on the day of placement. Concrete suppliers should be authorized to adjust LWA and normalweight fine aggregate batch weights to maintain the design quantity of IC water. It is also recommended that LWA absorption, specific gravity, and free surface moisture of LWA be measured by placing the material into a pre-wetted surface dry condition (PSD) condition using a

centrifuge rather than using the paper towel method described in ASTM C1761. The procedure used by KU researchers is described in Section 2.3.2.

5. The use of low paste content, proper consolidation, minimal finishing, early initiation of and extended curing can significantly reduce bridge deck cracking. Construction practices used by contractors for all bridge decks should be closely regulated by state transportation departments.
6. To minimize cracking, concrete should be thoroughly consolidated and a strict prohibition should be imposed on walking in or disturbing concrete after consolidation. Overfinishing in an attempt to remove excess bleed water, as well as delayed application of curing, results in cracking and durability damage of bridge decks and, therefore, should not be permitted. Tining can disrupt the aggregates on the upper surface and prevent the early application of curing. To obtain a rough surface, it is better to grind and groove the deck surface instead of tinning.
7. Curing compounds do not appear to mitigate cracking efficiently when compared to early wet curing (provided by wet burlap), as they slow down but do not stop drying. It is recommended that wet curing be initiated immediately after finishing.

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APPENDIX A: FREEZE-THAW AND SCALING TEST RESULTS FOR MIXTURES IN PROGRAM I AND II IN CHAPTER 3

Table A.1: Freeze-Thaw results for mixtures in Program I

Mixture: 23.7%-8.5-0.45									
Cycles	**0**			**24**			**33**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.7**	**2080.1**	**2050.8**	**2050.78**	**2065.4**	**2050.78**	**2050.78**	**2080.1**	**2065.4**
Mass [g]	**7100.5**	**7150.7**	**7139.3**	**7105.4**	**7148.8**	**7145.6**	**7099.9**	**7145.8**	**7140**
$E_{Dyn.}$ [Pa]	3.2E+10	3.4E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: 23.7%-8.5-0.45									
Cycles	**59**			**95**			**114**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2080.1**	**2065.4**	**2050.8**	**2080.1**	**2065.4**	**2050.78**	**2080.08**	**2050.78**
Mass [g]	**7100.2**	**7141.4**	**7139.5**	**7076.3**	**7117.5**	**7117.8**	**7062.8**	**7101.5**	**7105.8**
$E_{Dyn.}$ [Pa]	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: 23.7%-8.5-0.45									
Cycles	**139**			**174**			**203**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2080.08**	**2050.78**	**2021.48**	**2036.13**	**2036.13**	**2006.84**	**2021.48**	**2021.48**
Mass [g]	**7062.8**	**7101.5**	**7105.8**	**7020.3**	**7061.5**	**7053.6**	**6997.9**	**7045.1**	**7026.3**
$E_{Dyn.}$ [Pa]	3.2E+10	3.3E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.1E+10			3.1E+10		

Mixture: 23.7%-8.5-0.45									
Cycles	**234**			**255**			**287**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1977.54**	**1962.89**	**1962.89**	**1933.59**	**1918.95**	**1904.3**	**1757.81**
Mass [g]	**6978.6**	**7020.1**	**6999.6**	**6960.1**	**7003.9**	**6978.5**	**6940.3**	**6958.6**	**6946.7**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.0E+10	2.9E+10	2.9E+10	2.8E+10	2.8E+10	2.7E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.6E+10		

Mixture: 23.7%-8.5-0.45						
Cycles	**308**			**328**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1816.41**	**1567.38**	**1655.27**	**1669.92**	**1171.88**
Mass [g]	**6920.7**	**6919.2**	**6894.4**	**6909.1**	**6876.1**	**6862.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	1.8E+10	2.1E+10	2.1E+10	1.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			1.7E+10		

Mixture: 23.7%-12.8-0.45									
Cycles	**0**			**28**			**64**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2003**	**2050**	**2032**	**1998**	**2042**	**2035**	**1988**	**2023**	**2012**
Mass [g]	**6923**	**7019.4**	**7023.3**	**6932.6**	**7028.7**	**7033.5**	**6901.1**	**6997.8**	**7014.5**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.2E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.0E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 23.7%-12.8-0.45									
Cycles	98			120			153		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1979	1992	1989	1978	1985	1976	1950	1907	1930
Mass [g]	6860.1	6953.4	6985.8	6846.2	6942.7	6973.6	6790.6	6887.7	6930.7
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.8E+10	2.7E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.8E+10		
Mixture: 23.7%-12.8-0.45									
Cycles	176			197			223		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1913	1857	1892	1853	1712	1812	1738	1431	1624
Mass [g]	6765.3	6863	6911.3	6746.2	6815.1	6894.8	6693.5	6749	6865.3
$E_{Dyn.}$ [Pa]	2.7E+10	2.6E+10	2.7E+10	2.5E+10	2.2E+10	2.5E+10	2.2E+10	1.5E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.4E+10			1.9E+10		

Mixture: 23.7%-12.8-0.45			
Cycles	176		
Specimen	A	B	C
Frequency [Hz]	1913	1857	1892
Mass [g]	6765.3	6863	6911.3
$E_{Dyn.}$ [Pa]	2.7E+10	2.6E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10		

Mixture: 23.7%-12.9-0.45									
Cycles	0			35			70		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2029	2070	2008	2015	2067	2008	2012	2061	1998
Mass [g]	7044	7098	7006.1	7052	7108.8	7015.4	7046.7	7102.4	7005.1
$E_{Dyn.}$ [Pa]	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.1E+10		

Mixture: 23.7%-12.9-0.45									
Cycles	98			135			169		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1989	2047	1985	1885	1985	1937	1646	1868	1844
Mass [g]	7023	7074.1	6964	7001.7	7068.5	6952.6	6964.3	7022.5	6895.9
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.0E+10	2.7E+10	3.0E+10	2.8E+10	2.0E+10	2.7E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			2.8E+10			2.4E+10		

Mixture: 23.7%-12.9-0.45						
Cycles	190			211		
Specimen	A	B	C	A	B	C
Frequency [Hz]	1330	1720	1720	1075	1349	1470
Mass [g]	6944	7016.7	6881	6845.2	6977.5	6832.9
$E_{Dyn.}$ [Pa]	1.3E+10	2.2E+10	2.2E+10	8.6E+09	1.4E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	1.9E+10			1.3E+10		

Mixture: 26.7%-8.5-0.45									
Cycles	0			26			61		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1992.19	1977.5	1977.5	1992.19	1977.5	1977.5	1992.2	1977.54	1977.54
Mass [g]	6988	6949.3	6940	6992.3	6953.4	6944	6985.2	6942.3	6934.8
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-8.5-0.45									
Cycles	**80**			**106**			**141**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1977.54**	**1962.89**	**1977.54**	**1977.54**	**1962.89**	**1977.54**	**1977.54**	**1948.24**
Mass [g]	**6974.6**	**6926.5**	**6923.6**	**6958.6**	**6912.6**	**6901.2**	**6936.5**	**6889.3**	**6872.5**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 26.7%-8.5-0.45									
Cycles	**170**			**201**			**222**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1962.89**	**1948.24**	**1962.89**	**1948.24**	**1948.24**	**1948.24**	**1933.59**	**1948.24**
Mass [g]	**6915.9**	**6870**	**6859.2**	**6892.2**	**6839.1**	**6827**	**6871.7**	**6824**	**6801.4**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.8E+10		

Mixture: 26.7%-8.5-0.45									
Cycles	**254**			**275**			**295**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1889.65**	**1933.59**	**1904.3**	**1860.35**	**1918.95**	**1875**	**1816.41**	**1904.3**
Mass [g]	**6844.9**	**6800.1**	**6782.3**	**6818.9**	**6772.9**	**6763.1**	**6811.3**	**6756.8**	**6754**
$E_{Dyn.}$ [Pa]	2.8E+10	2.6E+10	2.7E+10	2.7E+10	2.5E+10	2.7E+10	2.6E+10	2.4E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.6E+10			2.6E+10		

Mixture: 26.7%-8.5-0.45									
Cycles	**321**			**348**			**367**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1743.16**	**1889.65**	**1713.87**	**1669.92**	**1845.7**	**1567.38**	**1567.38**	**1801.76**
Mass [g]	**6803.9**	**6737.4**	**6729.8**	**6767.6**	**6650.3**	**6681**	**6744.4**	**6628**	**6661.3**
$E_{Dyn.}$ [Pa]	2.5E+10	2.2E+10	2.6E+10	2.2E+10	2.0E+10	2.5E+10	1.8E+10	1.8E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.2E+10			2.0E+10		

Mixture: 26.7%-8.5-0.45			
Cycles	**399**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1303.71**	**1333.01**	**1684.57**
Mass [g]	**6724.9**	**6607.2**	**6530.7**
$E_{Dyn.}$ [Pa]	1.2E+10	1.3E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	1.5E+10		

Mixture: 26.7%-8.7-0.45									
Cycles	**0**			**26**			**61**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**2006.84**	**1962.89**	**1962.89**	**2006.84**	**1962.89**	**1962.89**	**2006.84**	**1962.89**
Mass [g]	**6964.8**	**7074.7**	**6944.5**	**6972**	**7080.8**	**6948.8**	**6962.8**	**7068**	**6936.6**
$E_{Dyn.}$ [Pa]	2.9E+10	3.1E+10	2.9E+10	2.9E+10	3.1E+10	2.9E+10	2.9E+10	3.1E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.7-0.45									
Cycles	**80**			**106**			**141**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**2006.84**	**1962.89**	**1962.89**	**2006.84**	**1962.89**	**1948.24**	**2006.84**	**1948.24**
Mass [g]	**6951.9**	**7068.5**	**6926**	**6939.1**	**7042.9**	**6912.3**	**6908.2**	**7014.3**	**6883.7**
$E_{Dyn.}$ [Pa]	2.9E+10	3.1E+10	2.9E+10	2.9E+10	3.1E+10	2.9E+10	2.8E+10	3.1E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			2.9E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-8.7-0.45									
Cycles	**170**			**201**			**222**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**2006.84**	**1948.24**	**1904.3**	**1992.19**	**1948.24**	**1889.65**	**1992.19**	**1948.24**
Mass [g]	**6889.7**	**6995.9**	**6862.2**	**6858.4**	**6975.1**	**6835.9**	**6839.1**	**6979.6**	**6824.1**
$E_{Dyn.}$ [Pa]	2.8E+10	3.1E+10	2.8E+10	2.7E+10	3.0E+10	2.8E+10	2.6E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.8E+10		
Mixture: 26.7%-8.7-0.45									
Cycles	**254**			**275**			**295**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1992.19**	**1948.24**	**1772.46**	**1992.19**	**1933.59**	**1684.57**	**1977.54**	**1933.59**
Mass [g]	**6803**	**6935.7**	**6769.8**	**6787.7**	**6915.6**	**6766.4**	**6776.2**	**6905.9**	**6735**
$E_{Dyn.}$ [Pa]	2.5E+10	3.0E+10	2.8E+10	2.3E+10	3.0E+10	2.7E+10	2.1E+10	2.9E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.6E+10		

Mixture: 26.7%-8.7-0.45									
Cycles	**321**			**348**			**367**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1552.73**	**1948.24**	**1904.3**	**1362.3**	**1904.3**	**1860.35**	**1259.77**	**1875**	**1831.05**
Mass [g]	**6774.8**	**6878.2**	**6720.8**	**6750.3**	**6853.7**	**6688.7**	**6704.1**	**6831.7**	**6661.5**
$E_{Dyn.}$ [Pa]	1.8E+10	2.8E+10	2.6E+10	1.4E+10	2.7E+10	2.5E+10	1.2E+10	2.6E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.2E+10			2.1E+10		

Mixture: 26.7%-8.7-0.45			
Cycles	**399**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1113.28**	**1787.11**	**1684.57**
Mass [g]	**6672.6**	**6804.8**	**6581.6**
$E_{Dyn.}$ [Pa]	9.0E+09	2.4E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	1.8E+10		

Mixture: 26.7%-12.3-0.45									
Cycles	**0**			**30**			**49**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1977.54**	**1962.84**	**1962.89**	**1962.89**	**1962.89**	**1962.89**	**1962.89**	**1948.24**
Mass [g]	**6872.9**	**6889.1**	**6855.4**	**6881.5**	**6889.6**	**6858.7**	**6870.5**	**6886.8**	**6854.1**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 26.7%-12.3-0.45									
Cycles	**74**			**110**			**139**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1948.24**	**1933.59**	**1933.59**	**1933.59**	**1918.95**	**1904.3**	**1918.95**	**1889.65**
Mass [g]	**6847.1**	**6872**	**6840**	**6806**	**6844.2**	**6817.8**	**6778.6**	**6821.6**	**6803.4**
$E_{Dyn.}$ [Pa]	2.9E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.7E+10	2.7E+10	2.7E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.8E+10			2.7E+10		

Mixture: 26.7%-12.3-0.45									
Cycles	**170**			**191**			**223**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1801.76**	**1831.05**	**1787.11**	**1713.87**	**1743.16**	**1713.87**	**1245.12**	**1391.6**	**1479.49**
Mass [g]	**6751.8**	**6798.7**	**6767.8**	**6715.6**	**6776.7**	**6731.4**	**6687**	**6747.6**	**6710.6**
$E_{Dyn.}$ [Pa]	2.4E+10	2.5E+10	2.3E+10	2.1E+10	2.2E+10	2.1E+10	1.1E+10	1.4E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.2E+10			1.4E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-12.8-0.45									
Cycles	**0**			**30**			**49**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1948.24**	**1962.89**	**1977.54**
Mass [g]	**6957.7**	**7054.3**	**7076.7**	**6959.9**	**7055.6**	**7080.5**	**6956.8**	**7054.1**	**7078.1**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			2.9E+10		

Mixture: 26.7%-12.8-0.45									
Cycles	**74**			**110**			**139**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1948.24**	**1962.89**	**1962.89**	**1948.24**	**1948.24**	**1933.59**	**1918.95**	**1918.95**	**1875**
Mass [g]	**6922.6**	**7037.1**	**7065.4**	**6873.6**	**7008.8**	**7051.9**	**6836.4**	**6973.4**	**7038.7**
$E_{Dyn.}$ [Pa]	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.7E+10	2.8E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.7E+10		

Mixture: 26.7%-12.8-0.45									
Cycles	**170**			**191**			**223**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**1845.7**	**1772.46**	**1860.35**	**1801.76**	**1611.33**	**1743.16**	**1508.79**	**1098.63**
Mass [g]	**6777.7**	**6914.9**	**7015.2**	**6690.8**	**6890.3**	**7002.4**	**6629.2**	**6842.7**	**6979.2**
$E_{Dyn.}$ [Pa]	2.5E+10	2.6E+10	2.4E+10	2.5E+10	2.4E+10	2.0E+10	2.2E+10	1.7E+10	9.1E+09
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.3E+10			1.6E+10		

Mixture: 33.7%-9.0-0.45									
Cycles	**0**			**35**			**63**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1855**	**1844**	**1875**	**1860**	**1854**	**1870**	**1859**	**1857**	**1882**
Mass [g]	**6802.6**	**6828.1**	**6812.2**	**6812.8**	**6840.9**	**6821.4**	**6791.2**	**6830.1**	**6807.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.6E+10	2.5E+10	2.6E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.6E+10			2.6E+10		

Mixture: 33.7%-9.0-0.45									
Cycles	**99**			**134**			**155**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1855**	**1853**	**1880**	**1847**	**1843**	**1873**	**1846**	**1842**	**1875**
Mass [g]	**6757.9**	**6801.7**	**6776.2**	**6736.4**	**6776.7**	**6755.7**	**6711.9**	**6760.6**	**6739.1**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.5E+10		

Mixture: 33.7%-9.0-0.45									
Cycles	**188**			**211**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1833**	**1829**	**1863**	**1822**	**1810**	**1845**	**1804**	**1795**	**1805**
Mass [g]	**6681.2**	**6743.4**	**6698.5**	**6665**	**6722.9**	**6681.1**	**6654.1**	**6710.1**	**6672.2**
$E_{Dyn.}$ [Pa]	2.4E+10	2.4E+10	2.5E+10	2.4E+10	2.4E+10	2.5E+10	2.3E+10	2.3E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.4E+10			2.3E+10		

Mixture: 33.7%-9.0-0.45									
Cycles	**258**			**294**			**319**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1746**	**1761**	**1783**	**1685**	**1636**	**1676**	**1630**	**1351**	**1545**
Mass [g]	**6629.7**	**6680.7**	**6652.8**	**6584.5**	**6642.5**	**6627.5**	**6542.3**	**6630.9**	**6598.6**
$E_{Dyn.}$ [Pa]	2.2E+10	2.2E+10	2.3E+10	2.0E+10	1.9E+10	2.0E+10	1.9E+10	1.3E+10	1.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			2.0E+10			1.6E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 33.7%-9.0-0.45			
Cycles	**328**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1470**	**1001**	**1380**
Mass [g]	**6510.5**	**6614.9**	**6540**
$E_{Dyn.}$ [Pa]	1.5E+10	7.2E+09	1.3E+10
Avg. $E_{Dyn.}$ [Pa]	1.2E+10		

Mixture: 33.7%-12.8-0.45									
Cycles	**0**			**28**			**64**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1777**	**1815**	**1824**	**1785**	**1818**	**1831**	**1776**	**1810**	**1834**
Mass [g]	**6577.9**	**6608.5**	**6623**	**6594**	**6627.4**	**6634.4**	**6579.4**	**6611.4**	**6589.5**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.4E+10	2.3E+10	2.4E+10	2.4E+10	2.2E+10	2.3E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.4E+10			2.3E+10		

Mixture: 33.7%-12.8-0.45									
Cycles	**98**			**120**			**153**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1758**	**1786**	**1818**	**1758**	**1786**	**1807**	**1729**	**1737**	**1764**
Mass [g]	**6564.2**	**6600**	**6561**	**6541.1**	**6574.5**	**6560.2**	**6520.7**	**6538.8**	**6511.4**
$E_{Dyn.}$ [Pa]	2.2E+10	2.3E+10	2.3E+10	2.2E+10	2.3E+10	2.3E+10	2.1E+10	2.1E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.3E+10			2.1E+10		

Mixture: 33.7%-12.8-0.45									
Cycles	**176**			**197**			**223**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1678**	**1688**	**1690**	**1641**	**1628**	**1604**	**1530**	**1480**	**1230**
Mass [g]	**6492**	**6504.2**	**6473.2**	**6470.2**	**6475.9**	**6442.2**	**6447.7**	**6436.1**	**6352.4**
$E_{Dyn.}$ [Pa]	2.0E+10	2.0E+10	2.0E+10	1.9E+10	1.9E+10	1.8E+10	1.6E+10	1.5E+10	1.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.0E+10			1.8E+10			1.4E+10		

Mixture: 33.7%-12.8-0.45			
Cycles	**233**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1464**	**1317**	**1060**
Mass [g]	**6407.2**	**6403.3**	**6146.7**
$E_{Dyn.}$ [Pa]	1.5E+10	1.2E+10	7.5E+09
Avg. $E_{Dyn.}$ [Pa]	1.1E+10		

Mixture: 23.7%-8.2-0.41									
Cycles	**0**			**30**			**65**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2065.43**	**2065.43**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2065.43**
Mass [g]	**7285.1**	**7058.2**	**7225.8**	**7284.1**	**7061.8**	**7229.2**	**7182.7**	**7059.6**	**7228.1**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.4E+10			3.3E+10		

Mixture: 23.7%-8.2-0.41									
Cycles	**100**			**130**			**159**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2050.78**	**2065.43**	**2065.43**	**2050.78**	**2050.78**	**2050.78**	**2050.78**	**2050.78**
Mass [g]	**7178.2**	**7055.8**	**7224.4**	**7176.7**	**7048**	**7222.4**	**7174.8**	**7042.7**	**7218.4**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 23.7%-8.2-0.41									
Cycles	**170**			**188**			**222**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2036.13**	**2050.78**	**2065.43**	**2036.13**	**2036.13**	**2050.78**	**2021.48**	**2036.13**
Mass [g]	**7165.2**	**7038.7**	**7201.9**	**7165.5**	**7033.5**	**7208.6**	**7162.4**	**7030.4**	**7201.7**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.2E+10			3.2E+10		
Mixture: 23.7%-8.2-0.41									
Cycles	**242**			**277**			**311**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.78**	**2006.84**	**2021.48**	**1992.19**	**1948.24**	**1948.24**	**1948.24**	**1889.65**	**1933.59**
Mass [g]	**7158.4**	**7024.5**	**7197.9**	**7155.1**	**7020.7**	**7193.4**	**7142.5**	**6999.8**	**7190.8**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.1E+10	2.9E+10	3.0E+10	2.9E+10	2.7E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.0E+10			2.9E+10		

Mixture: 23.7%-8.2-0.41									
Cycles	**346**			**381**			**416**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.6**	**1816.41**	**1801.76**	**1772.46**	**1640.63**	**1713.87**	**1625.98**	**1479.49**	**1508.79**
Mass [g]	**7140.1**	**6995.8**	**7188.2**	**7133.5**	**6984.4**	**7175.7**	**7121**	**6966.8**	**7162.8**
$E_{Dyn.}$ [Pa]	2.8E+10	2.5E+10	2.5E+10	2.4E+10	2.0E+10	2.3E+10	2.0E+10	1.7E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.2E+10			1.8E+10		

Mixture: 23.7%-12.5-0.41									
Cycles	**0**			**36**			**71**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2065.43**	**2021.48**	**2021.48**	**2065.43**	**2021.48**	**2021.48**	**2065.43**	**2006.84**
Mass [g]	**7117.6**	**7149.5**	**7093.1**	**7091.5**	**7122.1**	**7068.7**	**7054.9**	**7090.1**	**7039.8**
$E_{Dyn.}$ [Pa]	3.2E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-12.5-0.41									
Cycles	**101**			**136**			**171**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2050.78**	**1992.19**	**1977.54**	**2036.13**	**1977.54**	**1933.59**	**1977.54**	**1933.59**
Mass [g]	**7013.9**	**7065.1**	**7002.8**	**6978**	**7034.3**	**6962.8**	**6894.8**	**7012.6**	**6931.8**
$E_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.0E+10	3.0E+10	3.2E+10	3.0E+10	2.8E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.0E+10			2.9E+10		

Mixture: 23.7%-12.5-0.41									
Cycles	**201**			**230**			**241**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1933.59**	**1787.11**	**1684.57**	**1831.05**	**1625.98**	**1552.73**	**1625.98**	**1464.84**
Mass [g]	**6542.6**	**6987.9**	**6884.7**	**6317.6**	**6903.8**	**6830.5**	**6146.4**	**6449.7**	**6387.9**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.4E+10	1.9E+10	2.5E+10	2.0E+10	1.6E+10	1.8E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.1E+10			1.6E+10		

Mixture: 26.7%-8.5-0.41									
Cycles	**0**			**21**			**48**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2080.08**	**2094.73**	**2080.08**	**2080.08**	**2080.08**	**2094.73**	**2094.73**
Mass [g]	**7182.4**	**7210.1**	**7175.4**	**7190.1**	**7222**	**7181.4**	**7189.4**	**7218.1**	**7179.7**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-8.5-0.41									
Cycles	**68**			**94**			**130**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2094.73**	**2094.73**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**
Mass [g]	**7187.9**	**7216**	**7177.5**	**7193.9**	**7202.5**	**7180.8**	**7181.8**	**7207.7**	**7182.5**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		
Mixture: 26.7%-8.5-0.41									
Cycles	**165**			**195**			**230**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2080.08**	**2065.43**	**2021.48**	**2065.43**	**2050.78**	**1977.54**	**2050.78**	**2006.84**
Mass [g]	**7170.8**	**7186.5**	**7171.1**	**7158.2**	**7170.7**	**7150.7**	**7142.9**	**7157.1**	**7136.5**
$E_{Dyn.}$ [Pa]	3.3E+10	3.4E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.0E+10	3.3E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.2E+10			3.1E+10		

Mixture: 26.7%-8.5-0.41									
Cycles	**265**			**295**			**324**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**2006.84**	**1977.54**	**1875**	**1933.59**	**1889.65**	**1728.52**	**1801.76**	**1787.11**
Mass [g]	**7140.3**	**7144.7**	**7126.3**	**7139.4**	**7137.6**	**7116**	**7123.8**	**7129.6**	**7111.3**
$E_{Dyn.}$ [Pa]	2.9E+10	3.1E+10	3.0E+10	2.7E+10	2.9E+10	2.8E+10	2.3E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.8E+10			2.4E+10		

Mixture: 26.7%-8.5-0.41			
Cycles	**335**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1567.38**	**1538.09**	**1362.3**
Mass [g]	**7005.2**	**7033.7**	**6994.2**
$E_{Dyn.}$ [Pa]	1.9E+10	1.8E+10	1.4E+10
Avg. $E_{Dyn.}$ [Pa]	1.7E+10		

Mixture: 26.7%-8.6-0.41									
Cycles	**0**			**22**			**46**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	***B***	***C***
Frequency [Hz]	**2036.13**	**2021.48**	**2050.78**	**2036.13**	**2021.48**	**2050.78**	**2036.13**	***2021.48***	***2050.78***
Mass [g]	**7041.6**	**7157.7**	**7100.5**	**7049.3**	**7162.6**	**7106.1**	**7048.6**	***7159.8***	***7104.9***
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	*3.2E+10*	*3.2E+10*
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 26.7%-8.6-0.41									
Cycles	**78**			**98**			**128**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**2021.48**	**2050.78**	**2036.13**	**2021.48**	**2036.13**	**2050.78**	**2006.84**	**2036.13**
Mass [g]	**7022.6**	**7145.7**	**7100.4**	**7013.6**	**7137.4**	**7096.6**	**6971.4**	**7124.2**	**7086**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 26.7%-8.6-0.41									
Cycles	**156**			**181**			**202**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2006.84**	**2021.48**	**2036.13**	**2006.84**	**2006.84**	**2036.13**	**2006.84**	**1992.19**
Mass [g]	**6943.1**	**7111.7**	**7076.2**	**6912.9**	**7100.5**	**7063.7**	**6872.6**	**7079.6**	**7055.2**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-8.6-0.41									
Cycles	**229**			**264**			**301**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**1992.19**	**1977.54**	**2006.84**	**1977.54**	**1948.24**	**1962.89**	**1904.3**	**1889.65**
Mass [g]	**6737.3**	**7061.4**	**7044.2**	**6605.5**	**7003.1**	**7019.3**	**6623.1**	**6914.8**	**6934**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	2.9E+10	2.8E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.7E+10		

Mixture: 26.7%-8.6-0.41									
Cycles	**320**			**341**			**376**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1875**	**1845.7**	**1831.05**	**1743.16**	**1728.52**	**1171.88**	**1567.38**	**1538.09**
Mass [g]	**6613.8**	**6908.4**	**6921.7**	**6602.5**	**6902.4**	**6915.4**	**6592.5**	**6889.1**	**6903.4**
$E_{Dyn.}$ [Pa]	2.6E+10	2.6E+10	2.6E+10	2.4E+10	2.3E+10	2.2E+10	9.8E+09	1.8E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.3E+10			1.5E+10		

Mixture: 26.7%-12.5-0.41									
Cycles	**0**			**20**			**46**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1962.89**	**1962.89**	**1962.89**	**1948.24**	**1962.89**	**1948.22**	**1933.59**	**1948.24**
Mass [g]	**6825.4**	**6433.1**	**6950.7**	**6830.6**	**6846.5**	**6959.3**	**6837.3**	**6857.4**	**6974.3**
$E_{Dyn.}$ [Pa]	2.8E+10	2.7E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.8E+10	2.8E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.9E+10			2.8E+10		

Mixture: 26.7%-12.5-0.41									
Cycles	**82**			**117**			**147**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1948.24**	**1918.95**	**1948.24**	**1933.59**	**1889.65**	**1933.59**	**1889.65**	**1831.05**	**1904.3**
Mass [g]	**6833.4**	**6848**	**6961**	**6825.3**	**6829.8**	**6946.6**	**6807.6**	**6806.8**	**6929.1**
$E_{Dyn.}$ [Pa]	2.8E+10	2.7E+10	2.9E+10	2.8E+10	2.6E+10	2.8E+10	2.6E+10	2.5E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.7E+10			2.6E+10		

Mixture: 26.7%-12.5-0.41									
Cycles	**182**			**217**			**247**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1669.92**	**1772.46**	**1655.27**	**1523.44**	**1582.03**	**1186.5**	**1040.04**	**1098.63**
Mass [g]	**6770.2**	**6762.6**	**6922.8**	**6654.1**	**6722.7**	**6904.9**	**6366.9**	**6577.1**	**6857.3**
$E_{Dyn.}$ [Pa]	2.3E+10	2.0E+10	2.4E+10	2.0E+10	1.7E+10	1.9E+10	9.7E+09	7.7E+09	9.0E+09
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			1.8E+10			8.8E+9		

Mixture: 26.7%-13.1-0.41									
Cycles	**0**			**24**			**56**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**1962.89**	**1977.54**	**1992.19**	**1948.24**	**1962.89**	**1992.19**	**1948.24**	**1933.59**
Mass [g]	**7016.7**	**6921.9**	**6949.4**	**7025**	**6930.4**	**6957.7**	**7024.8**	**6931.2**	**6955.9**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.9E+10		

Mixture: 26.7%-13.1-0.41									
Cycles	**76**			**106**			**124**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1933.59**	**1918.95**	**1962.89**	**1904.3**	**1889.65**	**1918.95**	**1875**	**1860.35**
Mass [g]	**7019.3**	**6923**	**6947.6**	**7003.5**	**6907.4**	**6937.2**	**6996.7**	**6898.5**	**6930.2**
$E_{Dyn.}$ [Pa]	3.0E+10	2.8E+10	2.8E+10	2.9E+10	2.7E+10	2.7E+10	2.8E+10	2.6E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.7E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 26.7%-13.1-0.41									
Cycles	**133**			**159**			**180**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1845.7**	**1831.05**	**1669.92**	**1743.16**	**1757.81**	**1040.39**	**1596.68**	**1640.63**
Mass [g]	**6987.5**	**6894.2**	**6921**	**6969.7**	**6879.9**	**6913.1**	**6858.8**	**6829.8**	**6894.6**
$E_{Dyn.}$ [Pa]	2.7E+10	2.5E+10	2.5E+10	2.1E+10	2.3E+10	2.3E+10	8.0E+09	1.9E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.2E+10			1.6E+10		

Mixture: 33.7%-8.4-0.41									
Cycles	**0**			**27**			**47**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1860.35**	**1904.3**	**1889.65**	**1860.35**	**1904.3**	**1889.65**	**1860.35**	**1904.3**
Mass [g]	**6734.1**	**6755.8**	**6689.2**	**6732.5**	**6751.3**	**6685**	**6745.1**	**6762.3**	**6695.6**
$E_{Dyn.}$ [Pa]	2.6E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.6E+10			2.6E+10		

Mixture: 33.7%-8.4-0.41									
Cycles	**73**			**93**			**125**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1860.35**	**1889.95**	**1889.65**	**1860.35**	**1889.95**	**1875**	**1845.7**	**1875**
Mass [g]	**6742.2**	**6707.7**	**6693.8**	**6738.5**	**6702.4**	**6690.9**	**6736.8**	**6700.5**	**6681.1**
$E_{Dyn.}$ [Pa]	2.6E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.6E+10			2.5E+10		

Mixture: 33.7%-8.4-0.41									
Cycles	**150**			**184**			**210**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1875**	**1845.7**	**1875**	**1875**	**1831.05**	**1875**	**1860.35**	**1816.41**	**1860.35**
Mass [g]	**6726.6**	**6691.8**	**6666.1**	**6716.8**	**6680.6**	**6659.8**	**6710.7**	**6680.3**	**6648**
$E_{Dyn.}$ [Pa]	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.4E+10	2.5E+10	2.5E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.5E+10		

Mixture: 33.7%-8.4-0.41									
Cycles	**244**			**270**			**304**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**1801.76**	**1831.05**	**1845.7**	**1757.81**	**1816.41**	**1831.05**	**1699.22**	**1787.11**
Mass [g]	**6695.7**	**6668.8**	**6638.1**	**6688.8**	**6658.1**	**6634.8**	**6676.7**	**6653.7**	**6618.3**
$E_{Dyn.}$ [Pa]	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.2E+10	2.4E+10	2.4E+10	2.1E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.3E+10		

Mixture: 33.7%-8.4-0.41									
Cycles	**322**			**366**			**386**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1596.68**	**1713.87**	**1699.22**	**1479.49**	**1567.38**	**1611.33**	**1362.3**	**1479.49**
Mass [g]	**6663.4**	**6642.9**	**6614.1**	**6664.3**	**6654.1**	**6596.2**	**6634.3**	**6637.2**	**6580.9**
$E_{Dyn.}$ [Pa]	2.3E+10	1.8E+10	2.1E+10	2.1E+10	1.6E+10	1.8E+10	1.9E+10	1.3E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.1E+10			1.8E+10			1.6E+10		

Mixture: 33.7%-8.4-0.41			
Cycles	**401**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1479.49**	**1127.93**	***1362.3***
Mass [g]	**6545.8**	**6530.4**	***6488.1***
$E_{Dyn.}$ [Pa]	1.6E+10	9.0E+09	1.3E+10
Avg. $E_{Dyn.}$ [Pa]	1.3E+10		

Table A.1: (con't) Freeze-Thaw results for mixtures in Program I

Mixture: 33.7%-12.0-0.41									
Cycles	**0**			**36**			**62**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**1860.35**	**1860.35**	**1860.35**	**1875**	**1860.35**	**1845.7**	**1860.35**	**1845.7**
Mass [g]	**6578.1**	**6538.9**	**6531.2**	**6588.2**	**6569.4**	**6550.8**	**6598.1**	**6576.9**	**6557.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.4E+10		
Mixture: 33.7%-12.0-0.41									
Cycles	**89**			**109**			**135**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1860.35**	**1831.05**	**1831.05**	**1831.05**	**1816.41**	**1816.41**	**1801.76**	**1787.11**
Mass [g]	**6597.2**	**6579.8**	**6554**	**6590.7**	**6580.1**	**6556.2**	**6589**	**6580.4**	**6552.9**
$E_{Dyn.}$ [Pa]	2.4E+10	2.5E+10	2.4E+10	2.4E+10	2.4E+10	2.3E+10	2.4E+10	2.3E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.3E+10		

Mixture: 33.7%-12.0-0.41									
Cycles	**155**			**187**			**220**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1772.46**	**1772.46**	**1669.92**	**1640.63**	**1699.22**	**1274.41**	**1098.63**	**1289.06**
Mass [g]	**6588.6**	**6582.9**	**6551.4**	**6585.2**	**6579.8**	**6543.8**	**6580.3**	**6423.3**	**6493.6**
$E_{Dyn.}$ [Pa]	2.3E+10	2.2E+10	2.2E+10	2.0E+10	1.9E+10	2.0E+10	1.2E+10	8.4E+09	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.0E+10			1.1E+10		

Mixture: 33.7%-12.2-0.41									
Cycles	**0**			**32**			**62**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1845**	**1831.05**	**1816.41**	**1831.05**	**1816.41**	**1831.05**	**1831.05**	**1816.41**
Mass [g]	**6468.5**	**6516.3**	**6468.5**	**6477.1**	**6527.7**	**6512.7**	**6449.4**	**6514.5**	**6486.8**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.4E+10	2.3E+10	2.4E+10	2.3E+10	2.3E+10	2.4E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.3E+10			2.3E+10		

Mixture: 33.7%-12.2-0.41									
Cycles	**88**			**109**			**135**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1831.05**	**1801.76**	**1816.41**	**1816.41**	**1801.76**	**1801.76**	**1816.41**	**1772.46**
Mass [g]	**6433.4**	**6506**	**6469.4**	**6413.6**	**6494.7**	**6450.4**	**6396.1**	**6479.5**	**6433.6**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.3E+10	2.3E+10	2.3E+10	2.3E+10	2.3E+10	2.3E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.3E+10			2.3E+10		

Mixture: 33.7%-12.2-0.41									
Cycles	**162**			**198**			**220**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1787.11**	**1728.52**	**1743.16**	**1728.52**	**1640.63**	**1669.92**	**1640.63**	**1508.79**
Mass [g]	**6368.5**	**6470.3**	**6420.2**	**6325.8**	**6446.7**	**6400.8**	**6300.3**	**6430.7**	**6392.2**
$E_{Dyn.}$ [Pa]	2.2E+10	2.2E+10	2.1E+10	2.1E+10	2.1E+10	1.9E+10	1.9E+10	1.9E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			2.0E+10			1.8E+10		

Mixture: 33.7%-12.2-0.41						
Cycles	**224**			**276**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1567.38**	**1508.79**	**1245.12**	**1154.25**	**1435.55**	**952.15**
Mass [g]	**6245.8**	**6419.1**	**6368.7**	**6220.5**	**6401.2**	**6323.8**
$E_{Dyn.}$ [Pa]	1.7E+10	1.6E+10	1.1E+10	9.0E+09	1.4E+10	6.2E+09
Avg. $E_{Dyn.}$ [Pa]	1.4E+10			9.8E+9		

Table A.2: Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 23.7%-8.8-0.45									
Cycles	**0**			**16**			**48**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2006.84**	**2036.13**	**2021.48**	**2021.48**	**2036.13**	**2021.48**	**2036.13**	**2036.13**
Mass [g]	**6969.5**	**7033.1**	**6997**	**6977**	**7040.7**	**7002.8**	**6962.6**	**7038.1**	**6994.3**
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	**72**			**105**			**130**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**2006.84**	**2006.84**	**2021.48**
Mass [g]	**6948.5**	**7016.3**	**6983**	**6937.3**	**7004.3**	**6967.4**	**6929.4**	**6988.8**	**6960.1**
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	**155**			**182**			**205**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2006.84**	**2021.48**	**1992.19**	**1992.19**	**2006.84**	**1992.19**	**1977.54**	**1977.54**
Mass [g]	**6901.9**	**6935.6**	**6937.7**	**6883.7**	**6910.9**	**6926.4**	**6901.9**	**6935.6**	**6937.7**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.1E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			2.9E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	**238**			**277**			**311**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1933.59**	**1948.24**	**1918.95**	**1845.7**	**1889.65**	**1787.11**	**1772.46**	**1743.16**
Mass [g]	**6883.7**	**6910.9**	**6926.4**	**6873.9**	**6878.1**	**6924.7**	**6841.3**	**6855.5**	**6915.3**
$E_{Dyn.}$ [Pa]	2.9E+10	2.8E+10	2.8E+10	2.7E+10	2.5E+10	2.7E+10	2.4E+10	2.3E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.9E+10			2.3E+10		

Mixture: 23.7%-8.8-0.45			
Cycles	**342**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1552.73**	**1406.25**	**1464.81**
Mass [g]	**6827.5**	**6838.4**	**6905.1**
$E_{Dyn.}$ [Pa]	1.8E+10	1.5E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	1.6E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**0**			**29**			**50**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2006.84**
Mass [g]	**6731.7**	**6786.5**	**6809.2**	**6737**	**6792.9**	**6913.8**	**6733**	**6791.3**	**6806.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.1E+10	2.9E+10	3.0E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**82**			**106**			**139**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2021.48**	**1992.19**	**1992.19**	**2006.84**	**1977.54**	**1977.54**	**2006.84**	**1948.24**
Mass [g]	**6712.8**	**6778.6**	**6797.6**	**6703.9**	**6771**	**6782**	**6687.9**	**6754.9**	**6762**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.8E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.9E+10		

Table A.2: (con't) Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 23.7%-12.2-0.45									
Cycles	**164**			**189**			**216**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1977.54**	**1904.3**	**1845.7**	**1904.3**	**1816.41**	**1757.81**	**1772.46**	**1816.41**
Mass [g]	**6675.8**	**6753.3**	**6745.4**	**6602.8**	**6722**	**6702.1**	**6602.8**	**6722**	**6702.1**
$E_{Dyn.}$ [Pa]	2.7E+10	2.9E+10	2.7E+10	2.4E+10	2.6E+10	2.4E+10	2.2E+10	2.3E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.5E+10			2.3E+10		

Mixture: 23.7%-12.2-0.45						
Cycles	**239**			**249**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1567.38**	**1669.92**	**1596.68**	**1113.28**	**1464.83**	**1303.73**
Mass [g]	**6559.7**	**6666.6**	**6679.1**	**6500.4**	**6598.5**	**6622.1**
$E_{Dyn.}$ [Pa]	1.7E+10	2.0E+10	1.8E+10	8.7E+09	1.5E+10	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	1.9E+10			1.2E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**0**			**30**			**55**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1933.59**	**1948.24**	**1948.24**	**1948.24**	**1933.59**	**1948.24**	**1948.24**	**1933.59**
Mass [g]	**6940.3**	**6908.7**	**7030.1**	**6944.9**	**6917**	**7038.3**	**6935.9**	**6914.6**	**7036.2**
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.9E+10			2.8E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**82**			**105**			**138**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1948.24**	**1977.54**	**1933.59**	**1933.59**	**1948.24**	**1933.59**	**1933.59**	**1933.59**	**1933.59**
Mass [g]	**6915.9**	**6899.1**	**7028.5**	**6904.7**	**6883.3**	**7020.4**	**6885.5**	**6872.2**	**7008.6**
$E_{Dyn.}$ [Pa]	2.8E+10	2.9E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.8E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**160**			**177**			**211**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1933.59**	**1933.59**	**1904.3**	**1918.95**	**1918.95**	**1875**	**1904.3**	**1889.65**
Mass [g]	**6854.8**	**6870.5**	**6998.3**	**6825.7**	**6861.9**	**6955.8**	**6767.4**	**6857.8**	**6948.5**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.7E+10	2.8E+10	2.6E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.7E+10			2.7E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**242**			**273**			**304**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1875**	**1845.7**	**1728.52**	**1831.05**	**1743.16**	**1567.38**	**1669.92**	**1391.6**
Mass [g]	**6622.8**	**6851.6**	**6940.7**	**6547.8**	**6789.9**	**6833.6**	**6531.1**	**6702.4**	**6744.9**
$E_{Dyn.}$ [Pa]	2.4E+10	2.6E+10	2.6E+10	2.1E+10	2.5E+10	2.3E+10	1.7E+10	2.0E+10	1.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.3E+10			1.7E+10		

Mixture: 33.7%-9.0-0.45-2			
Cycles	**335**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**952.15**	**1347.66**	**1391.6**
Mass [g]	**6444.1**	**6621.5**	**6657.8**
$E_{Dyn.}$ [Pa]	6.3E+09	1.3E+10	1.4E+10
Avg. $E_{Dyn.}$ [Pa]	1.1E+10		

Table A.2: (con't) Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 33.7%-12.5-0.45									
Cycles	**0**			**22**			**49**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1816.41**	**1831.05**	**1831.05**	**1831.05**	**1831.05**	**1831.05**	**1816.41**	**1831.05**
Mass [g]	**6745.7**	**6579.3**	**6559.8**	**6768.4**	**6597.4**	**6575.8**	**6753.8**	**6595.7**	**6573.7**
$E_{Dyn.}$ [Pa]	2.5E+10	2.4E+10	2.4E+10	2.5E+10	2.4E+10	2.4E+10	2.5E+10	2.4E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**72**			**105**			**127**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1801.76**	**1816.41**	**1801.76**	**1787.11**	**1801.76**	**1801.76**	**1757.81**	**1787.11**
Mass [g]	**6746.6**	**6588.4**	**6570.6**	**6739.3**	**6579.4**	**6562.8**	**6724.8**	**6576.1**	**6559.4**
$E_{Dyn.}$ [Pa]	2.4E+10	2.3E+10	2.3E+10	2.4E+10	2.3E+10	2.3E+10	2.4E+10	2.2E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.3E+10			2.3E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**144**			**178**			**209**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1757.81**	**1728.52**	**1787.11**	**1699.22**	**1684.57**	**1567.38**	**1567.38**	**1611.33**	**1347.66**
Mass [g]	**6720.7**	**6573.4**	**6556.1**	**6716.3**	**6569.3**	**6530.8**	**6698.1**	**6541.4**	**6520**
$E_{Dyn.}$ [Pa]	2.3E+10	2.1E+10	2.3E+10	2.1E+10	2.0E+10	1.7E+10	1.8E+10	1.8E+10	1.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			2.0E+10			1.6E+10		

Mixture: 33.7%-12.5-0.45			
Cycles	**240**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1303.71**	**1142.58**	**1289.06**
Mass [g]	**6679.5**	**6530.7**	**6448.1**
$E_{Dyn.}$ [Pa]	1.2E+10	9.2E+09	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	1.1E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**0**			**14**			**38**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2006.84**	**1992.19**	**1992.19**	**2006.84**	**2006.84**	**2006.84**	**2006.84**	**2006.84**
Mass [g]	**7000**	**7011.2**	**7078**	**7004.8**	**7014.1**	**7080.05**	**6994.3**	**7010**	**7078.6**
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**71**			**96**			**121**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2021.48**	**2006.84**	**2006.84**	**2021.48**	**2006.84**	**2021.48**	**2006.84**	**1992.19**
Mass [g]	**6961.4**	**6979.2**	**7062.3**	**6947.1**	**6955.1**	**7053.8**	**6941.2**	**6944.1**	**7048.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.0E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**148**			**171**			**204**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**1992.19**	**1977.54**	**2006.84**	**1992.19**	**1992.19**	**1992.19**	**1992.19**	**1977.54**
Mass [g]	**6933.8**	**6938**	**7043.4**	**6921.5**	**6921.5**	**7039.4**	**6909.1**	**6925.1**	**7036.5**
$E_{Dyn.}$ [Pa]	3.1E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Table A.2: (con't) Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 23.7%-9.0-0.41									
Cycles	243			277			308		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1977.54	1977.54	1948.24	1948.24	1918.95	1904.3	1933.59	1904.3	1875
Mass [g]	6879.7	6900.7	7036.7	6858.3	6890.1	7033.4	6814.3	6875.7	7030.6
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.7E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	338			370			401		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1889.65	1860.35	1845.7	1787.1	1845.7	1801.76	1640.63	1596.69	1684.56
Mass [g]	6765.4	6849.8	7029.6	6716.6	6757.3	7030.3	6621.4	6712.7	7004.9
$E_{Dyn.}$ [Pa]	2.6E+10	2.6E+10	2.6E+10	2.3E+10	2.5E+10	2.5E+10	1.9E+10	1.9E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.4E+10			2.0E+10		

Mixture: 23.7%-9.0-0.41			
Cycles	415		
Specimen	A	B	C
Frequency [Hz]	1333.01	1303.71	1552.73
Mass [g]	6570.1	6668.5	6985.4
$E_{Dyn.}$ [Pa]	1.3E+10	1.2E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	1.4E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	0			33			58		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	2021.48	2021.48	2021.48	2021.48	2021.48	2006.84	2021.48	2036.13
Mass [g]	6830.9	6681.7	6862.8	6837	6689	6869.2	6830.3	6666.8	6860.3
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.0E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	83			110			133		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	2021.48	2021.48	1992.19	2006.84	2021.48	1992.19	1977.54	1977.54
Mass [g]	6802.3	6611.3	6835.6	6792.2	6589.1	6830.4	6788.1	6574.5	6827.3
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.8E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.9E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	166			188			205		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1977.54	1948.24	1948.24	1948.24	1904.3	1918.95	1918.95	1875	1904.3
Mass [g]	6784.9	6563.8	6822.4	6786.4	6557.3	6813.6	6756	6518.1	6794.5
$E_{Dyn.}$ [Pa]	2.9E+10	2.7E+10	2.8E+10	2.8E+10	2.6E+10	2.7E+10	2.7E+10	2.5E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.7E+10			2.6E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	239			270			301		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1875	1845.7	1889.65	1845.7	1772.46	1831.05	1669.92	1625.98	1748.16
Mass [g]	6722.3	6480.3	6660.8	6649.5	6446.2	6619.9	6583	6411.3	6555.3
$E_{Dyn.}$ [Pa]	2.6E+10	2.4E+10	2.6E+10	2.5E+10	2.2E+10	2.4E+10	2.0E+10	1.8E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.4E+10			2.0E+10		

Table A.2: (con't) Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 23.7%-13.0-0.41			
Cycles	**332**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1420.9**	**1362.3**	**1538.09**
Mass [g]	**6543.3**	**6370.1**	**6575.4**
$E_{Dyn.}$ [Pa]	1.4E+10	1.3E+10	1.7E+10
Avg. $E_{Dyn.}$ [Pa]	1.5E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**0**			**31**			**62**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1904.3**	**1948.24**	**1918.95**	**1889.65**	**1948.24**	**1918.95**	**1904.3**	**1962.89**
Mass [g]	**6760.7**	**6769.9**	**6890**	**6766.7**	**6715.5**	**6898.4**	**6754.7**	**6758.7**	**6899.3**
$E_{Dyn.}$ [Pa]	2.7E+10	2.7E+10	2.8E+10	2.7E+10	2.6E+10	2.8E+10	2.7E+10	2.7E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**93**			**124**			**149**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1904.3**	**1962.89**	**1904.3**	**1889.65**	**1962.89**	**1889.65**	**1875**	**1962.89**
Mass [g]	**6739.5**	**6733.5**	**6887.1**	**6730.3**	**6719.7**	**6876**	**6712.5**	**6682.8**	**6866.2**
$E_{Dyn.}$ [Pa]	2.7E+10	2.6E+10	2.9E+10	2.6E+10	2.6E+10	2.9E+10	2.6E+10	2.5E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**176**			**211**			**242**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1875**	**1962.89**	**1875**	**1831.05**	**1962.89**	**1816.41**	**1801.76**	**1933.59**
Mass [g]	**6710.8**	**6680.1**	**6864.4**	**6705.1**	**6661.8**	**6864**	**6698.2**	**6654.2**	**6863.7**
$E_{Dyn.}$ [Pa]	2.6E+10	2.5E+10	2.9E+10	2.6E+10	2.4E+10	2.9E+10	2.4E+10	2.3E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.6E+10			2.5E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**273**			**297**			**325**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1801.76**	**1757.81**	**1904.3**	**1743.16**	**1684.57**	**1875**	**1669.92**	**1582.03**	**1860.35**
Mass [g]	**6656.3**	**6609.5**	**6858.4**	**6636.3**	**6589.5**	**6828.4**	**6629.4**	**6581.7**	**6820.2**
$E_{Dyn.}$ [Pa]	2.3E+10	2.2E+10	2.7E+10	2.2E+10	2.0E+10	2.6E+10	2.0E+10	1.8E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.3E+10			2.1E+10		

Mixture: 33.7%-8.3-0.41			
Cycles	**356**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1508.79**	**1098.63**	**1772.46**
Mass [g]	**6538.1**	**6498.7**	**6750.8**
$E_{Dyn.}$ [Pa]	1.6E+10	8.5E+09	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	1.6E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**0**			**40**			**71**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1831.05**	**1845.7**	**1845.7**	**1845.7**	**1845.7**	**1845.7**	**1845.7**
Mass [g]	**6348.9**	**6379.2**	**6408.1**	**6357.1**	**6385.4**	**6413.9**	**6350.7**	**6378.9**	**6396.4**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.3E+10	2.3E+10	2.4E+10	2.4E+10	2.3E+10	2.4E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.4E+10			2.4E+10		

Table A.2: (con't) Freeze-Thaw results for mixtures in Program II (Procedure A)

Mixture: 33.7%-13.0-0.41									
Cycles	**102**			**133**			**164**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1801.76**	**1831.05**	**1831.05**	**1757.81**	**1845.7**	**1801.76**	**1713.87**	**1801.76**
Mass [g]	**6333.4**	**6366.7**	**6377.3**	**6316**	**6351.3**	**6352.6**	**6286**	**6335.1**	**6325**
$E_{Dyn.}$ [Pa]	2.3E+10	2.2E+10	2.3E+10	2.3E+10	2.1E+10	2.3E+10	2.2E+10	2.0E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.3E+10			2.2E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**189**			**216**			**251**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1757.81**	**1640.63**	**1772.46**	**1699.22**	**1582.03**	**1728.52**	**1567.38**	**1435.55**	**1508.79**
Mass [g]	**6263.1**	**6319.9**	**6295.8**	**6232.6**	**6303.7**	**6280.8**	**6200.4**	**6271.8**	**6241.8**
$E_{Dyn.}$ [Pa]	2.1E+10	1.8E+10	2.1E+10	2.0E+10	1.7E+10	2.0E+10	1.7E+10	1.4E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.0E+10			1.9E+10			1.5E+10		

Mixture: 33.7%-13.0-0.41			
Cycles	**282**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1098.63**	**1289.06**	**1450.2**
Mass [g]	**6188.8**	**6269.2**	**6230.4**
$E_{Dyn.}$ [Pa]	8.1E+09	1.1E+10	1.4E+10
Avg. $E_{Dyn.}$ [Pa]	1.1E+10		

Table A.3: Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 23.7%-8.8-0.45									
Cycles	0			36			63		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1992.19	1992.19	1933.59	1992.19	1992.19	1948.24	2006.84	2006.84	1948.24
Mass [g]	6910.1	6899	6910.9	6946.9	6932.5	6948.9	6949.1	6935.1	6949.9
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.8E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	100			125			158		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	2006.84	1962.89	2006.84	2006.84	1962.89	2006.84	2006.84	1962.89
Mass [g]	6953.7	6938.6	6954.2	6954.1	6939.9	6956.7	6955.9	6942.8	6959
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	189			212			235		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2021.48	2006.84	1962.89	2021.48	2006.84	1962.89	2006.48	2021.48	1977.54
Mass [g]	6957.5	6943.1	6960	6959.2	6944.6	6960.8	6960.8	6945.3	6961.2
$E_{Dyn.}$ [Pa]	3.1E+10	3.0E+10	2.9E+10	3.1E+10	3.0E+10	2.9E+10	3.0E+10	3.1E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	266			290			321		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2021.48	2021.48	1977.54	2021.48	2021.48	1977.54	2006.48	2021.48	1977.54
Mass [g]	6960.8	6947.1	6962.5	6960.9	6947	6963.7	6962.3	6947.4	6962.6
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	346			377			400		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.48	2006.48	1962.89	2006.48	2006.48	1962.89	2006.48	2006.48	1962.89
Mass [g]	6961.7	6947.6	6963.3	6963.3	6948.9	6964.3	6963.8	6950	6946.7
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	424			455			487		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1992.19	1992.19	1962.89	1992.19	1992.19	1962.89	1992.19	1992.19	1962.89
Mass [g]	6964.8	6949.3	6965.1	6963	6949.3	6964	6962.3	6949.7	6964.8
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	510			541			564		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1992.19	1992.19	1948.24	1992.19	1992.19	1948.24	1977.54	1992.19	1933.59
Mass [g]	6963.8	6949.8	6965.5	6963.4	6950.5	6964.6	6963	6950	6965.2
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 23.7%-8.8-0.45									
Cycles	**596**			**619**			**644**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1977.54**	**1933.59**	**1948.24**	**1962.89**	**1933.59**	**1948.24**	**1948.24**	**1933.59**
Mass [g]	**6963.7**	**6950.1**	**6964.4**	**6965**	**6944.6**	**6965.5**	**6964.5**	**6948.8**	**6966.5**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.8E+10		

Mixture: 23.7%-8.8-0.45									
Cycles	**674**			**709**			**733**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1933.59**	**1904.3**	**1918.95**	**1904.3**	**1889.65**	**1889.65**	**1889.65**	**1860.35**
Mass [g]	**6963**	**6950.2**	**6963.7**	**6963.3**	**6950**	**6964.4**	**6965.8**	**6950.7**	**6966.2**
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.7E+10	2.7E+10	2.7E+10	2.7E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.7E+10			2.7E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**0**			**36**			**63**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**1992.19**	**1977.54**	**1992.19**	**2006.84**	**1977.54**	**2006.84**	**2006.84**	**1992.19**
Mass [g]	**6792.6**	**6863.3**	**6729.5**	**6807.9**	**6874.9**	**6747.6**	**6812.1**	**6880.3**	**6749.2**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			3.0E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**100**			**125**			**158**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2006.84**	**1992.19**	**2006.84**	**2021.48**	**1992.19**	**2021.48**	**2021.48**	**1992.19**
Mass [g]	**6815.3**	**6881.6**	**6752.6**	**6816.5**	**6883.6**	**6753.1**	**6819.1**	**6885**	**6755.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**189**			**212**			**235**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**2006.84**
Mass [g]	**6821.4**	**6886.8**	**6756.2**	**6822.3**	**6887.3**	**6758.4**	**6824.2**	**6888.2**	**6759.6**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**266**			**290**			**321**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**2006.84**	**2021.48**	**2006.84**	**2006.84**
Mass [g]	**6830.2**	**6889.3**	**6757.2**	**6825.8**	**6888.9**	**6757.2**	**6827.3**	**6890.7**	**6757.3**
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	2.9E+10	3.0E+10	3.1E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**346**			**377**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2006.84**	**1992.19**	**2021.48**	**2006.84**	**1992.19**	**2006.84**	**1992.19**	**1992.19**
Mass [g]	**6826**	**6891**	**6757.9**	**6827.1**	**6892.5**	**6759.1**	**6825.9**	**6891.6**	**6757.8**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			3.0E+10			2.9E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 23.7%-12.2-0.45									
Cycles	**424**			**455**			**487**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**1992.19**	**1992.19**	**2006.84**	**1977.54**	**1992.19**	**2006.84**	**1977.54**	**1977.54**
Mass [g]	**6826.3**	**6890.6**	**6756.8**	**6825.3**	**6890.3**	**6756.9**	**6826.4**	**6890.8**	**6760**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**510**			**541**			**564**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**1962.89**	**1977.54**	**1992.18**	**1962.89**	**1962.89**	**1977.54**	**1948.24**	**1962.89**
Mass [g]	**6826.8**	**6892.3**	**6758.5**	**6828.9**	**6892.3**	**6758.7**	**6825.9**	**6891.2**	**6758.9**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.8E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**596**			**619**			**644**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1933.59**	**1962.89**	**1933.59**	**1904.3**	**1948.24**	**1933.59**	**1889.65**	**1962.89**
Mass [g]	**6826.8**	**6889.9**	**6758.7**	**6827.7**	**6891.7**	**6759.1**	**6827.1**	**6891.4**	**6758.9**
$E_{Dyn.}$ [Pa]	2.9E+10	2.8E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.8E+10			2.8E+10		

Mixture: 23.7%-12.2-0.45									
Cycles	**674**			**709**			**733**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1860.35**	**1948.24**	**1904.3**	**1845.7**	**1933.59**	**1889.65**	**1801.76**	**1918.95**
Mass [g]	**6826.9**	**6891.6**	**6757.7**	**6826.3**	**6890.3**	**6756.8**	**6825.8**	**6889.1**	**6757.5**
$E_{Dyn.}$ [Pa]	2.8E+10	2.6E+10	2.8E+10	2.7E+10	2.5E+10	2.7E+10	2.6E+10	2.4E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.6E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**0**			**38**			**53**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**1977.54**	**2021.48**	**2021.48**	**1977.54**	**2021.48**	**2021.48**	**1977.54**	**2021.48**
Mass [g]	**6840.2**	**6809.5**	**6895**	**6848**	**6819.2**	**6901**	**6848.7**	**6820.6**	**6902.2**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.1E+10	3.0E+10	2.9E+10	3.1E+10	3.0E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**84**			**108**			**137**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**1977.54**	**2021.48**	**2036.13**	**1977.54**	**2021.48**	**2036.13**	**1977.54**	**2021.48**
Mass [g]	**6852.2**	**6824**	**6905.1**	**6852.1**	**6823.2**	**6905.5**	**6853.5**	**6825.4**	**6908.1**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**1977.54**	**2021.48**	**2036.13**	**1977.54**	**2036.13**	**2036.13**	**1977.54**	**2021.48**
Mass [g]	**6857**	**6826.9**	**6910.2**	**6855.3**	**6827.2**	**6907.6**	**6856**	**6828.3**	**6910.3**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 26.7%-8.2-0.45									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**1977.54**	**2036.13**	**2036.13**	**1977.54**	**2036.13**	**2036.13**	**1977.54**	**2036.13**
Mass [g]	**6855.4**	**6828.3**	**6907.5**	**6855.1**	**6828.9**	**6908.2**	**6854.5**	**6828.4**	**6908**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**1977.54**	**2036.13**	**2036.13**	**1992.19**	**2036.13**	**2036.13**	**1992.19**	**2036.13**
Mass [g]	**6854.7**	**6828.3**	**6907.4**	**6854.4**	**6828.5**	**6907.9**	**6853.1**	**6827.4**	**6908.7**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**1977.54**	**2036.13**	**2036.13**	**1992.19**	**2036.13**	**2036.13**	**1977.54**	**2021.48**
Mass [g]	**6852.5**	**6828.5**	**6907.5**	**6850.9**	**6827.5**	**6909.6**	**6851**	**6829.5**	**6909.4**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10	3.1E+10	2.9E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**1977.54**	**2021.48**	**2021.48**	**1977.54**	**2006.84**	**2021.48**	**1977.54**	**2006.84**
Mass [g]	**6852.7**	**6831.1**	**6908**	**6851.9**	**6829.2**	**6908.2**	**6852.8**	**6829.8**	**6907.7**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.1E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.2-0.45									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**1977.54**	**2006.84**	**2021.48**	**1948.24**	**2006.84**	**2006.84**	**1948.24**	**2006.84**
Mass [g]	**6850.3**	**6828.7**	**6906.2**	**6849.9**	**6829.4**	**6909.8**	**6848**	**6829.1**	**6907.8**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.8E+10	3.0E+10	3.0E+10	2.8E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			2.9E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**0**			**38**			**53**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1904.3**	**1948.24**	**1933.59**	**1904.3**	**1948.24**	**1933.59**	**1904.3**	**1948.24**	**1933.59**
Mass [g]	**6634.7**	**6685.5**	**6675.9**	**6643.2**	**6696.2**	**6685.4**	**6644.1**	**6697.8**	**6686.8**
$E_{Dyn.}$ [Pa]	2.6E+10	2.7E+10	2.7E+10	2.6E+10	2.8E+10	2.7E+10	2.6E+10	2.8E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**84**			**108**			**137**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**
Mass [g]	**6645.7**	**6698.2**	**6689.6**	**6647.7**	**6700.3**	**6691.9**	**6647.9**	**6701.8**	**6693.5**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 26.7%-12.1-0.45									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**
Mass [g]	**6649.7**	**6702.3**	**6692.4**	**6650.8**	**6704.1**	**6691.9**	**6651.5**	**6702.9**	**6692.9**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**	**1918.95**	**1948.24**	**1948.24**
Mass [g]	**6649.5**	**6701.9**	**6691.7**	**6650.1**	**6705.2**	**6692.5**	**6649.4**	**6703.4**	**6649.8**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.8E+10	2.7E+10	2.8E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1918.95**	**1948.24**	**1948.24**	**1904.3**	**1948.24**	**1933.59**	**1904.3**	**1948.24**	**1933.59**
Mass [g]	**6650.2**	**6704.6**	**6693.3**	**6646.6**	**6705.1**	**6691.8**	**6645.8**	**6704.8**	**6691.8**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.8E+10	2.6E+10	2.8E+10	2.7E+10	2.6E+10	2.8E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1948.24**	**1933.59**	**1889.65**	**1904.3**	**1933.59**	**1875**	**1904.3**	**1918.95**
Mass [g]	**6643**	**6702.7**	**6690.9**	**6642.1**	**6703.8**	**6694.5**	**6640.1**	**6705.8**	**6693.8**
$E_{Dyn.}$ [Pa]	2.6E+10	2.8E+10	2.7E+10	2.6E+10	2.6E+10	2.7E+10	2.5E+10	2.6E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.6E+10			2.6E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1875**	**1889.65**	**1933.59**	**1860.35**	**1889.65**	**1889.65**	**1845.7**	**1860.35**	**1860.35**
Mass [g]	**6639.2**	**6702.1**	**6694**	**6638.2**	**6702.3**	**6691**	**6641.7**	**6705.9**	**6693.6**
$E_{Dyn.}$ [Pa]	2.5E+10	2.6E+10	2.7E+10	2.5E+10	2.6E+10	2.6E+10	2.5E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.6E+10			2.5E+10		

Mixture: 26.7%-12.1-0.45									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1860.35**	**1831.05**	**1831.05**	**1860.35**	**1816.41**	**1831.05**	**1831.05**
Mass [g]	**6638.5**	**6702.9**	**6691.2**	**6637.5**	**6703.5**	**6690.8**	**6635.4**	**6700.7**	**6689.8**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.5E+10	2.4E+10	2.4E+10	2.5E+10	2.4E+10	2.4E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**0**			**36**			**62**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1816.41**	**1816.41**	**1816.41**	**1816.41**	**1816.41**	**1831.05**	**1831.05**	**1816.41**
Mass [g]	**6923.3**	**6809.3**	**6816.1**	**6984.8**	**6870.4**	**6866.7**	**6993.2**	**6874.5**	**6880.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.4E+10	2.4E+10	2.5E+10	2.5E+10	2.5E+10	2.5E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.5E+10			2.5E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-9.0-0.45-2									
Cycles	**92**			**117**			**150**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1831.05**	**1816.41**	**1845.7**	**1831.05**	**1816.41**	**1845.7**	**1831.05**	**1816.41**
Mass [g]	**6995**	**6878.7**	**6885.2**	**6996.2**	**6879.7**	**6890**	**7000.5**	**6883.9**	**6889.1**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.5E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**181**			**204**			**227**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1831.05**	**1816.41**	**1845.7**	**1831.05**	**1816.41**	**1845.7**	**1831.05**	**1816.41**
Mass [g]	**7002.7**	**6884.4**	**6890.7**	**7004.9**	**6886.3**	**6891.9**	**7006.9**	**6887.5**	**6894.5**
$E_{Dyn.}$ [Pa]	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.5E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**258**			**282**			**313**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1831.05**	**1801.76**	**1831.05**	**1831.05**	**1801.76**	**1831.05**	**1845.7**	**1816.41**
Mass [g]	**7006.9**	**6889.7**	**6895.5**	**7007.7**	**6890.5**	**6897**	**7005**	**6888**	**6898.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.5E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.5E+10			2.5E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**338**			**369**			**392**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1831.05**	**1787.11**	**1816.41**	**1816.41**	**1772.46**	**1801.76**	**1801.76**	**1713.87**
Mass [g]	**7006.5**	**6889.1**	**6898.5**	**7006.7**	**6890.6**	**6848.6**	**7004.2**	**6889.9**	**6886.5**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.5E+10	2.3E+10	2.5E+10	2.4E+10	2.2E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**416**			**447**			**479**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1801.76**	**1713.87**	**1757.81**	**1801.76**	**1669.92**	**1728.52**	**1787.11**	**1625.98**
Mass [g]	**7001.3**	**6889.5**	**6896.5**	**7000.1**	**6888.1**	**6895.1**	**6996.1**	**6888.5**	**6891.5**
$E_{Dyn.}$ [Pa]	2.4E+10	2.4E+10	2.2E+10	2.3E+10	2.4E+10	2.1E+10	2.3E+10	2.4E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.3E+10			2.2E+10		

Mixture: 33.7%-9.0-0.45-2									
Cycles	**502**			**533**			**556**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1699.22**	**1757.81**	**1582.03**	**1625.98**	**1713.87**	**1523.44**	**1582.03**	**1699.22**	**1435.55**
Mass [g]	**6996.7**	**6889.1**	**6885.8**	**6992.9**	**6889.1**	**6884**	**6989.6**	**6889.3**	**6880.8**
$E_{Dyn.}$ [Pa]	2.2E+10	2.3E+10	1.9E+10	2.0E+10	2.2E+10	1.7E+10	1.9E+10	2.2E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.1E+10			2.0E+10			1.9E+10		

Mixture: 33.7%-9.0-0.45-2						
Cycles	**588**			**611**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1508.79**	**1596.68**	**1259.77**	**1435.55**	**1552.73**	**1127.93**
Mass [g]	**6983.7**	**6887.4**	**6880.8**	**6983.3**	**6888**	**6873.6**
$E_{Dyn.}$ [Pa]	1.9E+10	2.2E+10	1.5E+10	1.7E+10	1.9E+10	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	1.6E+10			1.4E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-12.5-0.45									
Cycles	**0**			**28**			**62**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1904.3**	**1889.65**	**1962.89**	**1933.59**	**1904.3**	**1948.24**	**1933.59**	**1918.95**
Mass [g]	**6593.8**	**6616.4**	**6582.3**	**6664.2**	**6683**	**6655.6**	**6668.1**	**6687.7**	**6660.5**
$E_{Dyn.}$ [Pa]	2.7E+10	2.6E+10	2.5E+10	2.8E+10	2.7E+10	2.6E+10	2.7E+10	2.7E+10	2.7E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.7E+10			2.7E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**92**			**117**			**150**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1933.59**	**1918.95**	**1904.3**	**1933.59**	**1918.95**	**1904.3**	**1933.59**	**1918.95**	**1904.3**
Mass [g]	**6675.3**	**6693.5**	**6666.3**	**6676.5**	**6693.1**	**6667.8**	**6677.8**	**6695.8**	**6669.1**
$E_{Dyn.}$ [Pa]	2.7E+10	2.7E+10	2.6E+10	2.7E+10	2.7E+10	2.6E+10	2.7E+10	2.7E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.7E+10			2.7E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**181**			**204**			**227**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1904.3**	**1918.95**	**1904.3**	**1904.3**	**1918.95**	**1904.3**	**1889.65**	**1904.3**	**1889.65**
Mass [g]	**6678.2**	**6697.4**	**6670.3**	**6680.1**	**6699.6**	**6672.3**	**6680.9**	**6699.7**	**6674**
$E_{Dyn.}$ [Pa]	2.6E+10	2.7E+10	2.6E+10	2.6E+10	2.7E+10	2.6E+10	2.6E+10	2.6E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.6E+10			2.6E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**258**			**282**			**313**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1875**	**1904.3**	**1875**	**1875**	**1889.65**	**1875**	**1860.35**	**1875**	**1860.35**
Mass [g]	**6681.3**	**6702.1**	**6674.6**	**6684.3**	**6701**	**6674.9**	**6684.7**	**6702.4**	**6675.1**
$E_{Dyn.}$ [Pa]	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10	2.5E+10	2.6E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.6E+10			2.5E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**338**			**369**			**392**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1860.35**	**1845.7**	**1816.41**	**1845.7**	**1831.05**	**1801.76**	**1831.05**	**1816.41**
Mass [g]	**6688.3**	**6702.6**	**6676.7**	**6685.7**	**6702.3**	**6678.7**	**6685.3**	**6703.7**	**6679.6**
$E_{Dyn.}$ [Pa]	2.4E+10	2.5E+10	2.5E+10	2.4E+10	2.5E+10	2.4E+10	2.4E+10	2.4E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.5E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**416**			**447**			**479**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1728.52**	**1787.11**	**1816.41**	**1699.22**	**1743.16**	**1787.11**	**1640.63**	**1713.87**	**1787.11**
Mass [g]	**6689.2**	**6704.7**	**6681.4**	**6689.8**	**6706.2**	**6683.9**	**6691**	**6708.1**	**6685.7**
$E_{Dyn.}$ [Pa]	2.2E+10	2.3E+10	2.4E+10	2.1E+10	2.2E+10	2.3E+10	2.0E+10	2.1E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			2.2E+10			2.1E+10		

Mixture: 33.7%-12.5-0.45									
Cycles	**502**			**533**			**556**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1611.33**	**1669.92**	**1743.16**	**1552.73**	**1640.63**	**1684.57**	**1523.44**	**1596.68**	**1669.92**
Mass [g]	**6693.7**	**6709.1**	**6685**	**6695.6**	**6712**	**6686**	**6697.3**	**6709.9**	**6687.7**
$E_{Dyn.}$ [Pa]	1.9E+10	2.0E+10	2.2E+10	1.7E+10	2.0E+10	2.1E+10	1.7E+10	1.9E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.0E+10			1.9E+10			1.9E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-12.5-0.45									
Cycles	**588**			**611**			**632**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1464.84**	**1567.38**	**1582.03**	**1420.9**	**1479.49**	**1596.68**	**1376.95**	**1245.12**	**1420.9**
Mass [g]	**6699.4**	**6711.9**	**6689.7**	**6699.4**	**6712.2**	**6690.2**	**6695.2**	**6708.8**	**6680.1**
$E_{Dyn.}$ [Pa]	1.6E+10	1.8E+10	1.8E+10	1.5E+10	1.6E+10	1.8E+10	1.4E+10	1.1E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	1.7E+10			1.6E+10			1.3E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**0**			**36**			**63**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2006.84**	**2036.13**	**2065.43**	**2021.48**	**2050.78**	**2065.43**	**2036.13**	**2050.78**
Mass [g]	**6988.9**	**6922.5**	**6986.7**	**7022**	**6953.8**	**7020.2**	**7024.6**	**6953.8**	**7020.3**
$E_{Dyn.}$ [Pa]	3.2E+10	3.0E+10	3.1E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**100**			**125**			**158**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2036.13**	**2050.78**	**2065.43**	**2036.13**	**2050.78**	**2065.43**	**2036.13**	**2065.43**
Mass [g]	**7026.5**	**6956.7**	**7025.2**	**7027.4**	**6959**	**7026.1**	**7030.9**	**6959.7**	**7027.7**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**189**			**212**			**235**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2036.13**	**2065.43**	**2080.08**	**2036.13**	**2065.43**	**2080.08**	**2036.13**	**2065.43**
Mass [g]	**7028.9**	**6958.5**	**7028.8**	**7030.7**	**6961.8**	**7028.6**	**7032.6**	**6962.4**	**7029.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.1E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**266**			**290**			**321**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2036.13**	**2065.43**	**2080.08**	**2050.78**	**2065.43**	**2080.08**	**2050.78**	**2065.43**
Mass [g]	**7033.4**	**6963**	**7028.6**	**7032.7**	**6962.7**	**7029.4**	**7034.5**	**6963.7**	**7029.9**
$E_{Dyn.}$ [Pa]	3.3E+10	3.1E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**346**			**377**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2050.78**	**2065.43**	**2080.08**	**2050.78**	**2065.43**	**2080.08**	**2050.78**	**2065.43**
Mass [g]	**7033.2**	**6963.3**	**7026.2**	**7035.1**	**6965.1**	**7025.5**	**7034.8**	**6965.3**	**7024.5**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**424**			**455**			**487**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2050.78**	**2065.43**	**2080.08**	**2050.78**	**2065.43**	**2080.08**	**2050.78**	**2065.43**
Mass [g]	**7033.8**	**6964.1**	**7023.9**	**7034.3**	**6963.5**	**7021.5**	**7031.1**	**6963.8**	**7020.3**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 23.7%-9.0-0.41									
Cycles	**510**			**541**			**564**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2050.78**	**2080.08**	**2094.73**	**2050.78**	**2065.43**	**2094.73**	**2050.78**	**2080.08**
Mass [g]	**7032.8**	**6963.6**	**7018.8**	**7023.5**	**6964.6**	**7018**	**7024.1**	**6964.8**	**7015.9**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**596**			**619**			**644**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2050.78**	**2080.08**	**2094.73**	**2050.78**	**2080.08**	**2094.73**	**2050.78**	**2080.08**
Mass [g]	**7023.7**	**6964.4**	**7013.6**	**7024.6**	**6964.5**	**7014.5**	**7020.5**	**6964.4**	**7011.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: 23.7%-9.0-0.41									
Cycles	**674**			**709**			**733**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2050.78**	**2080.08**	**2094.73**	**2050.78**	**2080.08**	**2094.73**	**2050.78**	**2080.08**
Mass [g]	**7019.1**	**6963.1**	**7009.1**	**7020**	**6962.3**	**7007.1**	**7020**	**6963.5**	**7008.1**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	**0**			**36**			**63**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**1977.54**	**1992.19**	**1992.19**	**1977.54**	**1992.19**	**1992.19**	**1992.19**	**1992.19**
Mass [g]	**6752.1**	**6765.4**	**6763.4**	**6792.3**	**6801.7**	**6803.5**	**6795.9**	**6805.1**	**6808.2**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	**100**			**125**			**158**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**1992.19**	**1992.19**	**1992.19**	**1992.19**	**1992.19**	**2006.84**	**1992.19**	**1992.19**
Mass [g]	**6799.5**	**6809.7**	**6811.9**	**6800.1**	**6810.5**	**6813.5**	**6804.8**	**6813.1**	**6816.5**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	**189**			**212**			**235**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**1992.19**	**1992.19**	**2006.84**	**1992.19**	**1992.19**	**2006.84**	**1992.19**	**2006.84**
Mass [g]	**6805.5**	**6813.9**	**6815.2**	**6803.1**	**6814**	**6814.3**	**6803.4**	**6816.7**	**6815.3**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	2.9E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	**266**			**290**			**321**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**1992.19**	**2006.84**	**2006.84**	**1992.19**	**2006.84**	**2006.84**	**1992.19**	**2006.84**
Mass [g]	**6804.5**	**6816**	**6817.4**	**6804.7**	**6815.9**	**6817.5**	**6803.4**	**6817.5**	**6819.9**
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 23.7%-13.0-0.41									
Cycles	346			377			400		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84
Mass [g]	6803.8	6817.7	6817.3	6803.1	6816.4	6816.2	6803.5	6816.9	6815.4
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	424			455			487		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84
Mass [g]	6802.1	6816.1	6815.9	6801.9	6817	6814.6	6802.2	6816.1	6814.9
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	510			541			564		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84
Mass [g]	6802.4	6815.4	6814.5	6801.6	6815	6812.8	6802.3	6815.4	6814.1
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	596			619			644		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84
Mass [g]	6802	6815.6	6814.3	6801.1	6815.7	6813.9	6802.4	6816.5	6812.5
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 23.7%-13.0-0.41									
Cycles	674			709			733		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84	2006.84	1992.19	2006.84
Mass [g]	6801.5	6816.3	6813.4	6801.5	6816.3	6813.4	6802.6	6815.3	6812.8
$E_{Dyn.}$ [Pa]	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10	3.0E+10	2.9E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			3.0E+10			3.0E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	0			38			53		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2094.73	2080.08	2109.38	2094.73	2094.73	2109.38	2094.73	2094.73	2109.38
Mass [g]	7075.3	6977.6	7124.6	7079.4	6908.8	7125.9	7081.9	6983.1	7126.8
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	84			108			137		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2094.73	2094.73	2109.38	2094.73	2094.73	2109.38	2094.73	2094.73	2109.38
Mass [g]	7080.5	6982.1	7126.1	7082.7	6984.4	7126.4	7083.4	6985.5	7127.9
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 26.7%-8.6-0.41-2									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2109.38**	**2109.38**	**2094.73**	**2109.38**	**2094.73**	**2094.73**	**2109.38**
Mass [g]	**7085.4**	**6984.4**	**7129.3**	**7084.3**	**6986.1**	**7128.8**	**7087.7**	**6989.3**	**7129**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2094.73**	**2109.38**	**2109.38**	**2094.73**	**2109.38**	**2109.38**	**2094.73**	**2109.38**
Mass [g]	**7083.2**	**6986**	**7127.7**	**7085.5**	**6986.9**	**7128.8**	**7088.1**	**6987.8**	**7129.2**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2094.73**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**
Mass [g]	**7085.1**	**6987.3**	**7127.4**	**7082.8**	**6987.2**	**7127.6**	**7082.7**	**6987.8**	**7127.9**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2094.73**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**
Mass [g]	**7084.1**	**6988.4**	**7128.6**	**7085.5**	**6985.4**	**7127.8**	**7084.2**	**6984.9**	**7127.9**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**
Mass [g]	**7082.3**	**6985.9**	**7127.4**	**7082.7**	**6986.2**	**7128.2**	**7083.3**	**6986.8**	**7128.5**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-8.6-0.41-2									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**
Mass [g]	**7082.7**	**6989**	**7127.7**	**7082.8**	**6989.8**	**7129.8**	**7082**	**6986.5**	**7128.8**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**0**			**38**			**53**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2050.78**	**2021.48**	**2006.84**	**2050.78**	**2021.48**	**2006.84**	**2050.78**	**2021.48**
Mass [g]	**6850.1**	**6953.1**	**6916**	**6856.4**	**6961.1**	**6920.4**	**6856.8**	**6962.2**	**6921.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 26.7%-12.7-0.41									
Cycles	**84**			**108**			**137**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2050.78**	**2021.48**	**2006.84**	**2050.78**	**2021.48**	**2006.84**	**2050.78**	**2021.48**
Mass [g]	**6856.1**	**6962.3**	**6920.6**	**6857.8**	**6963.2**	**6922.6**	**6858.4**	**6965.5**	**6923.4**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**	**2006.84**	**2050.78**	**2021.48**
Mass [g]	**6858.9**	**6964**	**6924.5**	**6860.3**	**6964.8**	**6924.1**	**6859.9**	**6967.7**	**6928.4**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**6858**	**6963.3**	**6923.3**	**6858.5**	**6963.8**	**6924.1**	**6859.2**	**6965.3**	**6924.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**6858.1**	**6963.8**	**6924**	**6857.4**	**6962.1**	**6921.3**	**6857**	**6961.8**	**6921.5**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**6856.8**	**6960.8**	**6920.8**	**6856.1**	**6859.4**	**6921.5**	**6855.9**	**6858.9**	**6920.4**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2050.78**	**2036.13**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**6855.7**	**6960.3**	**6919.2**	**6858.1**	**6961**	**6921.3**	**6856.7**	**6960.4**	**6920.4**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Mixture: 26.7%-12.7-0.41									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**6856.3**	**6958.6**	**6918.5**	**6856**	**6959.4**	**6919.4**	**6857.8**	**6958.1**	**6920.7**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10	3.0E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.1E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-8.3-0.41									
Cycles	**0**			**38**			**53**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1948.24**	**1962.89**	**1992.19**	**1948.24**	**1977.54**	**1992.19**	**1948.24**
Mass [g]	**6770.3**	**6827.5**	**6683.7**	**6781.3**	**6839.2**	**6696**	**6782.8**	**6841.1**	**6696.9**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.7E+10	2.8E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.8E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**84**			**108**			**137**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1997.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**
Mass [g]	**6785.4**	**6843.2**	**6700.7**	**6785.1**	**6843.5**	**6700.1**	**6787.5**	**6845.3**	**6703.4**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**
Mass [g]	**6787.5**	**6845.3**	**6703.4**	**6787.1**	**6846.7**	**6705.8**	**6787.4**	**6847**	**6707.2**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1962.89**	**1992.19**	**1992.19**	**1962.89**	**1992.19**	**1992.19**	**1962.89**
Mass [g]	**6786.9**	**6845.3**	**6705.7**	**6787.8**	**6843.3**	**6705**	**6787.9**	**6843.8**	**6705.8**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1962.89**	**1992.19**	**2006.84**	**1962.89**	**1977.54**	**2006.84**	**1962.89**
Mass [g]	**6787.7**	**6842.6**	**6704.4**	**6790.7**	**6840.9**	**6702.6**	**6786.8**	**6839.3**	**6702.2**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	3.0E+10	2.8E+10	2.9E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**2006.84**	**1962.89**	**1977.54**	**2006.84**	**1962.89**	**1977.54**	**2006.84**	**1962.89**
Mass [g]	**6786.8**	**6839.3**	**6702.2**	**6788.8**	**6836.4**	**6698.2**	**6788.8**	**6836.4**	**6698.2**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	2.8E+10	2.9E+10	3.0E+10	2.8E+10	2.9E+10	3.0E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-8.3-0.41									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**2006.84**	**1962.89**	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**
Mass [g]	**6788.8**	**6836.4**	**6698.2**	**6786.2**	**6834.2**	**6692.2**	**6784.2**	**6834.1**	**6693.5**
$E_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-8.3-0.41									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**	**1977.54**	**1992.19**	**1962.89**
Mass [g]	**6784.4**	**6833.7**	**6691**	**6779.8**	**6820.2**	**6687.2**	**6779.8**	**6820.2**	**6687.2**
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10	2.9E+10	2.9E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.9E+10			2.9E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**0**			**38**			**53**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1831.05**	**1875**	**1831.05**	**1831.05**	**1875**	**1831.05**	**1831.05**	**1875**
Mass [g]	**6231.8**	**6363**	**6429**	**6250**	**6377.3**	**6441.4**	**6247.7**	**6378.6**	**6442.7**
$E_{Dyn.}$ [Pa]	2.3E+10	2.3E+10	2.4E+10	2.3E+10	2.3E+10	2.5E+10	2.3E+10	2.3E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.3E+10			2.3E+10			2.3E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**84**			**108**			**137**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**1845.7**	**1875**	**1831.05**	**1845.7**	**1875**	**1845.7**	**1845.7**	**1875**
Mass [g]	**6252.2**	**6382.2**	**6446.2**	**6255**	**6384.8**	**6448.9**	**6256**	**6386.6**	**6450.5**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**175**			**209**			**232**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1875**	**1845.7**	**1845.7**	**1875**	**1845.7**	**1845.7**	**1889.65**
Mass [g]	**6256**	**6386.6**	**6450.5**	**6256**	**6387.3**	**6450.7**	**6255.8**	**6387.4**	**6452.6**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**264**			**296**			**318**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**
Mass [g]	**6254.5**	**6387.1**	**6452.5**	**6256.2**	**6386.1**	**6453.2**	**6256.2**	**6386.1**	**6453.2**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**343**			**380**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**
Mass [g]	**6255**	**6387**	**6452.5**	**6254**	**6386.3**	**6452.3**	**6254.3**	**6386.4**	**6452.3**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**430**			**465**			**501**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1889.65**	**1860.35**	**1845.7**	**1889.65**	**1860.35**	**1845.7**	**1889.65**
Mass [g]	**6254.3**	**6386.4**	**6452.3**	**6252.2**	**6381.8**	**6449.5**	**6252.2**	**6381.8**	**6449.5**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Table A.3: (con't) Freeze-Thaw results for mixtures in Program II (Procedure B and KTMR-22)

Mixture: 33.7%-13.0-0.41									
Cycles	**537**			**560**			**584**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**
Mass [g]	**6252.2**	**6381.8**	**6449.5**	**6253.9**	**6382.5**	**6450.5**	**6252.6**	**6381.3**	**6450.7**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Mixture: 33.7%-13.0-0.41									
Cycles	**615**			**635**			**670**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**	**1845.7**	**1845.7**	**1889.65**
Mass [g]	**6251.1**	**6382.2**	**6450.2**	**6243.5**	**6378.7**	**6447.1**	**6243.5**	**6378.7**	**6447.1**
$E_{Dyn.}$ [Pa]	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10	2.3E+10	2.4E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			2.4E+10			2.4E+10		

Table A.4: Scaling results for mixtures in Program II (ASTM C672)

Mixture: 23.7%-8.8-0.45															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.43	5.9	1.87E-04	11.8	3.74E-04	5.8	1.84E-04	2.3	7.29E-05	2.8	8.87E-05	3.3	1.05E-04	1.7	5.39E-05
B	73.84	7.1	2.21E-04	13.1	4.07E-04	5.5	1.71E-04	2	6.22E-05	2.7	8.39E-05	2.8	8.70E-05	1.6	4.97E-05
C	71.70	3.4	1.09E-04	11.1	3.55E-04	4.1	1.31E-04	1.5	4.80E-05	2.5	8E-05	2.1	6.72E-05	1.7	5.44E-05
Average	72.66		1.72E-04		3.79E-04		1.62E-04		6.10E-05		8.42E-05		8.63E-05		5.27E-05
Cumulative mass loss (lb/ft^2)			**2.48E-02**		**7.94E-02**		**1.03E-01**		**1.11E-01**		**1.24E-01**		**1.36E-01**		**1.44E-01**

Mixture: 23.7%-12.2-0.45															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.83	14.2	4.48E-04	11.4	3.59E-04	2.9	9.14E-05	3.7	1.17E-04	1.6	5.04E-05	2.3	7.25E-05	1.1	3.47E-05
B	71.16	24.9	8.03E-04	17.1	5.52E-04	4.7	1.52E-04	8.6	2.77E-04	6	1.94E-04	4.7	1.52E-04	3.5	1.13E-04
C	73.31	16.1	5.04E-04	10.7	3.35E-04	3.3	1.03E-04	4.5	1.41E-04	2.2	6.89E-05	2.1	6.58E-05	2.6	8.14E-05
Average	72.43		5.85E-04		4.15E-04		1.15E-04		1.78E-04		1.04E-04		9.66E-05		7.63E-05
Cumulative mass loss (lb/ft^2)			**8.42E-02**		**1.44E-01**		**1.61E-01**		**1.86E-01**		**2.01E-01**		**2.15E-01**		**2.26E-01**

Mixture: 33.7%-9.0-0.45-2															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.89	8.5	2.64E-04	21.1	6.56E-04	5.4	1.68E-04	5.2	1.62E-04	2.5	7.77E-05	5.3	1.65E-04	2.5	7.77E-05
B	72.88	26.5	8.35E-04	31.8	1.00E-03	6	1.89E-04	5.1	1.61E-04	3.3	1.04E-04	7.1	2.24E-04	2.5	7.88E-05
C	70.88	17	5.51E-04	17	5.51E-04	4.1	1.33E-04	4.4	1.43E-04	2.7	8.75E-05	6.3	2.04E-04	1.8	5.83E-05
Average	72.55		5.50E-04		7.36E-04		1.63E-04		1.55E-04		8.97E-05		1.97E-04		7.16E-05
Cumulative mass loss (lb/ft^2)			**7.92E-02**		**1.85E-01**		**2.09E-01**		**2.31E-01**		**2.44E-01**		**2.72E-01**		**2.83E-01**

Mixture: 33.7%-12.5-0.45															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.07	31.2	9.80E-04	22.3	7.01E-04	7.5	2.36E-04	6.2	1.95E-04	4.7	1.48E-04	8.4	2.64E-04	4.7	1.48E-04
B	71.07	19	6.14E-04	12.9	4.17E-04	4.5	1.45E-04	4.2	1.36E-04	3.1	1.00E-04	6.6	2.13E-04	1.9	6.14E-05
C	68.35	16.7	5.61E-04	16.6	5.58E-04	5.1	1.71E-04	5.7	1.91E-04	3.7	1.24E-04	9	3.02E-04	1.2	4.03E-05
Average	70.83		7.18E-04		5.58E-04		1.84E-04		1.74E-04		1.24E-04		2.60E-04		8.31E-05
Cumulative mass loss (lb/ft^2)			**1.03E-01**		**1.84E-01**		**2.10E-01**		**2.35E-01**		**2.53E-01**		**2.91E-01**		**3.03E-01**

Mixture: 23.7%-9.0-0.41															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	67.15	2.7	9.23E-05	2.9	9.92E-05	2.7	9.23E-05	1.1	3.76E-05	0.8	2.74E-05	0.9	3.08E-05	1.1	3.76E-05
B	73.07	5.6	1.76E-04	8.8	2.76E-04	4.2	1.32E-04	2	6.28E-05	1.4	4.40E-05	2.6	8.17E-05	2.1	6.60E-05
C	73.07	6.3	1.98E-04	6.5	2.04E-04	5.3	1.67E-04	2.6	8.17E-05	1.6	5.03E-05	2.8	8.80E-05	1.7	5.34E-05
Average	71.10		1.55E-04		1.93E-04		1.30E-04		6.07E-05		4.05E-05		6.68E-05		5.23E-05
Cumulative mass loss (lb/ft^2)			**2.24E-02**		**5.02E-02**		**6.90E-02**		**7.77E-02**		**8.35E-02**		**9.32E-02**		**1.01E-01**

Mixture: 23.7%-13.0-0.41															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	74.27	8.4	2.60E-04	6.8	2.10E-04	7.7	2.38E-04	5.8	1.79E-04	4.6	1.42E-04	5.7	1.76E-04	5.4	1.67E-04
B	71.67	10.3	3.30E-04	8.5	2.72E-04	6	1.92E-04	5.4	1.73E-04	4.2	1.35E-04	5.4	1.73E-04	6.2	1.99E-04
C	75.44	9.6	2.92E-04	7.3	2.22E-04	4.7	1.43E-04	3.3	1.00E-04	2.7	8.22E-05	3	9.13E-05	3.5	1.07E-04
Average	73.79		2.94E-04		2.35E-04		1.91E-04		1.51E-04		1.20E-04		1.47E-04		1.57E-04
Cumulative mass loss (lb/ft^2)			**4.23E-02**		**7.61E-02**		**1.04E-01**		**1.25E-01**		**1.43E-01**		**1.64E-01**		**1.86E-01**

Table A.4: (con't) Scaling results for mixtures in Program II (ASTM C672)

Mixture: 33.7%-8.3-0.41															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.11	7.4	2.36E-04	3.8	1.21E-04	1.6	5.09E-05	1.8	5.73E-05	3	9.55E-05	5	1.59E-04	8.2	2.61E-04
B	74.70	9	2.77E-04	5.5	1.69E-04	3	9.22E-05	2.6	7.99E-05	3.6	1.11E-04	5.7	1.75E-04	9.7	2.98E-04
C	76.92	10.3	3.07E-04	7	2.09E-04	2.5	7.46E-05	2.9	8.66E-05	4.4	1.31E-04	5.3	1.58E-04	8.9	2.66E-04
Average	74.58		2.73E-04		1.66E-04		7.26E-05		7.46E-05		1.12E-04		1.64E-04		2.75E-04
Cumulative mass loss (lb/ft^2)			**3.93E-02**		**6.33E-02**		**7.37E-02**		**8.45E-02**		**1.01E-01**		**1.24E-01**		**1.64E-01**

Mixture: 33.7%-13.0-0.41															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	70.92	15.9	5.15E-04	8.1	2.62E-04	3.8	1.23E-04	2.7	8.74E-05	2	6.47E-05	1.9	6.15E-05	1.9	6.15E-05
B	67.83	14.5	4.91E-04	7.4	2.50E-04	6	2.03E-04	3.8	1.29E-04	3.5	1.18E-04	2.7	9.14E-05	2.2	7.45E-05
C	69.72	16	5.27E-04	11.7	3.85E-04	5.8	1.91E-04	2.8	9.22E-05	4.8	1.58E-04	2.7	8.89E-05	3.6	1.19E-04
Average	69.49		5.11E-04		2.99E-04		1.72E-04		1.03E-04		1.14E-04		8.06E-05		8.48E-05
Cumulative mass loss (lb/ft^2)			**7.36E-02**		**1.17E-01**		**1.41E-01**		**1.56E-01**		**1.73E-01**		**1.84E-01**		**1.96E-01**

Table A.5: Scaling results for mixtures in Program II (BNQ NQ2621-900)

Mixture: 23.7%-8.8-0.45									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	71.97	0.8	2.55E-05	5	1.59E-04	5.1	1.63E-04	11.1	3.54E-04
B	73.36	0.5	1.56E-05	4.1	1.28E-04	5.2	1.63E-04	10.8	3.38E-04
C	70.44	1	3.26E-05	5	1.63E-04	4.9	1.60E-04	10.6	3.45E-04
Average	71.92		2.46E-05		1.50E-04		1.62E-04		3.46E-04
Cumulative mass loss (lb/ft^2)			**3.54E-03**		**2.52E-02**		**4.85E-02**		**9.83E-02**

Mixture: 23.7%-12.2-0.45									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.36	1.8	5.63E-05	8.3	2.60E-04	8.3	2.60E-04	11.2	3.50E-04
B	68.58	2.9	9.71E-05	8	2.68E-04	8.3	2.78E-04	11.3	3.78E-04
C	75.44	2.3	7.00E-05	6.5	1.98E-04	8.8	2.68E-04	12.9	3.93E-04
Average	72.46		7.45E-05		2.42E-04		2.68E-04		3.74E-04
Cumulative mass loss (lb/ft^2)			**1.07E-02**		**4.55E-02**		**8.42E-02**		**1.38E-01**

Mixture: 33.7%-9.0-0.45-2									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	71.72	0.2	6.40E-06	6.7	2.14E-04	8.7	2.78E-04	15	4.80E-04
B	68.58	0.9	3.01E-05	7	2.34E-04	7.6	2.54E-04	15	5.02E-04
C	70.40	1.7	5.54E-05	8.7	2.84E-04	7.4	2.41E-04	16.2	5.28E-04
Average	70.23		3.07E-05		2.44E-04		2.58E-04		5.04E-04
Cumulative mass loss (lb/ft^2)			**4.41E-03**		**3.96E-02**		**7.67E-02**		**1.49E-01**

Mixture: 33.7%-12.5-0.45									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	75.23	1.5	4.58E-05	14.9	4.55E-04	10.3	3.14E-04	21.1	6.44E-04
B	71.16	1.8	5.81E-05	9	2.90E-04	7.4	2.39E-04	19.7	6.36E-04
C	72.78	1.4	4.42E-05	9.7	3.06E-04	9.9	3.12E-04	18.9	5.96E-04
Average	73.06		4.93E-05		3.50E-04		2.88E-04		6.25E-04
Cumulative mass loss (lb/ft^2)			**7.10E-03**		**5.76E-02**		**9.91E-02**		**1.89E-01**

Mixture: 23.7%-9.0-0.41									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.64	1.4	4.42E-05	4.2	1.33E-04	4.1	1.30E-04	4.2	1.33E-04
B	73.31	0.9	2.82E-05	8.5	2.66E-04	4.9	1.53E-04	3.1	9.71E-05
C	76.56	0.7	2.10E-05	7.6	2.28E-04	3.1	9.30E-05	3	9.00E-05
Average	74.17		3.11E-05		2.09E-04		1.25E-04		1.07E-04
Cumulative mass loss (lb/ft^2)			**4.48E-03**		**3.46E-02**		**5.26E-02**		**6.80E-02**

Mixture: 23.7%-13.0-0.41									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	75.64	1.4	4.25E-05	-	-	-	-	-	-
B	73.71	1.7	5.29E-05	4.9	1.53E-04	7.6	2.37E-04	10.9	3.39E-04
C	73.36	2.2	6.88E-05	3.5	1.10E-04	5.3	1.66E-04	8.1	2.53E-04
Average	74.24		5.48E-05		1.31E-04		2.01E-04		2.96E-04
Cumulative mass loss (lb/ft^2)			**7.89E-03**		**2.68E-02**		**5.57E-02**		**9.84E-02**

Table A.5: (con't) Scaling results for mixtures in Program II (BNQ NQ2621-900)

Mixture: 33.7%-8.3-0.41									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	74.91	0.3	9.19E-06	6.5	1.99E-04	5	1.53E-04	10.4	3.19E-04
B	73.55	0.1	3.12E-06	7.4	2.31E-04	5.8	1.81E-04	7.5	2.34E-04
C	69.44	0.2	6.61E-06	5	1.65E-04	6	1.98E-04	10.9	3.60E-04
Average	72.63		6.31E-06		1.98E-04		1.78E-04		3.04E-04
Cumulative mass loss (lb/ft^2)			**9.09E-04**		**2.95E-02**		**5.51E-02**		**9.89E-02**

Mixture: 33.7%-13.0-0.41									
Specimen	**Effective Area**	**Mass at 7 days**		**Mass at 21 days**		**Mass at 35 days**		**Mass at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	70.83	0.2	6.48E-06	6.1	1.98E-04	6.6	2.14E-04	12.8	4.15E-04
B	73.19	0.3	9.41E-06	8.6	2.70E-04	4.1	1.29E-04	9.4	2.95E-04
C	71.43	0.2	6.43E-06	6.1	1.96E-04	7.1	2.28E-04	10	3.21E-04
Average	71.82		7.44E-06		2.21E-04		1.90E-04		3.44E-04
Cumulative mass loss (lb/ft^2)			**1.07E-03**		**3.29E-02**		**6.03E-02**		**1.10E-01**

APPENDIX B: SHRINKAGE, FREEZE-THAW, SCALING, RAPID CHLORIDE PERMEABILITY, AND SURFACE RESISTIVITY TEST RESULTS FOR MIXTURES IN PROGRAM III IN CHAPTER 3

Table B.1: Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (Mixture: T-3.4-L)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	0	0	0	**0**
0	0.17	10	0	20	**10**
0	1	10	0	30	**13**
0	2	0	0	30	**10**
0	3	0	10	40	**17**
0	4	10	10	40	**20**
0	5	10	10	40	**20**
0	6	10	10	40	**20**
0	7	10	10	40	**20**
0	8	10	10	40	**20**
0	9	10	10	40	**20**
0	10	10	10	40	**20**
0	11	10	20	40	**23**
0	12	10	20	40	**23**
0	13	10	20	40	**23**
0	14	10	10	40	**20**
1	15	-70	-70	-60	**-67**
2	16	-110	-110	-80	**-100**
3	17	-130	-130	-110	**-123**
4	18	-160	-150	-140	**-150**
5	19	-170	-160	-140	**-157**
6	20	-190	-180	-160	**-177**
7	21	-210	-200	-180	**-197**
8	22	-210	-200	-200	**-203**
9	23	-220	-210	-200	**-210**
10	24	-230	-220	-210	**-220**
11	25	-240	-230	-210	**-227**
12	26	-240	-230	-220	**-230**
13	27	-240	-230	-220	**-230**
14	28	-240	-230	-220	**-230**
15	29	-260	-240	-230	**-243**
16	30	-260	-250	-230	**-247**
17	31	-270	-260	-240	**-257**
18	32	-270	-260	-250	**-260**
19	33	-270	-270	-250	**-263**
20	34	-270	-270	-260	**-267**
21	35	-280	-280	-280	**-280**
22	36	-280	-270	-280	**-277**
23	37	-280	-270	-280	**-277**
24	38	-290	-270	-280	**-280**
25	39	-300	-270	-280	**-283**
27	41	-310	-270	-280	**-287**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (Mixture: T-3.4-L)			
		A	B	C	Average
28	42	-320	-270	-290	**0**
29	43	-320	-270	-290	**0**
31	45	-320	-280	-290	**10**
33	47	-330	-290	-300	**13**
35	49	-340	-300	-310	**10**
37	51	-340	-300	-310	**17**
39	53	-340	-300	-310	**20**
41	55	-340	-300	-310	**20**
43	57	-350	-300	-310	**20**
45	59	-350	-300	-320	**20**
47	61	-350	-300	-320	**20**
49	63	-350	-310	-330	**20**
51	65	-360	-310	-330	**20**
53	67	-360	-310	-330	**23**
55	69	-370	-320	-330	**23**
57	71	-370	-330	-350	**23**
59	73	-380	-340	-350	**20**
61	75	-390	-340	-349	**-67**
63	77	-390	-340	-350	**-100**
65	79	-390	-340	-360	**-123**
67	81	-400	-350	-370	**-150**
69	83	-400	-340	-360	**-157**
71	85	-400	-340	-360	**-177**
73	87	-410	-340	-370	**-197**
75	89	-410	-340	-370	**-203**
77	91	-410	-340	-370	**-210**
79	93	-410	-340	-370	**-220**
81	95	-410	-340	-380	**-227**
83	97	-430	-350	-390	**-230**
85	99	-430	-360	-390	**-230**
87	101	-430	-360	-390	**-230**
89	103	-430	-370	-390	**-243**
91	105	-420	-370	-390	**-247**
93	107	-420	-370	-390	**-257**
96	110	-420	-370	-390	**-260**
103	117	-450	-370	-410	**-263**
110	124	-480	-380	-420	**-267**
117	131	-510	-390	-440	**-280**
124	138	-520	-400	-450	**-277**
131	145	-510	-400	-440	**-277**
138	152	-510	-400	-440	**-280**
145	159	-520	-400	-440	**-283**
152	166	-540	-420	-460	**-287**
159	173	-550	-420	-460	**-293**
166	180	-550	-430	-480	**-293**
173	187	-540	-430	-470	**-293**
180	194	-540	-430	-470	**-297**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (Mixture: T-3.4-L)			
		A	B	C	Average
181	195	-540	-420	-470	**-477**
210	224	-540	-420	-460	**-467**
238	252	-530	-410	-460	**-470**
266	280	-540	-410	-470	**-477**
294	308	-540	-420	-470	**-483**
322	336	-550	-430	-470	**-487**
350	364	-560	-430	-480	**-497**
365	379	-570	-440	-470	**-477**

Time of Drying day	Time after Cast day	Strain, microstrain (T- 9.0-L)			
		A	B	C	Average
0	0.00	B	0	0	**0**
0	0.08	-20	0	0	**-7**
0	0.17	20	20	30	**23**
0	1	20	20	70	**37**
0	2	30	30	90	**50**
0	3	40	40	100	**60**
0	4	50	50	100	**67**
0	5	50	60	100	**70**
0	6	50	50	100	**67**
0	7	40	40	130	**70**
0	8	30	40	130	**67**
0	9	30	30	130	**63**
0	10	30	30	130	**63**
0	11	30	30	130	**63**
0	12	30	30	130	**63**
0	13	20	30	130	**60**
0	14	20	20	120	**53**
1	15	-10	0	90	**27**
2	16	-40	-30	70	**0**
3	17	-60	-50	50	**-20**
4	18	-80	-70	30	**-40**
5	19	-100	-80	10	**-57**
6	20	-120	-90	-10	**-73**
7	21	-130	-110	-20	**-87**
8	22	-140	-130	-30	**-100**
9	23	-160	-140	-40	**-113**
10	24	-170	-150	-50	**-123**
11	25	-180	-160	-60	**-133**
12	26	-180	-160	-60	**-133**
13	27	-190	-180	-70	**-147**
14	28	-210	-200	-90	**-167**
15	29	-220	-210	-100	**-177**
16	30	-220	-210	-100	**-177**
17	31	-220	-210	-110	**-180**
18	32	-220	-210	-110	**-180**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 9.0-L)			
		A	B	C	Average
19	33	-230	-220	-120	**-190**
20	34	-230	-220	-120	**-190**
21	35	-230	-220	-120	**-190**
22	36	-230	-230	-130	**-197**
23	37	-240	-230	-140	**-203**
24	38	-240	-240	-140	**-207**
25	39	-250	-250	-150	**-217**
26	40	-250	-250	-150	**-217**
27	41	-260	-250	-150	**-220**
28	42	-270	-250	-160	**-227**
29	43	-270	-260	-160	**-230**
31	45	-270	-260	-160	**-230**
33	47	-280	-260	-160	**-233**
35	49	-280	-260	-160	**-233**
37	51	-290	-270	-170	**-243**
39	53	-290	-280	-180	**-250**
41	55	-300	-290	-190	**-260**
43	57	-300	-300	-190	**-263**
45	59	-310	-300	-190	**-267**
47	61	-310	-300	-190	**-267**
49	63	-310	-310	-190	**-270**
51	65	-310	-310	-190	**-270**
53	67	-310	-310	-190	**-270**
55	69	-310	-310	-190	**-270**
57	71	-310	-310	-190	**-270**
59	73	-310	-310	-190	**-270**
61	75	-320	-310	-200	**-277**
63	77	-320	-310	-200	**-277**
65	79	-330	-320	-200	**-283**
67	81	-340	-330	-210	**-293**
69	83	-350	-330	-210	**-297**
71	85	-360	-340	-220	**-307**
73	87	-360	-350	-220	**-310**
75	89	-360	-350	-230	**-313**
77	91	-370	-350	-230	**-317**
79	93	-370	-350	-230	**-317**
81	95	-370	-350	-240	**-320**
83	97	-370	-350	-240	**-320**
85	99	-370	-360	-240	**-323**
87	101	-370	-360	-240	**-323**
89	103	-370	-360	-240	**-323**
91	105	-390	-360	-250	**-333**
93	107	-390	-380	-250	**-340**
96	110	-390	-380	-250	**-340**
103	117	-390	-380	-250	**-340**
110	124	-410	-380	-270	**-353**
117	131	-420	-390	-300	**-370**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 9.0-L)			
		A	B	C	Average
124	138	-430	-400	-330	**-387**
131	145	-430	-400	-330	**-387**
138	152	-430	-400	-330	**-387**
145	159	-430	-400	-330	**-387**
152	166	-430	-410	-340	**-393**
159	173	-440	-420	-350	**-403**
166	180	-440	-420	-350	**-403**
173	187	-450	-430	-350	**-410**
180	194	-450	-430	-350	**-410**
181	195	-450	-420	-360	**-410**
210	224	-460	-420	-350	**-410**
238	252	-450	-420	-330	**-400**
266	280	-460	-410	-340	**-403**
294	308	-470	-410	-350	**-410**
322	336	-470	-420	-350	**-413**
350	364	-470	-420	-350	**-413**
365	379	-480	-430	-350	**-420**

Time of Drying day	Time after Cast day	Strain, microstrain (T- 12.0-L)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	20	10	20	**17**
0	0.17	20	30	40	**30**
0	1	30	40	30	**33**
0	2	30	40	80	**50**
0	3	20	40	70	**43**
0	4	20	40	80	**47**
0	5	30	40	80	**50**
0	6	30	40	80	**50**
0	7	30	40	90	**53**
0	8	40	40	90	**57**
0	9	50	60	100	**70**
0	10	30	40	80	**50**
0	11	30	40	80	**50**
0	12	30	40	80	**50**
0	13	30	30	80	**47**
0	14	20	20	70	**37**
1	15	0	0	70	**23**
2	16	-30	-20	50	**0**
3	17	-40	-40	40	**-13**
4	18	-60	-50	30	**-27**
5	19	-80	-60	10	**-43**
6	20	-100	-60	0	**-53**
7	21	-90	-60	-20	**-57**
8	22	-90	-60	-20	**-57**
9	23	-90	-60	-30	**-60**
10	24	-110	-90	-50	**-83**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 12.0-L)			
		A	B	C	Average
11	25	-110	-90	-50	**-83**
12	26	-110	-100	-70	**-93**
13	27	-120	-100	-60	**-93**
14	28	-120	-110	-70	**-100**
15	29	-130	-110	-70	**-103**
16	30	-140	-120	-90	**-117**
17	31	-140	-120	-100	**-120**
18	32	-150	-130	-110	**-130**
19	33	-160	-140	-110	**-137**
20	34	-160	-140	-110	**-137**
21	35	-160	-140	-120	**-140**
22	36	-160	-140	-120	**-140**
23	37	-170	-150	-130	**-150**
24	38	-170	-150	-140	**-153**
25	39	-170	-150	-140	**-153**
26	40	-170	-150	-140	**-153**
27	41	-170	-160	-150	**-160**
28	42	-170	-160	-150	**-160**
29	43	-170	-170	-160	**-167**
31	45	-190	-170	-170	**-177**
33	47	-200	-180	-180	**-187**
35	49	-210	-170	-190	**-190**
37	51	-210	-200	-190	**-200**
39	53	-220	-210	-200	**-210**
41	55	-230	-220	-210	**-220**
43	57	-240	-230	-220	**-230**
45	59	-250	-240	-230	**-240**
47	61	-250	-250	-230	**-243**
49	63	-260	-260	-230	**-250**
51	65	-260	-250	-230	**-247**
53	67	-260	-250	-230	**-247**
55	69	-260	-250	-240	**-250**
57	71	-270	-250	-240	**-253**
59	73	-270	-260	-250	**-260**
61	75	-260	-260	-250	**-257**
63	77	-250	-260	-260	**-257**
65	79	-260	-260	-250	**-257**
67	81	-260	-260	-260	**-260**
69	83	-270	-270	-260	**-267**
71	85	-280	-280	-270	**-277**
73	87	-280	-260	-270	**-270**
75	89	-290	-280	-270	**-280**
77	91	-290	-290	-270	**-283**
79	93	-300	-290	-280	**-290**
81	95	-300	-290	-280	**-290**
83	97	-300	-300	-280	**-293**
85	99	-300	-290	-280	**-290**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 12.0-L)			
		A	B	C	Average
87	101	-310	-300	-290	**-300**
89	103	-310	-310	-290	**-303**
91	105	-320	-310	-300	**-310**
93	107	-320	-310	-300	**-310**
96	111	-320	-310	-300	**-310**
103	118	-320	-300	-300	**-307**
110	125	-320	-300	-300	**-307**
117	132	-330	-310	-310	**-317**
124	139	-340	-320	-330	**-330**
131	146	-360	-340	-350	**-350**
138	153	-360	-350	-340	**-350**
145	160	-370	-350	-340	**-353**
152	167	-360	-350	-360	**-357**
159	174	-360	-360	-350	**-357**
166	181	-370	-360	-360	**-363**
173	188	-370	-360	-370	**-367**
180	195	-370	-360	-370	**-367**
181	195	-370	-360	-380	**-370**
210	224	-360	-350	-360	**-357**
238	252	-350	-350	-360	**-353**
272	283	-370	-370	-380	**-373**
294	308	-380	-370	-360	**-370**
322	336	-380	-380	-370	**-377**
350	364	-400	-380	-380	**-387**
365	379	-400	-380	-390	**-390**

Time of Drying day	Time after Cast day	Strain, microstrain (C- 3.4-L)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	20	10	20	**17**
0	0.17	10	0	20	**10**
0	1	10	0	20	**10**
0	2	-10	10	40	**13**
0	3	-10	10	40	**13**
0	4	0	10	40	**17**
0	5	10	20	40	**23**
0	6	-10	10	40	**13**
0	7	0	10	40	**17**
0	8	0	10	40	**17**
0	9	0	10	40	**17**
0	10	0	10	40	**17**
0	11	0	20	40	**20**
0	12	0	20	40	**20**
0	13	10	20	50	**27**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (C- 3.4-L)			
		A	B	C	Average
0	14	10	30	50	**30**
1	15	-120	-140	-150	**-137**
2	16	-150	-170	-180	**-167**
3	17	-170	-190	-200	**-187**
4	18	-190	-220	-220	**-210**
5	19	-210	-240	-240	**-230**
6	20	-230	-260	-270	**-253**
7	21	-240	-270	-280	**-263**
8	22	-260	-290	-290	**-280**
9	23	-270	-310	-300	**-293**
10	24	-280	-320	-320	**-307**
11	25	-290	-320	-340	**-317**
12	26	-300	-330	-350	**-327**
13	27	-300	-340	-350	**-330**
14	28	-310	-350	-350	**-337**
15	29	-320	-360	-360	**-347**
16	30	-340	-390	-380	**-370**
17	31	-340	-390	-380	**-370**
18	32	-330	-390	-380	**-367**
19	33	-330	-390	-380	**-367**
20	34	-360	-390	-410	**-387**
21	35	-370	-410	-410	**-397**
22	36	-370	-420	-420	**-403**
23	37	-370	-420	-420	**-403**
24	38	-370	-420	-420	**-403**
25	39	-380	-430	-420	**-410**
26	40	-380	-440	-420	**-413**
27	41	-380	-440	-420	**-413**
28	42	-390	-440	-430	**-420**
29	43	-390	-440	-430	**-420**
30	44	-390	-440	-440	**-423**
32	46	-400	-450	-440	**-430**
34	48	-410	-460	-450	**-440**
36	50	-410	-470	-460	**-447**
38	52	-410	-460	-460	**-443**
40	54	-410	-460	-460	**-443**
42	56	-430	-470	-480	**-460**
44	58	-430	-470	-480	**-460**
46	60	-440	-470	-490	**-467**
48	62	-450	-480	-500	**-477**
50	64	-450	-480	-500	**-477**
52	66	-450	-480	-500	**-477**
54	68	-460	-490	-510	**-487**
56	70	-460	-490	-510	**-487**
58	72	-460	-490	-510	**-487**
60	74	-470	-500	-510	**-493**
62	76	-480	-510	-520	**-503**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (C- 3.4-L)			
		A	B	C	Average
64	78	-480	-520	-520	**-507**
66	80	-480	-520	-520	**-507**
68	82	-480	-520	-520	**-507**
70	84	-480	-530	-520	**-510**
72	86	-480	-530	-530	**-513**
74	88	-480	-530	-530	**-513**
76	90	-490	-540	-520	**-517**
78	92	-490	-540	-530	**-520**
80	94	-490	-540	-530	**-520**
82	96	-490	-540	-530	**-520**
84	98	-490	-550	-540	**-527**
86	100	-500	-550	-540	**-530**
88	102	-500	-550	-540	**-530**
90	104	-500	-550	-540	**-530**
92	106	-510	-570	-530	**-537**
97	111	-500	-540	-540	**-527**
104	118	-510	-540	-560	**-537**
111	125	-510	-550	-560	**-540**
118	132	-510	-550	-560	**-540**
125	139	-500	-510	-540	**-517**
132	146	-500	-520	-550	**-523**
139	153	-510	-520	-560	**-530**
146	160	-510	-520	-560	**-530**
153	167	-510	-520	-560	**-530**
160	174	-510	-530	-560	**-533**
167	181	-520	-530	-560	**-537**
174	188	-520	-530	-560	**-537**
181	195	-550	-550	-580	**-560**
181	195	-550	-550	-580	**-560**
210	224	-520	-550	-580	**-550**
238	252	-520	-560	-580	**-553**
266	280	-530	-560	-580	**-557**
294	308	-540	-560	-590	**-563**
322	336	-530	-570	-590	**-563**
350	364	-540	-570	-590	**-567**
365	379	-540	-570	-600	**-570**

Time of Drying day	Time after Cast day	Strain, microstrain (C-8.7-L)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	10	60	40	**37**
0	0.17	30	80	40	**50**
0	1	30	80	50	**53**
0	2	30	70	40	**47**
0	3	30	80	40	**50**
0	4	30	80	40	**50**
0	5	30	80	40	**50**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (C-8.7-L)			
		A	B	C	Average
0	6	30	80	40	**50**
0	7	40	80	40	**53**
0	8	40	80	40	**53**
0	9	40	80	50	**57**
0	10	50	80	50	**60**
0	11	50	80	50	**60**
0	12	50	80	50	**60**
0	13	50	80	60	**63**
0	14	50	80	60	**63**
1	15	-10	20	0	**3**
2	16	-80	-40	-80	**-67**
3	17	-100	-60	-90	**-83**
4	18	-120	-80	-110	**-103**
5	19	-140	-110	-130	**-127**
6	20	-160	-130	-140	**-143**
7	21	-180	-140	-160	**-160**
8	22	-190	-160	-180	**-177**
9	23	-210	-190	-210	**-203**
10	24	-230	-200	-220	**-217**
11	25	-230	-210	-230	**-223**
12	26	-250	-220	-240	**-237**
13	27	-250	-230	-250	**-243**
14	28	-270	-250	-270	**-263**
15	29	-270	-260	-280	**-270**
16	30	-280	-270	-280	**-277**
17	31	-280	-280	-280	**-280**
18	32	-290	-290	-290	**-290**
19	33	-300	-300	-300	**-300**
20	34	-310	-310	-320	**-313**
21	35	-320	-310	-320	**-317**
22	36	-320	-320	-330	**-323**
23	37	-330	-320	-330	**-327**
24	38	-330	-330	-340	**-333**
25	39	-330	-330	-340	**-333**
26	40	-330	-330	-340	**-333**
27	41	-330	-330	-340	**-333**
28	42	-350	-360	-360	**-357**
29	43	-360	-360	-370	**-363**
31	45	-350	-360	-370	**-360**
33	47	-360	-380	-380	**-373**
35	49	-370	-380	-390	**-380**
37	51	-380	-390	-400	**-390**
39	53	-390	-390	-400	**-393**
41	55	-390	-390	-400	**-393**
43	57	-400	-410	-410	**-407**
45	59	-400	-410	-410	**-407**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (C-8.7-L)			
		A	B	C	Average
47	61	-400	-420	-420	**-413**
49	63	-410	-420	-430	**-420**
51	65	-420	-430	-440	**-430**
53	67	-420	-430	-440	**-430**
55	69	-400	-440	-450	**-430**
57	71	-420	-440	-460	**-440**
59	73	-430	-460	-460	**-450**
61	75	-430	-460	-460	**-450**
63	77	-440	-460	-460	**-453**
65	79	-430	-460	-460	**-450**
67	81	-440	-460	-460	**-453**
69	83	-440	-460	-470	**-457**
71	85	-440	-460	-480	**-460**
73	87	-450	-470	-480	**-467**
75	89	-450	-470	-480	**-467**
77	91	-450	-470	-480	**-467**
79	93	-470	-480	-480	**-477**
81	95	-470	-480	-480	**-477**
83	97	-460	-480	-490	**-477**
85	99	-460	-480	-490	**-477**
87	101	-450	-480	-490	**-473**
89	103	-460	-490	-500	**-483**
91	105	-460	-500	-510	**-490**
93	107	-470	-490	-500	**-487**
97	111	-470	-490	-500	**-487**
104	118	-470	-470	-510	**-483**
111	125	-480	-490	-500	**-490**
118	132	-490	-490	-500	**-493**
125	139	-480	-500	-490	**-490**
132	146	-480	-490	-490	**-487**
139	153	-480	-480	-490	**-483**
146	160	-480	-490	-490	**-487**
153	167	-490	-490	-500	**-493**
160	174	-490	-500	-500	**-497**
167	181	-490	-500	-500	**-497**
174	188	-490	-510	-510	**-503**
181	195	-490	-510	-510	**-503**
181	195	-490	-510	-510	**-503**
210	224	-510	-530	-520	**-520**
238	252	-500	-510	-520	**-510**
266	280	-500	-520	-520	**-513**
294	308	-510	-510	-520	**-513**
322	336	-510	-520	-520	**-517**
350	364	-520	-530	-530	**-527**
365	379	-520	-540	-530	**-530**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T-3.0-G)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	0	0	0	**0**
0	0.17	0	0	0	**0**
0	1	10	10	10	**10**
0	2	10	10	10	**10**
0	3	10	10	20	**13**
0	4	10	10	20	**13**
0	5	10	10	20	**13**
0	6	10	10	20	**13**
0	7	10	10	20	**13**
0	8	0	10	20	**10**
0	9	10	10	20	**13**
0	10	10	10	30	**17**
0	11	10	20	30	**20**
0	12	20	20	30	**23**
0	13	20	20	30	**23**
0	14	20	20	30	**23**
1	15	-100	-50	-30	**-60**
2	16	-130	-80	-50	**-87**
3	17	-150	-100	-70	**-107**
4	18	-170	-110	-100	**-127**
5	19	-210	-150	-140	**-167**
6	20	-190	-130	-120	**-147**
7	21	-210	-170	-160	**-180**
8	22	-230	-180	-170	**-193**
9	23	-260	-190	-180	**-210**
10	24	-280	-200	-190	**-223**
11	25	-290	-210	-200	**-233**
12	26	-300	-220	-210	**-243**
13	27	-300	-230	-210	**-247**
14	28	-310	-230	-220	**-253**
15	29	-310	-250	-230	**-263**
16	30	-310	-250	-240	**-267**
17	31	-320	-260	-250	**-277**
18	32	-330	-270	-250	**-283**
19	33	-330	-280	-250	**-287**
20	34	-340	-290	-260	**-297**
21	35	-350	-290	-270	**-303**
22	36	-370	-300	-280	**-317**
23	37	-360	-300	-290	**-317**
24	38	-360	-310	-290	**-320**
25	39	-370	-300	-300	**-323**
26	40	-370	-300	-310	**-327**
27	41	-370	-310	-310	**-330**
28	42	-370	-310	-310	**-330**
29	43	-370	-310	-320	**-333**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T-3.0-G)			
		A	B	C	Average
30	44	-370	-310	-320	**-333**
32	46	-370	-320	-320	**-337**
34	48	-380	-330	-330	**-347**
36	50	-390	-330	-340	**-353**
38	52	-390	-330	-340	**-353**
40	54	-390	-340	-340	**-357**
42	56	-410	-350	-350	**-370**
44	58	-410	-350	-350	**-370**
46	60	-420	-360	-350	**-377**
48	62	-420	-370	-360	**-383**
50	64	-420	-370	-360	**-383**
52	66	-430	-370	-360	**-387**
54	68	-430	-370	-360	**-387**
56	70	-430	-380	-370	**-393**
58	72	-440	-390	-380	**-403**
60	74	-450	-390	-380	**-407**
62	76	-450	-390	-380	**-407**
64	78	-450	-400	-390	**-413**
66	80	-460	-430	-390	**-427**
68	82	-460	-420	-400	**-427**
70	84	-460	-410	-410	**-427**
72	86	-460	-400	-410	**-423**
74	88	-470	-410	-410	**-430**
76	90	-470	-420	-420	**-437**
78	92	-480	-420	-420	**-440**
80	94	-470	-420	-420	**-437**
82	96	-470	-420	-420	**-437**
84	98	-480	-420	-430	**-443**
86	100	-480	-430	-440	**-450**
88	102	-480	-430	-440	**-450**
90	104	-480	-420	-430	**-443**
92	106	-480	-420	-430	**-443**
97	111	-480	-430	-440	**-450**
104	118	-470	-410	-420	**-433**
111	125	-470	-410	-420	**-433**
118	132	-480	-410	-420	**-437**
125	139	-480	-420	-430	**-443**
132	146	-490	-430	-440	**-453**
139	153	-490	-430	-440	**-453**
146	160	-510	-450	-450	**-470**
153	167	-510	-450	-450	**-470**
160	174	-510	-450	-460	**-473**
167	181	-510	-460	-470	**-480**
174	188	-530	-460	-480	**-490**
181	195	-530	-470	-470	**-490**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T-3.0-G)			
		A	B	C	Average
210	224	-530	-470	-470	**-490**
238	252	-530	-470	-470	**-490**
266	280	-530	-470	-470	**-490**
294	308	-540	-480	-480	**-500**
322	336	-540	-490	-500	**-510**
350	364	-540	-480	-500	**-507**
365	379	-540	-480	-500	**-507**

Time of Drying day	Time after Cast day	Strain, microstrain (T- 8.7-G)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	20	0	10	**10**
0	0.17	20	10	10	**13**
0	1	30	10	20	**20**
0	2	30	10	20	**20**
0	3	30	10	20	**20**
0	4	30	10	20	**20**
0	5	40	10	20	**23**
0	6	40	20	20	**27**
0	7	40	20	20	**27**
0	8	40	20	20	**27**
0	9	40	20	30	**30**
0	10	50	30	30	**37**
0	11	50	30	30	**37**
0	12	50	30	30	**37**
0	13	50	30	30	**37**
0	14	50	30	30	**37**
1	15	-20	-20	-20	**-20**
2	16	-30	-60	-80	**-57**
3	17	-40	-80	-100	**-73**
4	18	-40	-80	-120	**-80**
5	19	-50	-80	-120	**-83**
6	20	-60	-90	-130	**-93**
7	21	-70	-100	-140	**-103**
8	22	-80	-110	-150	**-113**
9	23	-90	-130	-160	**-127**
10	24	-90	-130	-180	**-133**
11	25	-100	-130	-170	**-133**
12	26	-100	-130	-170	**-133**
13	27	-110	-140	-170	**-140**
14	28	-110	-140	-170	**-140**
15	29	-140	-160	-200	**-167**
16	30	-150	-160	-220	**-177**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 8.7-G)			
		A	B	C	Average
17	31	-150	-190	-250	**-197**
18	32	-160	-200	-260	**-207**
19	33	-150	-200	-270	**-207**
20	34	-160	-200	-280	**-213**
21	35	-160	-200	-290	**-217**
22	36	-160	-200	-280	**-213**
23	37	-160	-210	-280	**-217**
24	38	-170	-210	-290	**-223**
25	39	-170	-210	-290	**-223**
26	40	-180	-220	-290	**-230**
27	41	-190	-230	-290	**-237**
28	42	-200	-240	-290	**-243**
29	43	-220	-270	-290	**-260**
30	44	-210	-260	-290	**-253**
32	46	-210	-260	-290	**-253**
34	48	-210	-260	-290	**-253**
36	50	-210	-260	-300	**-257**
38	52	-220	-270	-310	**-267**
40	54	-230	-270	-310	**-270**
42	56	-240	-280	-320	**-280**
44	58	-250	-290	-330	**-290**
46	60	-250	-290	-330	**-290**
48	62	-250	-300	-340	**-297**
50	64	-260	-300	-340	**-300**
52	66	-270	-300	-350	**-307**
54	68	-270	-310	-350	**-310**
56	70	-270	-310	-350	**-310**
58	72	-280	-310	-360	**-317**
60	74	-270	-310	-360	**-313**
62	76	-280	-320	-370	**-323**
64	78	-290	-330	-380	**-333**
66	80	-300	-340	-370	**-337**
68	82	-300	-340	-390	**-343**
70	84	-300	-340	-400	**-347**
72	86	-300	-340	-400	**-347**
74	88	-300	-340	-400	**-347**
76	90	-300	-340	-400	**-347**
78	92	-300	-340	-390	**-343**
80	94	-290	-330	-380	**-333**
82	96	-310	-340	-400	**-350**
84	98	-320	-350	-410	**-360**
86	100	-320	-360	-410	**-363**
88	102	-320	-350	-420	**-363**
90	104	-330	-350	-420	**-367**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 8.7-G)			
		A	B	C	Average
92	106	-330	-360	-430	**-373**
98	112	-310	-340	-410	**-353**
105	119	-330	-330	-400	**-353**
112	126	-310	-360	-400	**-357**
119	133	-320	-360	-400	**-360**
126	140	-320	-360	-410	**-363**
133	147	-330	-370	-410	**-370**
140	154	-340	-370	-420	**-377**
147	161	-340	-380	-420	**-380**
154	168	-350	-390	-430	**-390**
161	175	-350	-390	-430	**-390**
168	182	-360	-400	-440	**-400**
175	189	-370	-410	-440	**-407**
182	196	-380	-400	-460	**-413**
183	197	-380	-400	-460	**-413**
210	224	-370	-410	-470	**-417**
238	252	-380	-420	-480	**-427**
266	280	-380	-420	-490	**-430**
294	308	-380	-430	-490	**-433**
322	336	-390	-440	-500	**-443**
350	364	-400	-440	-500	**-447**
365	379	-410	-450	-510	**-457**

Time of Drying day	Time after Cast day	Strain, microstrain (T-12.5-H)			
		A	B	C	Average
0	0.00	0	0	0	**0**
0	0.08	50	20	0	**23**
0	0.17	50	30	20	**33**
0	1	80	60	40	**60**
0	2	80	60	40	**60**
0	3	80	60	40	**60**
0	4	90	60	50	**67**
0	5	90	60	50	**67**
0	6	100	60	60	**73**
0	7	100	60	60	**73**
0	8	100	60	60	**73**
0	9	110	70	70	**83**
0	10	110	60	70	**80**
0	11	110	60	70	**80**
0	12	130	60	80	**90**
0	13	120	60	80	**87**
0	14	130	60	80	**90**
1	15	90	20	50	**53**
2	16	70	10	30	**37**
3	17	60	0	20	**27**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 9.0-L)			
		A	B	C	Average
4	18	50	-20	10	**13**
5	19	40	-30	0	**3**
6	20	30	-40	0	**-3**
7	21	20	-50	-10	**-13**
8	22	0	-60	-30	**-30**
9	23	0	-70	-30	**-33**
10	24	-10	-90	-50	**-50**
11	25	-20	-90	-50	**-53**
12	26	-30	-100	-60	**-63**
13	27	-40	-110	-70	**-73**
14	28	-50	-120	-80	**-83**
15	29	-50	-130	-90	**-90**
16	30	-60	-140	-100	**-100**
17	31	-70	-140	-100	**-103**
18	32	-70	-150	-100	**-107**
19	33	-80	-150	-100	**-110**
20	34	-90	-160	-110	**-120**
21	35	-90	-160	-120	**-123**
22	36	-100	-170	-120	**-130**
23	37	-100	-170	-130	**-133**
24	38	-110	-180	-140	**-143**
25	39	-110	-180	-140	**-143**
26	40	-110	-180	-150	**-147**
27	41	-120	-190	-160	**-157**
28	42	-120	-200	-160	**-160**
29	43	-120	-210	-170	**-167**
30	44	-120	-210	-170	**-167**
32	46	-120	-220	-180	**-173**
34	48	-120	-230	-190	**-180**
36	50	-130	-240	-200	**-190**
38	52	-170	-250	-210	**-210**
40	54	-150	-260	-210	**-207**
42	56	-140	-270	-220	**-210**
44	58	-150	-270	-220	**-213**
46	60	-150	-270	-230	**-217**
48	62	-160	-280	-240	**-227**
50	64	-170	-290	-250	**-237**
52	66	-160	-300	-250	**-237**
54	68	-160	-300	-250	**-237**
56	70	-150	-310	-260	**-240**
58	72	-230	-320	-280	**-277**
60	74	-220	-310	-270	**-267**
62	76	-220	-310	-270	**-267**
64	78	-220	-320	-270	**-270**
66	80	-220	-320	-270	**-270**
68	82	-230	-330	-270	**-277**

Table B.1: (con't) Shrinkage results for mixtures in Program III

Time of Drying day	Time after Cast day	Strain, microstrain (T- 9.0-L)			
		A	B	C	Average
70	84	-230	-340	-290	**-287**
72	86	-240	-340	-300	**-293**
74	88	-240	-340	-290	**-290**
76	90	-250	-340	-300	**-297**
78	92	-250	-350	-300	**-300**
80	94	-270	-350	-300	**-307**
82	96	-270	-350	-310	**-310**
84	98	-270	-350	-320	**-313**
86	100	-270	-360	-310	**-313**
88	102	-270	-370	-310	**-317**
90	104	-270	-370	-310	**-317**
92	106	-260	-360	-310	**-310**
97	111	-260	-360	-300	**-307**
104	118	-260	-360	-300	**-307**
111	125	-260	-360	-300	**-307**
118	133	-260	-360	-310	**-310**
125	140	-250	-360	-320	**-310**
132	147	-270	-360	-330	**-320**
139	154	-280	-360	-340	**-327**
146	161	-280	-350	-340	**-323**
153	168	-290	-360	-340	**-330**
160	175	-300	-370	-360	**-343**
167	182	-320	-390	-380	**-363**
174	189	-330	-380	-370	**-360**
181	196	-340	-380	-370	**-363**
181	196	-340	-380	-370	**-363**
209	224	-340	-390	-380	**-370**
237	252	-350	-390	-380	**-373**
265	280	-360	-400	-390	**-383**
293	308	-370	-400	-400	**-390**
321	336	-370	-400	-400	**-390**
349	364	-370	-410	-400	**-393**
365	379	-380	-410	-400	**-397**

Table B.2: Freeze-Thaw results for mixtures in Program III

Mixture: T-3.4-L									
Cycles	**0**			**22**			**48**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167.97**	**2197.27**	**2211.91**	**2167.97**	**2197.27**	**2211.91**	**2167.97**	**2197.27**	**2211.91**
Mass [g]	**7546.6**	**7577.6**	**7561**	**7551.7**	**7583.7**	**7565.5**	**7553.3**	**7586.2**	**7568.3**
$E_{Dyn.}$ [Pa]	3.8E+10	4.0E+10	4.0E+10	3.8E+10	4.0E+10	4.0E+10	3.8E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.9E+10			3.9E+10			3.9E+10		

Mixture: T-3.4-L									
Cycles	**73**			**94**			**130**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2211.91**	**2211.91**	**2182.62**	**2211.91**	**2197.27**	**2182.62**	**2211.91**	**2226.56**
Mass [g]	**7555.1**	**7587.1**	**7567.1**	**7554.2**	**7586.4**	**7568.2**	**7551.5**	**7584.3**	**7567.1**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	4.0E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.0E+10			4.0E+10			4.0E+10		

Mixture: T-3.4-L									
Cycles	**156**			**183**			**203**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2211.91**	**2226.56**	**2197.27**	**2211.91**	**2226.56**	**2197.27**	**2197.27**	**2226.56**
Mass [g]	**7547.5**	**7577.5**	**7563**	**7538.1**	**7573.34**	**7560**	**7534.4**	**7573.1**	**7559.1**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.0E+10			4.0E+10			4.0E+10		

Mixture: T-3.4-L									
Cycles	**229**			**264**			**300**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2197.27**	**2197.27**	**2226.56**	**2197.27**	**2197.27**	**2211.91**	**2182.62**	**2182.62**	**2211.91**
Mass [g]	**7531**	**7564.9**	**7554.7**	**7523.5**	**7559.8**	**7545.8**	**7516**	**7559**	**7545.1**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	4.1E+10	3.9E+10	4.0E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	4.0E+10			4.0E+10			4.0E+10		

Mixture: T-3.4-L									
Cycles	**340**			**366**			**400**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2188.62**	**2197.27**	**2167.97**	**2167.97**	**2182.62**	**2153.32**	**2153.32**	**2167.97**
Mass [g]	**7527.2**	**7552.2**	**7544.9**	**7502.1**	**7543.4**	**7533.8**	**7497.4**	**7543.1**	**7531.8**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.9E+10	3.8E+10	3.8E+10	3.9E+10	3.8E+10	3.8E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.9E+10			3.9E+10			3.8E+10		

Mixture: T-3.4-L									
Cycles	**426**			**460**			**488**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2138.67**	**2138.67**	**2153.32**	**2124.02**	**2109.38**	**2124.02**	**2094.73**	**2080.08**	**2080.08**
Mass [g]	**7490.5**	**7530.2**	**7521.1**	**7491**	**7531.4**	**7519.7**	**7480.3**	**7521.6**	**7512.5**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.6E+10	3.7E+10	3.6E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.7E+10			3.7E+10			3.5E+10		

Mixture: T-3.4-L									
Cycles	**522**			**542**			**577**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2036.13**	**2036.13**	**2021.48**	**2006.84**	**1992.19**	**1948.24**	**1948.24**	**1933.59**
Mass [g]	**7472**	**7505.3**	**7505.2**	**7460.9**	**7499.6**	**7497.9**	**7453.6**	**7489.9**	**7490.3**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.4E+10	3.3E+10	3.3E+10	3.2E+10	3.1E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.3E+10			3.1E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: T-3.4-L									
Cycles	611			646			681		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1889.65	1889.65	1860.35	1816.41	1845.7	1801.76	1743.16	1757.31	1713.87
Mass [g]	7437.5	7479.4	7478.5	7429.8	7469.9	7470.7	7411.2	7453.3	7462.5
$E_{Dyn.}$ [Pa]	2.9E+10	2.9E+10	2.8E+10	2.7E+10	2.8E+10	2.6E+10	2.4E+10	2.5E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.7E+10			2.4E+10		

Mixture: T-3.4-L			
Cycles	716		
Specimen	A	B	C
Frequency [Hz]	1625.98	1640.63	1625.98
Mass [g]	7400.8	7442.8	7452.1
$E_{Dyn.}$ [Pa]	2.1E+10	2.2E+10	2.1E+10
Avg. $E_{Dyn.}$ [Pa]	2.1E+10		

Mixture: T- 9.0-L									
Cycles	0			37			63		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2094.73	2109.38	2094.73	2094.73	2109.38	2094.73	2094.73	2109.38	2094.73
Mass [g]	7171.6	7167.7	7121.1	7186.8	7186.4	7134.7	7196.4	7194.3	7142.5
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.4E+10		

Mixture: T- 9.0-L									
Cycles	85			111			136		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2094.73	2109.38	2094.73	2094.73	2109.38	2094.73	2109.38	2124.02	2094.73
Mass [g]	7200.4	7197.5	7146.3	7190	7193.7	7142.3	7178.7	7188.1	7138.1
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.5E+10		

Mixture: T- 9.0-L									
Cycles	157			193			219		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2094.73	2109.38	2080.08	2094.73	2109.38	2050.78	2080.08	2094.73	2006.84
Mass [g]	7172.2	7183.8	7136.3	7168.3	7174.3	7122.2	7154.5	7159.3	7118
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.3E+10	3.4E+10	3.5E+10	3.2E+10	3.4E+10	3.4E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.4E+10			3.3E+10		

Mixture: T- 9.0-L									
Cycles	246			266			292		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2065.43	2080.08	1962.89	2050.78	2050.78	1904.3	2021.48	2021.48	1816.41
Mass [g]	7150.8	7157.3	7115.1	7151	7151.6	7117.1	7151.8	7152.5	7111.8
$E_{Dyn.}$ [Pa]	3.3E+10	3.4E+10	3.0E+10	3.3E+10	3.3E+10	2.8E+10	3.2E+10	3.2E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.1E+10			3.0E+10		

Mixture: T- 9.0-L									
Cycles	327			363			403		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1904.3	1918.95	1640.63	1728.52	1728.52	1433.35	1552.73	1479.94	1347.66
Mass [g]	7152.6	7148.2	7108.3	7142.1	7136.9	7112.1	7128.8	7130	7094.6
$E_{Dyn.}$ [Pa]	2.8E+10	2.9E+10	2.1E+10	2.3E+10	2.3E+10	1.6E+10	1.9E+10	1.7E+10	1.4E+10
Avg. $E_{Dyn.}$ [Pa]	2.6E+10			2.1E+10			1.7E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: T-9.0-L			
Cycles	429		
Specimen	A	B	C
Frequency [Hz]	1347.66	1025.39	1318.36
Mass [g]	7111.9	7118.1	7084.6
$E_{Dyn.}$ [Pa]	1.4E+10	8.1E+09	1.3E+10
Avg. $E_{Dyn.}$ [Pa]	1.2E+10		

Mixture: T- 12.0-L									
Cycles	0			36			62		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2109.38	2109.38	2109.38	2109.38	2094.73	2109.38	2109.38	2094.73	2094.73
Mass [g]	7121.2	7206.6	7156.6	7128.2	7211.9	7160.2	7127.2	7212	7158.7
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.5E+10			3.4E+10			3.4E+10		

Mixture: T- 12.0-L									
Cycles	89			109			135		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2109.38	2109.38	2094.73	2094.73	2109.38	2094.73	2094.73	2094.73	2080.08
Mass [g]	7126.1	7199.4	7152.3	7123.5	7196.5	7145.1	7115.6	7183.6	7137.1
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.5E+10			3.4E+10			3.4E+10		

Mixture: T- 12.0-L									
Cycles	170			206			246		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2080.08	2080.08	2050.78	2021.48	2065.43	2021.48	1933.59	2006.84	1918.95
Mass [g]	7108.8	7174.5	7122.3	7096.6	7152.4	7114	7091.4	7143.9	7104.6
$E_{Dyn.}$ [Pa]	3.3E+10	3.4E+10	3.2E+10	3.1E+10	3.3E+10	3.2E+10	2.9E+10	3.1E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.2E+10			2.9E+10		

Mixture: T- 12.0-L									
Cycles	272			306			332		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	1831.05	1948.24	1816.41	1582	1816.41	1625.98	1406.25	1640.63	1450.2
Mass [g]	7082.5	7134.3	7099	7078	7124.8	7076	7053	7104.8	7061.9
$E_{Dyn.}$ [Pa]	2.6E+10	2.9E+10	2.5E+10	1.9E+10	2.5E+10	2.0E+10	1.5E+10	2.1E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.2E+10			1.7E+10		

Mixture: T- 12.0-L			
Cycles	366		
Specimen	A	B	C
Frequency [Hz]	1113.28	1391.6	1171.88
Mass [g]	7034.5	7086.7	7038.8
$E_{Dyn.}$ [Pa]	9.4E+09	1.5E+10	1.0E+10
Avg. $E_{Dyn.}$ [Pa]	1.2E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: C- 3.4-L									
Cycles	**0**			**20**			**54**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2241.21**	**2241.21**	**2226.56**	**2241.21**	**2241.21**	**2226.56**	**2241.21**	**2255.86**	**2226.56**
Mass [g]	**7549.8**	**7625.6**	**7644.9**	**7552.9**	**7629.3**	**7647.3**	**7554.4**	**7630.7**	**7651.9**
$E_{Dyn.}$ [Pa]	4.1E+10	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.1E+10			4.1E+10			4.1E+10		

Mixture: C- 3.4-L									
Cycles	**89**			**124**			**159**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2255.86**	**2255.86**	**2226.56**	**2255.86**	**2255.86**	**2241.21**	**2270.51**	**2270.51**	**2241.21**
Mass [g]	**7548.8**	**7628.1**	**7649.2**	**7543.2**	**7623.9**	**7647.1**	**7539.4**	**7623.1**	**7646.5**
$E_{Dyn.}$ [Pa]	4.2E+10	4.2E+10	4.1E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.3E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.2E+10			4.2E+10			4.2E+10		

Mixture: C- 3.4-L									
Cycles	**189**			**230**			**261**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2270.51**	**2270.51**	**2241.21**	**2270.51**	**2270.51**	**2241.21**	**2285.16**	**2270.51**	**2241.21**
Mass [g]	**7536.5**	**7614.7**	**7644.3**	**7533.5**	**7607.1**	**7641.8**	**7529.7**	**7601.1**	**7641.7**
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	4.2E+10	4.2E+10	4.2E+10	4.2E+10	4.3E+10	4.2E+10	4.2E+10
Avg. $E_{Dyn.}$ [Pa]	4.2E+10			4.2E+10			4.2E+10		

Mixture: C- 3.4-L									
Cycles	**294**			**327**			**356**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2285.16**	**2270.51**	**2241.21**	**2299.8**	**2285.16**	**2241.21**	**2299.8**	**2285.16**	**2226.56**
Mass [g]	**7520**	**7596.3**	**7632.1**	**7513**	**7590.7**	**7623.1**	**7509.9**	**7587.5**	**7619.4**
$E_{Dyn.}$ [Pa]	4.3E+10	4.2E+10	4.2E+10	4.3E+10	4.3E+10	4.1E+10	4.3E+10	4.3E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.2E+10			4.3E+10			4.2E+10		

Mixture: C- 3.4-L									
Cycles	**384**			**418**			**427**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2299.8**	**2285.16**	**2226.56**	**2299.8**	**2285.16**	**2226.56**	**2299.8**	**2285.16**	**2211.91**
Mass [g]	**7503.1**	**7578**	**7608**	**7496.3**	**7566.1**	**7602.4**	**7492.5**	**7556.9**	**7600.8**
$E_{Dyn.}$ [Pa]	4.3E+10	4.3E+10	4.1E+10	4.3E+10	4.3E+10	4.1E+10	4.3E+10	4.3E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	4.2E+10			4.2E+10			4.2E+10		

Mixture: C- 3.4-L									
Cycles	**460**			**493**			**522**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2299.8**	**2299.8**	**2197.27**	**2299.8**	**2285.16**	**2153.32**	**2285.16**	**2285.16**	**2094.73**
Mass [g]	**7482.4**	**7549.8**	**7589**	**7467.6**	**7539.4**	**7576.8**	**7454.9**	**7528**	**7570.4**
$E_{Dyn.}$ [Pa]	4.3E+10	4.3E+10	4.0E+10	4.3E+10	4.3E+10	3.8E+10	4.2E+10	4.3E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	4.2E+10			4.1E+10			4.0E+10		

Mixture: C- 3.4-L									
Cycles	**555**			**584**			**619**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2285.16**	**2299.8**	**2036.13**	**2299.8**	**2299.8**	**2036.13**	**2285.16**	**2285.16**	**1962.89**
Mass [g]	**7437.8**	**7522.1**	**7546.9**	**7428.3**	**7491.8**	**7539.1**	**7399.9**	**7470.8**	**7491.9**
$E_{Dyn.}$ [Pa]	4.2E+10	4.3E+10	3.4E+10	4.3E+10	4.3E+10	3.4E+10	4.2E+10	4.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.0E+10			4.0E+10			3.8E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: C- 3.4-L									
Cycles	**632**			**665**			**698**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2241.21**	**2241.21**	**2226.56**	**2241.21**	**2241.21**	**2226.56**	**2241.21**	**2255.86**	**2226.56**
Mass [g]	**7549.8**	**7625.6**	**7644.9**	**7552.9**	**7629.3**	**7647.3**	**7554.4**	**7630.7**	**7651.9**
$E_{Dyn.}$ [Pa]	4.1E+10	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10	4.1E+10	4.2E+10	4.1E+10
Avg. $E_{Dyn.}$ [Pa]	4.1E+10			4.1E+10			4.1E+10		

Mixture: C- 3.4-L									
Cycles	**745**			**764**			**800**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	***2138.67***	***2197.27***	***1230.47***	***2065.43***	***2167.97***	***981.42***	***1860.35***	***2021.48***	***1230.47***
Mass [g]	***7234.3***	***7376.1***	***7226.9***	***7202.4***	***7362.6***	***7180.6***	***7158.1***	***7327.5***	***6941.3***
$E_{Dyn.}$ [Pa]	3.6E+10	3.9E+10	1.2E+10	3.3E+10	3.7E+10	7.5E+09	2.7E+10	3.2E+10	1.1E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.6E+10			2.4E+10		

Mixture: C- 8.7-L									
Cycles	**0**			**19**			**39**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2138.67**	**2124.02**	**2153.32**	**2124.02**	**2124.02**	**2138.67**	**2138.67**	**2124.02**	**2138.67**
Mass [g]	**7323**	**7379.9**	**7322.2**	**7326.4**	**7385.3**	**7325.9**	**7320.2**	**7377.4**	**7321.4**
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.7E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.6E+10			3.6E+10			3.6E+10		

Mixture: C- 8.7-L									
Cycles	**74**			**108**			**143**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2138.67**	**2138.67**	**2153.32**	**2153.32**	**2138.67**	**2167.97**	**2167.97**	**2153.32**	**2167.67**
Mass [g]	**7303.4**	**7361.4**	**7309.2**	**7284.2**	**7346.5**	**7294.2**	**7274.6**	**7330.9**	**7285.9**
$E_{Dyn.}$ [Pa]	3.6E+10	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.6E+10			3.7E+10			3.7E+10		

Mixture: C- 8.7-L									
Cycles	**178**			**213**			**243**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167.97**	**2153.32**	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2153.32**	**2182.62**
Mass [g]	**7271.2**	**7325**	**7282**	**7266.3**	**7318**	**7277.9**	**7265.1**	**7312.2**	**7277.3**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.7E+10			3.7E+10			3.7E+10		

Mixture: C- 8.7-L									
Cycles	**284**			**315**			**348**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2167.97**	**2182.62**
Mass [g]	**7263.4**	**7307.4**	**7272.6**	**7268.9**	**7302.8**	**7275.3**	**7260.9**	**7296.4**	**7271.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.7E+10			3.7E+10			3.7E+10		

Mixture: C- 8.7-L									
Cycles	**381**			**410**			**438**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2153.32**	**2167.97**	**2182.62**
Mass [g]	**7261.1**	**7293.3**	**7269**	**7259.3**	**7290.3**	**7269.2**	**7256.7**	**7290.6**	**7270.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.7E+10			3.7E+10			3.7E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: C- 8.7-L									
Cycles	**472**			**481**			**514**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2153.32**	**2167.97**	**2182.62**	**2138.67**	**2167.97**	**2182.62**	**2124.02**	**2167.97**	**2167.97**
Mass [g]	**7257.1**	**7283.5**	**7261.9**	**7252.3**	**7281.4**	**7261.3**	**7253.6**	**7280.8**	**7257.4**
$E_{Dyn.}$ [Pa]	3.6E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10	3.5E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.7E+10			3.7E+10			3.7E+10		

Mixture: C- C- 8.7-L									
Cycles	**547**			**576**			**609**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2167.97**	**2167.97**	**2050.78**	**2153.32**	**2153.32**	**2006.84**	**2153.32**	**2153.32**
Mass [g]	**7255.4**	**7278.4**	**7258.1**	**7250.7**	**7275.3**	**7254.6**	**7242.4**	**7274.2**	**7255.6**
$E_{Dyn.}$ [Pa]	3.4E+10	3.7E+10	3.7E+10	3.3E+10	3.7E+10	3.6E+10	3.2E+10	3.7E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.6E+10			3.5E+10			3.5E+10		

Mixture: C- 8.7-L									
Cycles	**638**			**673**			**686**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1977.54**	**2138.67**	**2153.32**	**1875**	**2124.02**	**2138.67**	**1831.05**	**2109.38**	**2124.02**
Mass [g]	**7203.2**	**7272.1**	**7251.1**	**7195**	**7267.3**	**7247.5**	**7193.1**	**7263.2**	**7249.6**
$E_{Dyn.}$ [Pa]	3.1E+10	3.6E+10	3.6E+10	2.7E+10	3.6E+10	3.6E+10	2.6E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.4E+10			3.3E+10			3.2E+10		

Mixture: C- 8.7-L									
Cycles	**719**			**752**			**799**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1831.05**	**2065.43**	**2094.73**	**1787.11**	**2006.84**	**2065.43**	**1611.33**	**1875**	**1962.89**
Mass [g]	**7180.5**	**7253.6**	**7246.2**	**7166.9**	**7247.8**	**7237.8**	**7074.6**	**7250.4**	**7233.3**
$E_{Dyn.}$ [Pa]	2.6E+10	3.4E+10	3.4E+10	2.5E+10	3.2E+10	3.3E+10	2.0E+10	2.8E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.0E+10			2.6E+10		

Mixture: C- 8.7-L						
Cycles	**818**			**854**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1479.49**	**1816.41**	**1933.59**	**1230.47**	**1508.79**	**1831.05**
Mass [g]	**7026.6**	**7224.7**	**7224.2**	**6894.9**	**7161.7**	**7170.3**
$E_{Dyn.}$ [Pa]	1.7E+10	2.6E+10	2.9E+10	1.1E+10	1.8E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	2.4E+10			1.8E+10		

Mixture: T- 3.0-G									
Cycles	**0**			**40**			**70**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2050.78**	**2021.48**	**2050.78**	**2050.78**	**2021.48**	**2050.78**	**2050.78**	**2036.13**
Mass [g]	**7161.9**	**7142.5**	**7186.6**	**7164.9**	**7147.8**	**7192.27**	**7157.7**	**7141.5**	**7186.3**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: T- 3.0-G									
Cycles	**111**			**142**			**175**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2065.43**	**2036.13**	**2065.43**	**2065.43**	**2050.78**	**2080.08**	**2065.43**	**2050.78**
Mass [g]	**7148.1**	**7123.3**	**7176.2**	**7140.1**	**7111.7**	**7171**	**7119.6**	**7093.3**	**7153.6**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: T- 3.0-G									
Cycles	**208**			**237**			**265**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2050.78**	**2080.08**	**2080.08**	**2065.43**	**2094.73**	**2080.08**	**2065.43**
Mass [g]	**7096.6**	**7076.6**	**7141.2**	**7082.8**	**7052**	**7131.9**	**7068.2**	**7032.5**	**7124.4**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T- 3.0-G									
Cycles	**299**			**308**			**341**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2065.43**	**2094.73**	**2094.73**	**2065.43**	**2094.73**	**2094.73**	**2065.43**
Mass [g]	**7046.7**	**7011.5**	**7107.1**	**7041.9**	**7004.6**	**7102.3**	**7024.1**	**6991.7**	**7093.1**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T- 3.0-G									
Cycles	**374**			**403**			**436**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2065.43**	**2094.73**	**2094.73**	**2065.43**	**2094.73**	**2094.73**	**2065.43**
Mass [g]	**7014**	**6976.3**	**7080.7**	**7001**	**6965.2**	**7069.6**	**6989**	**6950.7**	**7060.4**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T- 3.0-G									
Cycles	**465**			**500**			**513**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2065.43**	**2109.38**	**2094.73**	**2065.43**	**2109.38**	**2094.73**	**2065.43**
Mass [g]	**6981.7**	**6941.2**	**7054.1**	**6967.4**	**6926**	**7044.2**	**6962.7**	**6923.4**	**7041.5**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T- 3.0-G									
Cycles	**546**			**579**			**626**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2094.73**	**2065.43**	**2109.38**	**2094.73**	**2065.43**	**2109.38**	**2094.73**	**2065.43**
Mass [g]	**6955.9**	**6915.6**	**7033**	**6945.5**	**6908.6**	**7021.5**	**6936.5**	**6898**	**7007.7**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.3E+10	3.3E+10	3.2E+10	3.3E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T- 3.0-G									
Cycles	**645**			**681**			**712**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2080.08**	**2050.78**	**2109.38**	**2080.08**	**2050.78**	**2109.38**	**2080.08**	**2036.13**
Mass [g]	**6925.3**	**6883.6**	**7000.3**	**6916.1**	**6864.9**	**6995.9**	**6914.6**	**6860.9**	**6990.8**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.2E+10			3.2E+10		

Mixture: T- 3.0-G									
Cycles	**746**			**781**			**817**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2080.08**	**2036.13**	**2050.78**	**2050.78**	**2021.48**	**1997.54**	**2021.48**	**1977.54**
Mass [g]	**6912.5**	**6858.1**	**6989.3**	**6888.5**	**6847.1**	**6982.8**	**6885.4**	**6845.8**	**6980.9**
$E_{Dyn.}$ [Pa]	3.3E+10	3.2E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.0E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.1E+10			3.0E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: T- 3.0-G									
Cycles	**848**			**880**			**914**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**1992.19**	**1933.59**	**2021.48**	**1977.54**	**1889.65**	**1992.19**	**1948.24**	**1845.7**
Mass [g]	**6870.7**	**6848.7**	**6979.8**	**6861.7**	**6832.2**	**6973.6**	**6852.1**	**6817.4**	**6969**
$E_{Dyn.}$ [Pa]	3.1E+10	2.9E+10	2.8E+10	3.0E+10	2.9E+10	2.7E+10	2.9E+10	2.8E+10	2.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.0E+10			2.9E+10			2.8E+10		

Mixture: T- 3.0-G									
Cycles	**947**			**980**			**1015**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1962.89**	**1904.3**	**1801.76**	**1904.3**	**1845.7**	**1728.52**	**1831.05**	**1801.76**	**1611.32**
Mass [g]	**6828.9**	**6810.7**	**6965.3**	**6812.6**	**6792.5**	**6859.3**	**6801.9**	**6785.4**	**6852.1**
$E_{Dyn.}$ [Pa]	2.9E+10	2.7E+10	2.5E+10	2.7E+10	2.5E+10	2.2E+10	2.5E+10	2.4E+10	1.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.7E+10			2.5E+10			2.3E+10		

Mixture: T- 3.0-G			
Cycles	**1039**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1699.22**	**1669.92**	**1464.82**
Mass [g]	**6779.5**	**6782.1**	**6849.2**
$E_{Dyn.}$ [Pa]	2.1E+10	2.0E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	1.9E+10		

Mixture: T-8.7-G									
Cycles	**0**			**36**			**70**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**2036.13**	**2065.43**	**2036.13**	**2050.78**	**2080.08**	**2050.78**	**2050.78**	**2080.08**
Mass [g]	**7061.6**	**6999.3**	**7084.1**	**7070.2**	**7007.8**	**7091.3**	**7062**	**6995.7**	**7081.6**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: T-8.7-G									
Cycles	**100**			**141**			**172**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2050.78**	**2094.73**	**2050.78**	**2065.43**	**2094.73**	**2065.43**	**2065.43**	**2094.73**
Mass [g]	**7055**	**6986.8**	**7071.4**	**7038.5**	**6973.5**	**7069**	**7038.8**	**6961.3**	**7063.3**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.4E+10	3.2E+10	3.2E+10	3.4E+10	3.3E+10	3.2E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T-8.7-G									
Cycles	**205**			**238**			**267**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2065.43**	**2109.38**	**2065.43**	**2065.43**	**2109.38**	**2065.43**	**2065.43**	**2094.73**
Mass [g]	**7016.7**	**6947.3**	**7050**	**7003.2**	**6934.3**	**7036.8**	**6993.7**	**6922.6**	**7031.1**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.4E+10	3.2E+10	3.2E+10	3.4E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.3E+10			3.3E+10		

Mixture: T-8.7-G									
Cycles	**295**			**329**			**338**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2065.43**	**2094.73**	**2065.43**	**2065.43**	**2094.73**	**2065.43**	**2065.43**	**2094.73**
Mass [g]	**6978.7**	**6916.4**	**7026.9**	**6970**	**6900.8**	**7011.9**	**6968.9**	**6896**	**7007.3**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10	3.2E+10	3.2E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.3E+10			3.2E+10			3.2E+10		

Table B.2: (con't) Freeze-Thaw results for mixtures in Program III

Mixture: T-8.7-G									
Cycles	**371**			**404**			**433**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2050.78**	**2094.73**	**2036.13**	**2050.78**	**2080.08**	**2036.13**	**2036.13**	**2080.08**
Mass [g]	**6957.2**	**6893.8**	**6998.6**	**6951**	**6877.3**	**6988.3**	**6933.4**	**6866.5**	**6981.8**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.2E+10			3.2E+10			3.2E+10		

Mixture: T-8.7-G									
Cycles	**466**			**495**			**530**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2021.48**	**2080.08**	**1992.19**	**1992.19**	**2050.78**	**1962.89**	**1948.24**	**2021.48**
Mass [g]	**6930.3**	**6848.5**	**6969.6**	**6911.9**	**6840.7**	**6964.9**	**6908.4**	**6832**	**6958.8**
$E_{Dyn.}$ [Pa]	3.0E+10	3.0E+10	3.3E+10	3.0E+10	2.9E+10	3.2E+10	2.9E+10	2.8E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.0E+10			2.9E+10		

Mixture: T-8.7-G									
Cycles	**543**			**576**			**609**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1948.24**	**1933.59**	**2021.48**	**1904.3**	**1875**	**1962.89**	**1860.35**	**1816.41**	**1918.95**
Mass [g]	**6897.9**	**6828.9**	**6954.2**	**6893.2**	**6816.2**	**6944.4**	**6877.9**	**6808**	**6930.7**
$E_{Dyn.}$ [Pa]	2.8E+10	2.8E+10	3.1E+10	2.7E+10	2.6E+10	2.9E+10	2.6E+10	2.4E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.9E+10			2.7E+10			2.6E+10		

Mixture: T-8.7-G									
Cycles	**656**			**675**			**711**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1699.22**	**1699.22**	**1801.76**	**1582.03**	**1582.03**	**1772.46**	**1400.25**	**1333.01**	**1640.63**
Mass [g]	**6858.4**	**6793.8**	**6915.7**	**6850**	**6779.4**	**6908.1**	**6853**	**6741**	**6883.7**
$E_{Dyn.}$ [Pa]	2.1E+10	2.1E+10	2.4E+10	1.9E+10	1.8E+10	2.4E+10	1.5E+10	1.3E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.2E+10			2.0E+10			1.6E+10		

Mixture: T-12.5-H									
Cycles	**0**			**36**			**77**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**1977.54**	**2006.86**	**1992.19**	**1977.54**	**2006.86**	**1948.24**	**1977.54**	**1992.19**
Mass [g]	**7155.4**	**7075**	**7103.2**	**7170.8**	**7091.4**	**7121.6**	**7172.5**	**7090.7**	**7123.5**
$E_{Dyn.}$ [Pa]	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.0E+10	3.0E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.1E+10			3.1E+10			3.0E+10		

Mixture: T-12.5-H									
Cycles	**108**			**141**			**174**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**1918.95**	**1948.24**	**1655.25**	**1801.76**	**1831.05**	**1406.25**	**1552.73**	**1596.68**
Mass [g]	**7175.3**	**7078**	**7112.4**	**7174.3**	**7080.3**	**7108.8**	**7151.4**	**7076.6**	**7082.7**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.9E+10	2.1E+10	2.5E+10	2.6E+10	1.5E+10	1.8E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.8E+10			2.4E+10			1.8E+10		

Mixture: T-12.5-H			
Cycles	**203**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1127.93**	**1259.77**	**1289.06**
Mass [g]	**7131.5**	**7037.1**	**7050.7**
$E_{Dyn.}$ [Pa]	9.8E+09	1.2E+10	1.3E+10
Avg. $E_{Dyn.}$ [Pa]	1.2E+10		

Table B.3: Scaling results for mixtures in Program III (ASTM C672)

Mixture: T-3.4-L

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	74.94	9.5	2.91E-04	3.4	1.04E-04	1.2	3.68E-05	0.9	2.76E-05	0.3	9.19E-06	1.6	4.90E-05	1.7	5.21E-05
B	74.03	8.1	2.51E-04	2.4	7.44E-05	0.8	2.48E-05	0.4	1.24E-05	0.4	1.24E-05	0.7	2.17E-05	0.8	2.48E-05
C	71.35	10	3.22E-04	2.1	6.76E-05	0.9	2.90E-05	0.7	2.25E-05	0.6	1.93E-05	0.9	2.90E-05	0.7	2.25E-05
Average	73.44		2.88E-04		8.20E-05		3.02E-05		2.08E-05		1.36E-05		3.32E-05		3.31E-05
Cumulative mass loss (lb/ft^2)			**4.15E-02**		**5.33E-02**		**5.76E-02**		**6.06E-02**		**6.26E-02**		**6.74E-02**		**7.21E-02**

Mixture: T- 9.0-L

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	74.66	3.8	1.17E-04	2.1	6.46E-05	0.6	1.84E-05	0.3	9.22E-06	0.2	6.15E-06	0.4	1.23E-05	0.5	1.54E-05
B	75.35	6.9	2.10E-04	2.2	6.7E-05	0.7	2.13E-05	0.6	1.83E-05	0.3	9.14E-06	0.5	1.52E-05	0.6	1.83E-05
C	76.53	4.6	1.38E-04	1.5	4.5E-05	0.6	1.8E-05	0.3	9.00E-06	0.2	6.00E-06	0.3	9.00E-06	0.5	1.50E-05
Average	75.51		1.55E-04		5.89E-05		1.93E-05		1.22E-05		7.10E-06		1.22E-05		1.62E-05
Cumulative mass loss (lb/ft^2)			**2.23E-02**		**3.08E-02**		**3.36E-02**		**3.53E-02**		**3.63E-02**		**3.81E-02**		**4.04E-02**

Mixture: T- 12.0-L

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	68.44	2	6.71E-05	1.4	4.7E-05	0.5	1.68E-05	0.2	6.71E-06	0.9	3.02E-05	0.4	1.34E-05	0.5	1.68E-05
B	70.13	2.1	6.87E-05	1.3	4.26E-05	0.6	1.96E-05	0.3	9.82E-06	0.4	1.31E-05	0.3	9.82E-06	0.3	9.82E-06
C	72.83	1.5	4.73E-05	1.1	3.47E-05	0.5	1.58E-05	0.1	3.15E-06	0.2	6.30E-06	0.2	6.30E-06	0.4	1.26E-05
Average	70.47		6.10E-05		4.14E-05		1.74E-05		6.56E-06		1.65E-05		9.85E-06		1.31E-05
Cumulative mass loss (lb/ft^2)			**8.79E-03**		**1.48E-02**		**1.73E-02**		**1.82E-02**		**2.06E-02**		**2.20E-02**		**2.39E-02**

Mixture: C- 3.4-L

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	77.03	8.8	2.62E-04	3	8.94E-05	2.9	8.64E-05	2.9	8.64E-05	3.6	1.07E-04	2.9	8.64E-05	10.3	3.07E-04
B	72.31	2.1	6.67E-05	2.5	7.94E-05	1.5	4.76E-05	1.4	4.45E-05	1.3	4.13E-05	2	6.35E-05	3.5	1.11E-04
C	75.22	6.2	1.89E-04	2.9	8.85E-05	2.3	7.02E-05	2.4	7.32E-05	2.8	8.55E-05	2.3	7.02E-05	8.3	2.53E-04
Average	74.85		1.73E-04		8.58E-05		6.81E-05		6.80E-05		7.80E-05		7.34E-05		2.24E-04
Cumulative mass loss (lb/ft^2)			**7.92E-03**		**3.72E-02**		**4.70E-02**		**5.68E-02**		**6.81E-02**		**7.86E-02**		**1.11E-01**

Mixture: C-8.7-L

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	75.40	4.7	1.43E-04	2.1	6.39E-05	1.5	4.57E-05	1.6	4.87E-05	1.7	5.18E-05	3.4	1.04E-04	5.2	1.58E-04
B	74.48	4.5	1.39E-04	2.2	6.78E-05	2.4	7.4E-05	0.9	2.77E-05	1	3.08E-05	2.4	7.40E-05	4.1	1.26E-04
C	71.67	1.5	4.80E-05	1.9	6.09E-05	0.8	2.56E-05	0.3	9.61E-06	0.4	1.28E-05	0.6	1.92E-05	0.9	2.88E-05
Average	73.85		1.10E-04		6.42E-05		4.84E-05		2.87E-05		3.18E-05		6.56E-05		1.05E-04
Cumulative mass loss (lb/ft^2)			**1.58E-02**		**2.51E-02**		**3.21E-02**		**3.62E-02**		**4.08E-02**		**5.02E-02**		**6.53E-02**

Mixture: T-3.0-G

Specimen	Effective Area	Mass at 5 days		Mass at 10 days		Mass at 15 days		Mass at 20 days		Mass at 25 days		Mass at 35 days		Mass at 50 days	
	in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2	g	lb/in^2
A	74.62	5.8	1.78E-04	4.2	1.29E-04	0.7	2.15E-05	0.1	3.08E-06	0.1	3.08E-06	0.1	3.08E-06	0	0.00E+00
B	75.40	6.3	1.92E-04	2.8	8.53E-05	0.6	1.83E-05	0.1	3.04E-06	0.2	6.09E-06	0.1	3.04E-06	0.1	3.04E-06
C	74.03	5.8	1.80E-04	2.8	8.68E-05	0.7	2.17E-05	0.1	3.10E-06	0.2	6.20E-06	0.1	3.10E-06	0	0.00E+00
Average	74.68		1.83E-04		1.00E-04		2.05E-05		3.07E-06		5.12E-06		3.07E-06		1.01E-06
Cumulative mass loss (lb/ft^2)			**2.64E-02**		**4.09E-02**		**4.38E-02**		**4.43E-02**		**4.50E-02**		**4.54E-02**		**4.56E-02**

Table B.3: (con't) Scaling results for mixtures in Program III (ASTM C672)

Mixture: T-8.7-G															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	74.42	3.9	1.20E-04	1.5	4.63E-05	0.3	9.25E-06	0	0.00E+00	0.2	6.17E-06	0.1	3.08E-06	0	0.00E+00
B	73.49	2.9	9.06E-05	1.1	3.44E-05	0.2	6.25E-06	0.1	3.12E-06	0.1	3.12E-06	0.1	3.12E-06	0	0.00E+00
C	73.16	4.1	1.29E-04	1.2	3.77E-05	0.3	9.41E-06	0.1	3.14E-06	0.1	3.14E-06	0	0.00E+00	0.1	3.14E-06
Average	73.69		1.13E-04		3.94E-05		8.31E-06		2.09E-06		4.14E-06		2.07E-06		1.05E-06
Cumulative mass loss (lb/ft^2)			**1.63E-02**		**2.20E-02**		**2.32E-02**		**2.35E-02**		**2.41E-02**		**2.44E-02**		**2.45E-02**

Mixture: T-12.5-H															
Specimen	**Effective Area**	**Mass at 5 days**		**Mass at 10 days**		**Mass at 15 days**		**Mass at 20 days**		**Mass at 25 days**		**Mass at 35 days**		**Mass at 50 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	77.03	4	1.19E-04	2.1	6.26E-05	0.6	1.79E-05	0.3	8.94E-06	0.1	2.98E-06	0.1	2.98E-06	0.2	5.96E-06
B	72.31	4.4	1.40E-04	1.9	6.03E-05	0.7	2.22E-05	0.3	9.53E-06	0.1	3.18E-06	0.2	6.35E-06	0.1	3.18E-06
C	75.22	4.2	1.28E-04	2.2	6.71E-05	0.7	2.14E-05	0.3	9.16E-06	0.1	3.05E-06	0.1	3.05E-06	0.2	6.10E-06
Average	74.85		1.29E-04		6.34E-05		2.05E-05		9.21E-06		3.07E-06		4.13E-06		5.08E-06
Cumulative mass loss (lb/ft^2)			**1.86E-02**		**2.77E-02**		**3.07E-02**		**3.20E-02**		**3.24E-02**		**3.30E-02**		**3.37E-02**

Table B.4: Rapid chloride permeability results (Coulombs) for mixtures in Program III

Mix ID	T-3.4-L			
	A	B	C	Average
28-Day	807	1076	797	890
56-Day	698	693	708	700

Mix ID	C-8.7-L			
	A	B	C	Average
28-Day	4003	4628	3354	3990
56-Day	3489	2761	3378	3210

Mix ID	T-9.0-L			
	A	B	C	Average
28-Day	859	874	720	820
56-Day	613	640	621	620

Mix ID	T-3.0-G			
	A	B	C	Average
28-Day	1196	1371	943	1170
56-Day	680	726	680	700

Mix ID	T-12.0-L			
	A	B	C	Average
28-Day	979	1003	886	960
56-Day	741	716	793	750

Mix ID	T-8.7-G			
	A	B	C	Average
28-Day	859	962	771	860
56-Day	552	502	635	560

Mix ID	C-3.4-L			
	A	B	C	Average
28-Day	2931	3366	2812	3040
56-Day	2609	2612	3025	2750

Mix ID	T-12.5-H			
	A	B	C	Average
28-Day	1204	1107	1209	1170
56-Day	803	746	814	790

Table B.5: *p* values obtained from Student's t-test for the differences in 28-day RCP values for mixtures in Program III

Mixture ID[a]	Average 28-day RCP (Coulombs)	T-3.4-L	T-9.0-L	T-12.0-L	C-3.4-L	C-8.7-L	T-3.0-G	T-8.7-G	T-12.5-H
		890	820	960	3040	3990	1170	860	1170
T-3.4-L	890		0.51	0.56	**3.64×10^{-4}**	**1.21×10^{-3}**	0.15	0.80	**0.045**
T-9.0-L	820			0.09	**2.24×10^{-4}**	**1.02×10^{-3}**	0.06	0.57	**3.88×10^{-3}**
T-12.0-L	960				**2.68×10^{-4}**	**1.19×10^{-3}**	0.17	0.23	**0.01**
C-3.4-L	3040					**0.08**	**8.72×10^{-4}**	**2.53×10^{-4}**	**4.08×10^{-4}**
C-8.7-L	3990						**1.89×10^{-3}**	**1.09×10^{-3}**	**1.57×10^{-3}**
T-3.0-G	1170							0.09	0.98
T-8.7-G	860								**0.01**

Table B.6: *p* values obtained from Student's t-test for the differences in 56-day RCP values for mixtures in Program III

Mixture ID[a]	Average 56-day RCP (Coulombs)	T-3.4-L	T-9.0-L	T-12.0-L	C-3.4-L	C-8.7-L	T-3.0-G	T-8.7-G	T-12.5-H
		700	620	750	2750	3210	700	560	790
T-3.4-L	700		**1.1×10^{-3}**	0.09	**1.21×10^{-4}**	**3.78×10^{-4}**	0.80	**0.03**	0.15
T-9.0-L	620			**0.01**	**1.06×10^{-4}**	**3.38×10^{-4}**	**0.01**	0.20	**1.91×10^{-3}**
T-12.0-L	750				**1.41×10^{-4}**	**4.17×10^{-4}**	0.12	**0.01**	0.29
C-3.4-L	2750					0.16	**1.23×10^{-4}**	**1.09×10^{-4}**	**1.50×10^{-4}**
C-8.7-L	3210						**3.79×10^{-4}**	**3.25×10^{-4}**	**4.42×10^{-4}**
T-3.0-G	700							**0.03**	**0.02**
T-8.7-G	560								**0.01**

Table B.7: Surface resistivity measurements (kΩ-cm) for mixtures in Program III

T-3.4-L									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	29.4	29.1	28.9	29.0	29.6	29.2	29.2	28.8	29.2
B	26.6	29.8	30.2	29.5	26.5	29.7	30.2	30.0	29.1
C	28.5	27.1	28.7	27.5	28.4	27.1	29.1	27.7	28.0
Average:	**31.6**								

T-9.0-L									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	28.8	30.3	28.9	28	29.1	30.1	29.2	28.3	29.1
B	28.3	27.8	27.4	26.2	28.8	27.9	27.5	25.8	27.5
C	27.4	27.6	27.6	28.5	27	28	28	13.5	26.0
Average:	**30.3**								

T-12.0-L									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	28.1	29.6	31.4	29.7	27.9	29.3	31.2	29.8	29.6
B	28.9	30.3	28.3	26.8	29.3	30.2	28.5	27.2	28.7
C	32	29.4	26.4	27.5	31.9	30.6	26.8	28.1	29.1
Average:	**32.0**								

C-3.4-L									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	10.3	9.1	9.3	9.4	10.2	8.9	9.2	9.6	9.5
B	10.3	10.2	9.2	10.1	9.8	10.1	9.3	10.2	9.9
C	9.9	10	10.4	9.8	10	10.2	9.9	10.3	10.1
Average:	**10.8**								

C-8.7-L									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	8.6	8.4	8.7	8.1	8.8	8.6	8.6	8.6	8.6
B	8.2	8.6	8.4	8.3	8.1	8.4	9	8.2	8.4
C	9.9	9	8.3	7	9.1	9.3	8.4	7.3	8.5
Average:	**9.3**								

T-3.0-G									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	24.4	26.7	28.3	26.5	27.3	26.9	29	27	27.0
B	23.7	25.6	23.5	24.3	24	25.8	23.2	24	24.3
C	24	23.1	23.8	26.1	23.3	23	23.7	26	24.1
Average:	**27.6**								
T-8.7-G									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	31.9	31.6	31.9	33.1	31.3	32.1	32.1	32.7	32.1
B	30.6	29.8	31.9	31	30.4	29.3	31.8	30.8	30.7
C	31.8	32	33.8	35.3	33.3	31.9	33.3	34.8	33.3
Average:	**35.2**								
T-12.5-H									
Cyl. ID	0°	90°	180°	270°	0°	90°	180°	270°	Average
A	22.1	22.6	23	24.2	22.3	22.7	23.7	24.6	23.2
B	23.8	23.1	24.6	25.5	23.6	22.1	24.7	25.5	24.1
C	22.6	25	23.9	22.5	21.7	25.1	24.3	22.4	23.4
Average:	**25.9**								

Table B.8: *p* values obtained from Student's t-test for the differences in 28-day SRM values for mixtures in Program III

Mixture ID[a]	Average mass loss (lb/ft^2)	T-3.4-L	T-9.0-L	T-12.0-L	C-3.4-L	C-8.7-L	T-3.0-G	T-8.7-G	T-12.5-H
		31.6	30.3	32	10.8	9.3	27.6	35.2	25.9
T-3.4-L	31.6		0.27	0.44	**1.22×10^{-6}**	**6.58×10^{-7}**	**0.02**	**0.02**	**3.67×10^{-4}**
T-9.0-L	30.3			0.16	**4.34×10^{-5}**	**3.07×10^{-5}**	0.14	**0.02**	**0.01**
T-12.0-L	32				**4.45×10^{-7}**	**1.91×10^{-7}**	**0.02**	**0.02**	**1.45×10^{-4}**
C-3.4-L	10.8					**1.59×10^{-3}**	**8.85×10^{-5}**	**8.29×10^{-6}**	**2.00×10^{-6}**
C-8.7-L	9.3						**6.03×10^{-5}**	**6.02×10^{-6}**	**8.12×10^{-7}**
T-3.0-G	27.6							**4.55×10^{-3}**	0.19
T-8.7-G	35.2								**4.5×10^{-4}**

APPENDIX C: MINNESOTA DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR INTERNALLY-CURED LOW-CRACKING HIGH-PERFORMANCE CONCRETE

SB2-8 (2401) CONCRETE BRIDGE CONSTRUCTION

The provisions of 2401, "Concrete Bridge Construction," are supplemented as follows:

SB2-9 STRUCTURAL CONCRETE – INTERNALLY CURED HIGH PERFORMANCE CONCRETE BRIDGE DECKS (CONTRACTOR CONCRETE MIX DESIGN)

Delete the contents of 2401.2.A, "Concrete," and replace with the following:

Design an internally cured concrete mixture that will minimize cracking by incorporating saturated lightweight fine aggregate. Perform the work in accordance with the applicable requirements of MnDOT 2401, "Concrete Bridge Construction," 2461, "Structural Concrete," and the following:

2.A.1 Fine Aggregate Requirements

Provide fine aggregates complying with quality requirements of 3126.2.D, "Deleterious Material," 3126.2.E, "Organic Impurities," and 3126.2.F, "Structural Strength."

2.A.1.a Fine Aggregate Lightweight Requirements

Incorporate fine lightweight aggregate as a means to provide internal curing water for concrete. The requirements of ASTM C1761 and C330 shall apply, except as modified in this specification.

(1) Size all lightweight aggregate to pass a 3/8 in. sieve.

(2) Proportion the volume of lightweight aggregate such that is does not exceed 10 percent of total aggregate volume. Lightweight aggregate used as a replacement for normal weight aggregate shall be made on a volume basis.

(3) Pre-wet lightweight aggregate prior to adding at the time of batching. Recommendations for pre-wetting made by the lightweight aggregate supplier shall be followed to ensure that the lightweight aggregate has achieved an acceptable absorbed moisture content at the time of batching. Mixture proportions shall not be adjusted based on the absorbed water in the lightweight aggregate.

(4) Handling and Stockpiling Lightweight Aggregates:

Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.

Transport aggregate in a manner that insures uniform grading.

Do not use aggregates that have become mixed with earth or foreign material.

Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.

Provide additional stockpiling or binning in cases of high or non-uniform moisture.

2.A.1.b Fine Aggregate Alkali Silica Reactivity (ASR) Requirements

The Department will routinely test fine aggregate sources for alkali silica reactivity (ASR) in accordance with the following:

(1) Multiple sources of certified portland cement in accordance with ASTM C 1260 MnDOT Modified; and
(2) Multiple combinations of certified portland cement and supplementary cementitious materials in accordance with ASTM C 1567 MnDOT Modified.

The Concrete Engineer, in conjunction with the Engineer, will review the 14-day fine aggregate expansion test results to determine the acceptability of the proposed fine aggregate and cement combination in accordance with the following:
(1) For fine aggregate and cement combinations previously tested by the Department, the Concrete Engineer will use the average of all 14-day unmitigated test results for an individual source to determine necessary mitigation in accordance with Table HPC-1.
(2) If the previously tested proposed fine aggregate and cement combination requires less mitigation than the average 14-day unmitigated test result, the Concrete Engineer will allow mitigation at the lesser rate in accordance with Table HPC-1.
(3) Alkali silica reactivity (ASR) ASTM C1260 and ASTM C1567 test results are available on the MnDOT Concrete Engineering Unit website.

<table>
<tr><th colspan="9">Table HPC-1
Fine Aggregate ASR Mitigation Requirements</th></tr>
<tr><th>14-day Fine Aggregate Unmitigated Expansion Limits</th><th>Class F Fly Ash</th><th>Class C Fly Ash</th><th>Slag</th><th>Slag/Class F Fly Ash</th><th>Slag/Class C Fly Ash</th><th>IS(20)/Class F Fly Ash</th><th>IS(20)/Class C Fly Ash</th></tr>
<tr><td>≤ 0.150</td><td colspan="7">No mitigation required</td></tr>
<tr><td>>0.150 - 0.200</td><td>Not Allowed</td><td>Not Allowed</td><td>35%</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td></tr>
<tr><td>> 0.200 – 0.300</td><td>Not Allowed</td><td>Not Allowed</td><td>35%</td></tr>
<tr><td>> 0.300</td><td colspan="7">The Department will reject the fine aggregate</td></tr>
</table>

The Concrete Engineer may reject the fine aggregate if mortar bar specimens exhibit an indication of external or internal distress not represented by the expansion results. The Concrete Engineer will make the final acceptance of the aggregate.

2.A.2 Intermediate Aggregate Requirements

Provide intermediate aggregates complying with the quality requirements of 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure," except as modified in Table HPC-2. If the intermediate aggregate is from the same source as the ¾ in- fraction, the aggregate quality is determined based upon the composite of the ¾ in- and intermediate aggregate.

The Concrete Engineer classifies intermediate aggregate in accordance with Table HPC-2.

Table HPC-2
Intermediate Aggregate for Use in Concrete

If the gradation meets the following:	Classify material type as:	Gradation Test Procedures	Quality Test Requirements
100% passing the 1/2" and ≤90% passing #4	Intermediate Aggregate	Coarse Aggregate (+4 Portion)	Spec. 3137.2.D.2 except 3137.2.D.2(i) modified to maximum 40% carbonate
		Fine Aggregate (-4 Portion)	Shale in Sand (-4 Portion)
100% passing the 1/2" and >90% passing #4	Intermediate Aggregate	Fine Aggregate (Minimum 1000 g sample)	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)
100% passing the 3/8" and ≤90% passing #4	Coarse Sand	Fine Aggregate	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)

For any intermediate aggregate size not previously tested by the Department, the Concrete Engineer reserves the right to test for alkali silica reactivity, in accordance with ASTM C1260, prior to allowing incorporation into the concrete mix design.

2.A.3 Coarse Aggregate Requirements

Provide Class A, B or C coarse aggregate meeting the quality requirements in accordance with 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure."

When providing Class B aggregate, the maximum absorption percent by weight is 1.10%.

2.A.3.a Coarse Aggregate Alkali Silica Reactivity (ASR) Requirements

When using coarse aggregate identified as quartzite or gneiss, the Concrete Engineer will review ASTM C1293 testing to determine the necessary ASR mitigation requirements in accordance with Table HPC-3.

ASR ASTM C1293 test results are available on the MnDOT Concrete Engineering Unit website.

Table HPC-3 Coarse Aggregate ASR Mitigation Requirements*							
ASTM C1293 Expansion Results	**Class F Fly Ash**	**Class C Fly Ash**	**Slag**	**Slag/Class F Fly Ash**	**Slag/Class C Fly Ash**	**IS(20)/Class F Fly Ash**	**IS(20)/Class C Fly Ash**
≤ 0.040	No mitigation required						
>0.040	Not Allowed	Not Allowed	35%	Not Allowed	Not Allowed	Not Allowed	Not Allowed
* The Engineer will allow the Contractor to substitute a portion of the minimum required supplementary cementitious material with up to 2% silica fume by weight for mitigation purposes.							

2.A.4 Cementitious Materials

Provide only cementitious materials from the Approved/Qualified Products List.

2.A.4.a Cement

Use Type I or Type I/II cement complying with Specification 3101, "Portland Cement," or blended cement in accordance with Specification 3103, "Blended Hydraulic Cement."

(1) Total alkalis (Na_2Oe) no greater than 0.60 percent in the portland cement, and
(2) Total alkalis (Na_2Oe) no greater than 3.0 lb per yd^3 of concrete resulting from the portland cement.

2.A.4.b Ground Granulated Blast Furnace Slag

Use ground granulated blast furnace slag conforming to Specification 3102, "Ground Granulated Blast-Furnace Slag."

2.A.4.c Silica Fume

Use silica fume conforming to ASTM C 1240.

2.A.4.d Ternary Mixes

Ternary mixes are defined as portland cement and two other supplementary cementitious materials, or blended cement and one other supplementary cementitious material with a maximum replacement of 40% by weight.

2.A.5 Allowable Admixtures

Use any of the following admixtures on the MnDOT Approved/Qualified Products as listed under "Concrete Admixtures A-S":

(A) Type A, Water Reducing Admixture,
(B) Type B, Retarding Admixture,
(C) Type C, Accelerating Admixture,
(D) Type D, Water Reducing and Retarding Admixture,
(E) Type F, High Range Water Reducing Admixture, and
(F) Type S, Specific Performance Based Admixture

Obtain a written statement from the manufacturer of the admixtures verifying:

(1) Compatibility of the combination of materials, and
(2) Manufacturer recommended sequence of incorporating the admixtures into the concrete.

The manufacturer will further designate a technical representative to dispense the admixture products.

Utilize the technical representative in an advisory capacity and have them report to the Contractor any operations or procedures which are considered as detrimental to the integrity of the placement. Verify with the Engineer whether the Manufacturer's technical representative's presence is required during the concrete placement.

2.A.6 Concrete Mix Design Requirements

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department's website at least 21 calendar days before the initial concrete placement. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

2.A.6.a Concrete Mix Design Requirements

Design and produce 3YHPCIC-M or 3YPHCIC-S concrete mixes based on an absolute volume of 27.0 ft^3 [1.0 m^3] in accordance with the Table HPC-4 and the following requirements:

<table>
<tr><th colspan="9">Table HPC-4
High Performance Bridge Deck Concrete Mix Design Requirements</th></tr>
<tr><th>Concrete Grade</th><th>Mix Number *</th><th>Intended Use</th><th>w/c ratio</th><th>Target Air Content</th><th>Maximum %SCM (Fly Ash/Slag/ Silica Fume/ Ternary) ‖</th><th>Slump Range †, inches</th><th>Minimum/Maximum Compressive Strength, f'c (28-day)</th><th>3137 Spec.</th></tr>
<tr><td rowspan="2">HPC</td><td>3YHPCIC-M</td><td>Bridge Deck – Monolithic</td><td rowspan="2">0.43-0.45</td><td rowspan="2">6.5% to 10%</td><td rowspan="2">0/28/2/30</td><td rowspan="2">1 1/2" to 5 "</td><td rowspan="2">4000psi/5500 psi</td><td rowspan="2">2.D.2</td></tr>
<tr><td>3YHPCIC-S</td><td>Bridge – Structural Slab</td></tr>
<tr><td colspan="9">* Provide a Job Mix Formula in accordance with 2401.2.A.7. Use any good standard practice to develop a job mix formula and gradation working range by using procedures such as but not limited to 8-18, 8-20 gradation control, Shilstone process, FHWA 0.45 power chart or any other performance related gradation control to produce a workable and pumpable concrete mixture meeting all the requirements of this contract.
‖ The individual limits of each SCM shall apply to ternary mixtures.
† Keep the consistency of the concrete uniform during entire placement.
Limit volume of water plus cementitious materials to a maximum of 27% of total concrete volume.
Add all mix water at the plant. No water will be allowed to be added on site.</td></tr>
</table>

2.A.6.b Required Preliminary Testing

Prior to placement of any 3YHPCIC-M or 3YHPCIC-S Concrete, the Engineer will require preliminary batching and testing of the concrete mix design.

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department's website at least 14 calendar days prior to the beginning of preliminary laboratory mixing and testing of the proposed mix designs. Any changes or adjustments to the material or mix design require a new Contractor mix design submittal. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

Batch the concrete and place in mixing truck for the max anticipated delivery time. Test the concrete for the following hardened concrete properties in accordance with Table HPC-5:

Table HPC-5 Required Hardened Concrete Properties for Mixes 3YHPCIC-M and 3YHPCIC-S		
Test	Requirement	Test Method
Required Strength (Average of 3 cylinders)	4000 psi min. at 28 days, 5500 psi max. at 28 days	ASTM C31
Rapid Chloride Permeability	≤ 2500 coulombs at 28 days (For Preliminary Approval) ≤ 1500 coulombs at 56 days	ASTM C1202
Freeze-Thaw Durability	Greater than 90% at 300 cycles	ASTM C666 Procedure A
Shrinkage	No greater than 0.040 percent at 28 days	ASTM C157
Scaling	Visual rating not greater than 1 at 50 cycles	ASTM C672

The Engineer will allow the maturity method for subsequent strength determination. Perform all maturity testing in accordance with ASTM C1074 and the MnDOT Concrete Manual.

If a mix is approved, the Concrete Engineer will consider the mix design and testing as acceptable for a period of 5 years provided the actual concrete mixed and placed in the field meets the Contract Requirements. The Concrete Engineer will not require new testing within that 5-year period as long as all the constituents (including the aggregates) of the proposed mix design are the same as the original mix design.

The Engineer determines final acceptance of concrete for payment based on satisfactory field placement and performance.

2.A.7 Job Mix Formula

A Job Mix Formula (JMF) contains the following:

(a) Proportions for each aggregate fraction,
(b) Individual gradations for each aggregate fraction, and
(c) Composite gradation of the combined aggregates including working ranges on each sieve in accordance with Table HPC-6.

Table HPC-6 Job Mix Formula Working Range	
Sieve Sizes	**Working Range, %***
1 in [25 mm] and larger	±5
¾ in [19 mm]	±5
½ in [12.5 mm]	±5
⅜ in [9.5 mm]	±5
No.4 [4.75 mm]	±5
No.8 [2.36 mm]	±4
No.16 [1.18 mm]	±4
No.30 [600 µm]	±4
No.50 [300 µm]	±3
No.100 [150 µm]	±2
No.200 [75 µm]	≤ 1.6
* Working range limits of the composite gradation based on a moving average of 4 tests (N=4).	

2.A.7.a Verification of JMF

Prior to beginning placements of bridge deck concrete, perform gradation testing to ensure current materials comply with the approved JMF. Perform gradation testing in accordance with the Schedule of Materials Control.

(1) Take samples at the belt leading to the weigh hopper or other locations close to the incorporation of the work as approved by the Engineer.
(2) Add fill-in sieves as needed during the testing process to prevent overloading.

The Producer and Engineer will test and record the individual gradation results using the Concrete Aggregate Worksheet.

(1) Using the JMF Moving Average Summary Worksheet, calculate the moving average of Producer aggregate gradation test results during production.
(2) The Engineer will randomly verify Producer combined aggregate gradation results as defined in the Schedule of Materials Control.

If, during production, the approved JMF falls outside of the allowable working range immediately sample and test additional gradation and continue production.

2.A.7.b JMF Adjustment

If it is determined that the current aggregates do not meet the approved JMF, submit a new mix design including JMF to the Concrete Engineer in accordance with 2401.2.A.7.

2.A.7.c JMF Acceptance

The Engineer will make monetary adjustments for the quantity of bridge deck concrete represented by the JMF Working Range failure, from the failing test to the next passing test, at a minimum rate of \$500.00 or \$5.00 per cubic yard, whichever is greater.

2.A.8 Laboratory batching, testing requirements and submittals:

To determine the characteristics of the Contractor proposed mix design, the Concrete Engineer will require the Contractor to prepare test batches and do laboratory testing. Conduct all batching and testing of concrete at a **single** AMRL certified laboratory using the exact materials proposed in the mix design.

Lab testing requirements:

(a) Slump and air content at <5 minutes, 15 minutes, and 30 minutes after the completion of mixing,
(b) Compressive strength (Make cylinders in accordance with AASHTO T126 and tested in accordance with AASHTO T22) at 1, 3, 7, 28, 56 days (sets of 3),
(c) Hardened air content (ASTM C457) at a minimum of 7 days,
(d) Rapid chloride permeability (ASTM C1202) at 28 days and 56 days (2 specimens for 28 day test and 2 test specimens for 56 day test (Take 2 specimens from each batch of a 2 batch mix)),
(e) Concrete Durability (ASTM C666, Procedure A) at 300 cycles, and
(f) Concrete Shrinkage (ASTM C157) at 28 days.

The Contractor is required to contact the MnDOT Concrete Engineering Unit a minimum of 2-days prior to any mixing so that a MnDOT representative can observe the process. This same 2-day notification is required prior to any physical testing on hardened concrete samples. Additionally, retain any hardened concrete test specimens for a minimum of 90 days and make available for MnDOT to examine.

Perform all testing for plastic concrete after all admixtures additions to the concrete mixture.

After completion of the laboratory testing specified herein and, at least, 15 working days prior to the trial placement, submit the laboratory test data to the MnDOT for review and acceptance.

Include the following information in the laboratory reports of the design mixes:

(a) Exact batch weights and properties of all ingredients used and all aggregate gradations
(b) Slump and air content
(c) Cylinder identification, including mix designation
(d) Date and time of cylinder preparation
(e) Date and time cylinder specimen was tested
(f) Compressive strength of each cylinder specimen at 1, 3, 7, 28, and 56 day (sets of 3)
(g) A graphic plot of age, from 0 to 56 days, vs. strength for each mix design
(h) Hardened air content at a minimum of 7 days
(i) Rapid chloride permeability at 28 days and 56 days
(j) Concrete Durability at 300 cycles and
(k) Concrete Shrinkage at 28 days.

2.A.9 Prior to Actual Bridge Deck Placement

2.A.9.a Trial Placement

A minimum of 14 calendar days prior to the actual placement of the bridge deck slab concrete, successfully complete a separate trial placement utilizing a minimum of two (2) - 10 yd^3 loads.

The Engineer may allow the incorporation of the concrete for trial batches into the bridge footings, abutments or end diaphragms. The Contractor may also choose to incorporate the trial batches into residential /commercial construction in the immediate vicinity of the project. In any case, the Engineer will require mixing, transporting, and placing the concrete using the same methods as the actual placement of the bridge deck.

If the concrete is incorporated into the permanent work, the Engineer will test the plastic concrete in accordance with the Schedule of Materials Control. The Engineer may require additional trial batches if the concrete delivered to the project does not comply with the plastic concrete requirements of the Contract.

The concrete mix design, laboratory batching and mixing, and the trial placement is incidental to the concrete furnished and placed.

Use the same materials, same supplier, and same supplier's manufacturing plant, and proportions in the permanent work as in the trial placement. Strength requirements specified for each mix are applicable to the cylinder tests taken during the production work.

2.A.9.b Slab Placement and Curing Plan

At least 14 calendar days prior to slab placement, provide a slab placement and curing plan for each bridge to the Engineer for approval. Include the following information in the placement and curing plan:

(1) Anticipated concrete delivery rates
(2) Estimated start and finish time
(3) Material, labor and equipment proposed for placing, finishing, and curing including placement of wet burlap, soaker hose, or other system to maintain the deck in a moist condition during the curing period
(4) Number of work bridges proposed for use
(5) Number of people responsible for the various tasks and
(6) Bulkheading methods and materials proposed for use if the Contractor cannot maintain the proposed concrete placement rates.

For full depth monolithic decks, the finishing machine will consist of a cylindrical finisher mated with horizontal adjustable augers, both of which are mounted on a transversely moving carriage unless otherwise approved by the State Bridge Construction Engineer.

A 10 ft [3 m] bull float is required for full-depth decks prior to carpet dragging regardless of whether texture planing is specified for the final ride surface. Float slab in accordance with MnDOT Construction Manual 5-393.358 to ensure the final surface does not vary by greater than ⅛ in [3 mm] within a 10 ft [3 m] straightedge laid longitudinally on the final surface. This surface tolerance includes areas near expansion devices and other breaks in the continuity of the bridge slab.

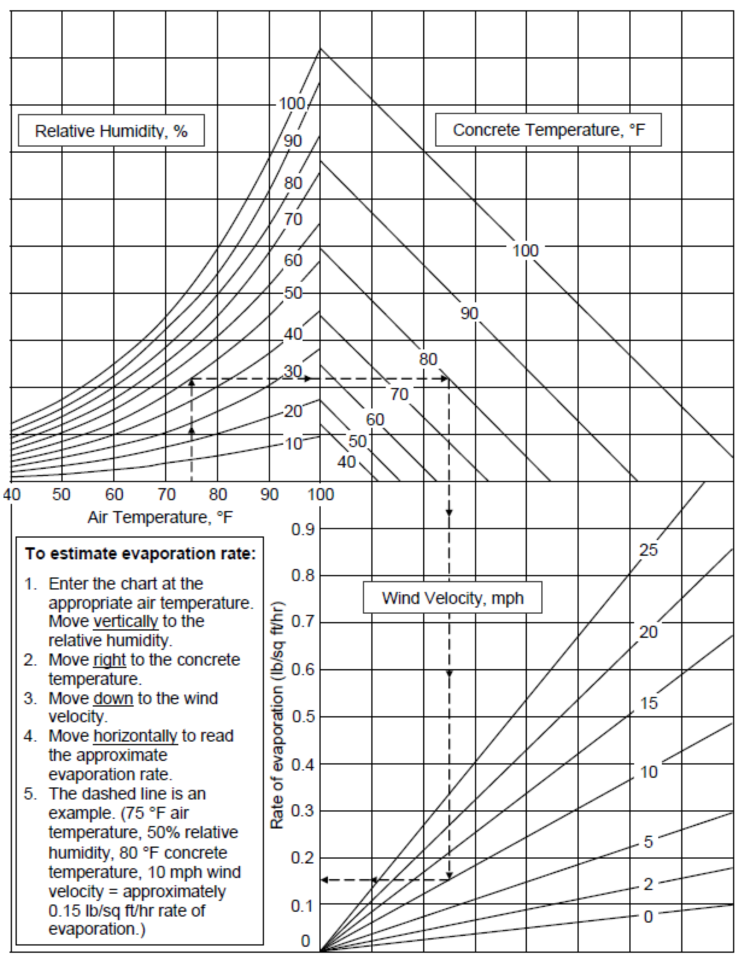
Attend a pre-placement meeting 10 days to 15 days before the slab placement to review the information and details provided in the placement and curing plan. The following project personnel are required to attend the pre-placement meeting:

(1) Contractor
(2) Engineer
(3) Concrete supplier and
(4) If required by the Engineer, the concrete pump supplier.

2.A.9.c Three (3) Hours Prior to Beginning Bridge Deck Concrete Placement

The Engineer requires the Contractor to comply with <u>all</u> of the following conditions prior to allowing the Contractor to begin the bridge deck concrete placement:

(1) Provide a forecast to the Engineer three (3) hours before placement. The Engineer will review the forecast for the following:
   (a) No forecasted precipitation two (2) hours prior to the scheduled placement duration, nor up to two (2) hours after the anticipated completion of the placement, and
   (b) Less than 30% chance of precipitation for the entire placement window and
(2) Only if the combination of air temperature, relative humidity, concrete temperature and wind velocity produces an evaporation rate of less than 0.20 pounds per square foot of surface area per hour, according Figure HPC-1:



[1] Based on ACI 305 R, "Hot Weathering Concreting"

FIGURE HPC-1

SB2-9.1 Concrete Curing and Protection

Delete the 16th paragraph through 18th paragraphs of 2401.3.G, "Concrete Curing and Protection," and replace with the following:

2.A.9.d Actual Bridge Deck Placement and Curing Requirements

In addition to the requirements set forth in 2461.3.G.4, "Field Adjustments," if any adjustments are necessary on site, comply with the following:

(1) The Engineer will only allow the addition of admixtures originally incorporated into the mix, except Viscosity Modifying Admixture (VMA) is allowed to adjust slump even if they were not used in the original testing

(2) The Engineer will allow a maximum of 1 gal of water additions per yd^3 of concrete on site provided additional water is available to add per the Certificate of Compliance, including any water necessary to dilute admixtures and

(3) Mix the load a minimum of 5 minutes or 50 revolutions after any additions.

The Engineer will not allow finishing aids or evaporation retarders for use in finishing of the concrete.

The Contractor is fully responsible for curing methods. Comply with the following curing methods unless other methods are approved by the Engineer in writing.

Table HPC-7
Required Curing Method Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Required Curing Method ‖
Bridge structural slab curing (3YHPCIC-S)	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks (3YHPCIC-M)	Epoxy Chip Seal Wearing Course or Premixed Polymer Wearing Course	Conventional wet curing after carpet drag
	Bridge Deck Planing	Conventional wet curing after carpet drag.
	Tined Texturing*	Conventional wet curing after tine texturing AMS curing Compound after wet cure period
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)*	Conventional wet curing after applying transverse broom finish AMS curing Compound after wet cure period

‖ Apply conventional wet curing to bridge slabs following the finishing machine or air screed.
* Prevent marring of broomed finish or tined textured surface by careful placement of wet curing.

Use conventional wet curing consisting of pre-wetted burlap covered with white plastic sheeting in accordance with the following. Presoak the burlap for a minimum of 12 hours prior to application:

(1) Place the burlap to cover 100 percent of the deck area without visible openings

(2) Place the wet curing within 20 min after the finishing machine completes the final strike-off of the concrete surface

(3) If the Contractor fails to place the wet curing within 20 min, the Department will monetarily deduct $500 for every 5 min period, or any portion thereof, after the initial time period until the Contractor places the wet curing as approved by the Engineer, the Department may assess the deduction more than once
(4) Keep the slab surface continuously wet for an initial curing period of at least 7 calendar days
(5) Use a work bridge to follow the finish machine and
(6) Provide an additional center rail on wide bridges, if necessary.

Where marring of the broomed finish or tined texturing surface finish is a concern, the Engineer may authorize curing as follows:

(1) Apply a membrane curing compound meeting the requirements of 3754, "Poly-Alpha Methylsytrene (AMS) Membrane Curing Compound"
(2) Apply curing compound using approved power-operated spray equipment
(3) Provide a uniform, solid white, opaque coverage of membrane cure material on exposed concrete surfaces (equal to a white sheet of paper)
(4) Place the membrane cure within 30 min of concrete placement unless otherwise directed by the Engineer
(5) Provide curing compound for moisture retention until the placement of a conventional wet curing
(6) Apply conventional wet curing when walking on the concrete will not produce imprints deeper than $^{1}/_{16}$ in [1.6 mm]
(7) Keep the deck slab surface continuously wet for an initial curing period of at least 7 calendar days including weekends, holidays, or both if these fall within the 7-calendar-day curing period
(8) The Engineer will not allow placement of membrane curing compound on any concrete surface that expects future placement of additional concrete on that surface and
(9) If the Contractor fails to meet these requirements, the Department may reduce the contract unit price for the concrete item in accordance with 1512, "Conformity with Contract Documents."

A. Method of Measurement

If measuring bridge slab concrete by area, the Engineer will base the measurement on end-of-slab stationing and out-to-out transverse dimensions of the slab.

B. Basis of Payment

Payment for Item No. 2401.618 "BRIDGE SLAB CONCRETE (3YHPCIC-M)" will be made at the Contract price per square foot and shall be compensation in full for all costs of forming, placing, finishing, curing, crack sealing, and all associated incidentals necessary to construct the bridge deck and end diaphragms as detailed in the Plans in accordance with these specifications.

APPENDIX D: TRIP TICKETS AND PLASTIC CONCRETE TEST RESULTS FOR MNDOT IC-LC-HPC AND CONTROL DECK PLACEMENTS

Table D.1: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-1

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water[a]	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1[a]	384	163	239	1680	1146	203	0.44	24.8	6	65	7
2	388	163	240	1651	1104	191	0.44	24.9	2½	65	7
3	385	164	235	1651	1104	191	0.43	24.6	3½	68	7.5
4	388	165	239	1651	1097	189	0.43	24.9	-	-	-
5	390	165	239	1649	1100	189	0.43	25.0	4	-	8.1
6	386	165	239	1647	1098	189	0.43	24.9	-	-	-
7	386	165	240	1651	1102	190	0.44	24.9	-	-	-
8	384	163	240	1649	1105	189	0.44	24.9	-	-	-

[a] Truck rejected

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.2: Trip tickets and plastic concrete properties for MN-Control-1

Truck	Material Proportions, SSD Basis (lb/yd^3)					w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Class F Fly Ash	Water	Coarse Agg.	Fine Agg.			Slump (in.)	Temp. (°F)	Air (%)
1	445	150	216	1312	1312	0.36	24.9	4	62	5.8
2	443	147	216	1314	1358	0.37	24.8	-	-	-
3	445	149	221	1314	1358	0.37	25.2	-	-	-
4	444	148	228	1315	1360	0.39	25.6	-	-	-
5	446	150	227	1315	1360	0.37	25.6	-	-	6.0
6	444	151	220	1317	1362	0.37	25.2	-	-	-
7	447	149	221	1314	1358	0.37	25.2	-	-	-
8	444	147	220	1314	1358	0.37	25.1	-	-	-
9	445	148	225	1315	1360	0.38	25.4	-	-	-
10	445	150	225	1314	1358	0.38	25.4	3¾	70	5.6
11	447	149	225	1315	1360	0.38	25.4	-	-	6.8

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.3: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-2

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	412	156	174	1413	1146	244	0.40	24.6	3½	76	9.1
2	412	153	182	1417	1142	243	0.42	25.0	-	-	-
3	413	154	182	1417	1144	246	0.43	25.6	-	-	-
4	410	154	182	1415	1146	246	0.44	25.7	-	-	-
5	410	155	182	1415	1142	246	0.44	25.6	-	-	-
6	413	154	182	1413	1142	246	0.42	25.1	-	-	-
7	410	152	182	1417	1144	243	0.44	25.5	-	-	-
8	410	152	182	1415	1141	246	0.44	25.4	-	-	-
9	410	154	182	1417	1144	243	0.43	25.4	-	-	-
10	416	153	182	1415	1142	246	0.43	25.5	-	-	-
11	410	154	182	1417	1142	243	0.44	25.5	3½	81	9.0
12	417	154	182	1419	1144	244	0.43	25.7	-	-	-
13	410	155	182	1417	1141	246	0.44	25.5	-	-	-
14	410	154	182	1415	1144	244	0.44	25.5	-	-	-
15	410	154	182	1413	1144	244	0.44	25.6	-	-	-
16	411	154	182	1413	1142	244	0.43	25.3	-	-	-
17	411	153	182	1415	1144	246	0.43	25.5	-	-	-
18	410	155	182	1415	1144	246	0.44	25.5	-	-	-
19	414	154	182	1417	1142	243	0.43	25.5	-	-	-
20	411	154	182	1413	1144	246	0.44	25.6	3½	78	9.3
21	411	154	182	1417	1146	243	0.43	25.5	-	-	-
22	410	154	182	1415	1142	246	0.44	25.6	-	-	-
23	410	154	182	1416	1143	245	0.44	25.6	-	-	-
24	411	154	182	1416	1145	247	0.43	25.4	-	-	-
25	411	154	182	1416	1144	243	0.43	25.4	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.4: Trip tickets and plastic concrete properties for MN-Control-2

Truck	Material Proportions, SSD Basis (lb/yd^3)					*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Class F Fly Ash	Water	Coarse Agg.	Fine Agg.			Slump (in.)	Temp. (°F)	Air (%)
1	378	203	234	1738	1243	0.40	26.0	3½	72	7.2
2	378	203	231	1740	1245	0.40	25.9	-	-	-
3	381	204	226	1738	1245	0.39	25.6	-	-	-
4	379	202	226	1738	1245	0.39	25.6	-	-	-
5	378	202	228	1742	1247	0.39	25.6	-	-	-
6	380	204	228	1742	1243	0.39	25.7	-	-	-
7	379	205	226	1738	1245	0.39	25.6	-	-	-
8	378	203	223	1738	1245	0.38	25.4	-	-	-
9	381	205	226	1740	1247	0.39	25.7	-	-	-
10	377	203	228	1738	1245	0.39	25.7	3¼	75	6.1
11	386	202	229	1740	1247	0.39	25.8	-	-	-
12	385	203	223	1738	1245	0.38	25.5	-	-	-
13	378	205	234	1740	1247	0.40	26.1	-	-	-
14	382	202	227	1738	1247	0.39	25.7	-	-	-
15	378	203	231	1738	1243	0.40	25.8	-	-	-
16	378	205	237	1742	1243	0.41	26.2	-	-	-
17	381	203	226	1738	1245	0.39	25.6	-	-	-
18	379	204	238	1738	1245	0.41	26.3	-	-	-
19	380	202	230	1738	1245	0.39	25.8	-	-	-
20	379	205	230	1738	1245	0.39	25.8	-		
21	382	202	231	1740	1247	0.40	25.9	3	73	5.5
22	377	205	236	1742	1243	0.41	26.1	-	-	-
23	380	204	229	1744	1243	0.39	25.8	-	-	-
24	378	204	233	1742	1243	0.40	26.0	-	-	-
25	378	203	231	1738	1243	0.40	25.9	-	-	-
26	377	201	238	1740	1243	0.41	26.2	-	-	-
27	378	202	227	1760	1243	0.39	25.6	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.5: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-3

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	410	154	237	1416	1140	246	0.42	25.0	3¾	77	9.1
2	416	155	227	1414	1140	244	0.40	24.5	2½	77	8.5
3	411	156	237	1412	1142	244	0.42	25.0	-	-	-
4	410	155	238	1412	1144	248	0.42	25.0	-	-	-
5	411	154	238	1439	1146	244	0.42	25.0	-	-	-
6	410	155	237	1415	1144	248	0.42	25.0	-	-	-
7	411	155	237	1415	1142	246	0.42	25.0	-	-	-
8	410	154	242	1413	1140	250	0.43	25.3	-	-	-
9	412	154	246	1403	1144	246	0.43	25.5	-	-	-
10	410	155	244	1415	1142	248	0.43	25.4	-	-	-
11	412	153	242	1413	1146	244	0.43	25.3	-	-	-
12	413	155	244	1417	1140	244	0.43	25.5	-	-	-
13	424	154	241	1417	1146	246	0.42	25.5	-	-	-
14	428	156	240	1417	1144	244	0.41	25.5	3¾	74	8
15	419	154	240	1413	1146	244	0.42	25.3	-	-	-
16	410	155	234	1415	1144	248	0.41	24.8	-	-	-
17	414	153	241	1415	1144	246	0.42	25.3	-	-	-
18	438	153	240	1415	1144	244	0.41	25.6	4	73	8.8
19	411	155	235	1415	1144	244	0.42	24.9	-	-	-
20	411	155	242	1419	1142	254	0.43	25.3	-	-	-
21	410	154	244	1413	1146	248	0.43	25.4	3¾	74	8
22	411	155	246	1414	1144	248	0.43	25.5	-	-	-
23	411	153	242	1412	1146	248	0.43	25.3	-	-	-
24	413	155	242	1412	1144	246	0.43	25.3	-	-	-
25	411	154	235	1412	1142	246	0.42	24.8	-	-	-
26	411	155	245	1416	1144	250	0.43	25.5	-	-	-
27	412	154	245	1412	1140	248	0.43	25.5	-	-	-
28	411	154	238	1414	1144	250	0.42	25.0	-	-	-
29	414	156	237	1412	1146	248	0.42	25.0	-	-	-
30	418	155	233	1412	1144	248	0.41	24.9	3	74	7.5
31	411	153	240	1414	1142	246	0.43	25.2	-	-	-
32	411	155	237	1414	1144	246	0.42	25.0	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.6: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-4

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water*	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	415	166	249	1721	974	199	0.43	25.9	5½	68	11.0
2	420	167	250	1691	968	199	0.43	26.0	5½	66	10.0
3[a]	418	163	248	1735	968	197	0.43	25.8	6	66	11.2, 9.0
4	415	163	251	1700	962	199	0.43	25.9	4½	64	7.4
5	417	165	245	1729	972	199	0.42	25.6	-	-	-
6	418	164	244	1710	982	201	0.42	25.6	4	-	8.2
7	417	163	243	1700	974	199	0.42	25.5	3¾	61	9.4
8	415	164	243	1700	976	200	0.42	25.5	-	-	-
9	415	167	245	1685	970	215	0.42	25.7	3¾	70	8.0
10	415	168	246	1687	976	207	0.42	25.7	-	-	-
11	417	166	245	1723	976	207	0.42	25.7	-	-	-
12	417	163	243	1721	964	199	0.42	25.5	-	-	-
13	417	163	246	1756	996	206	0.42	25.7	-	-	-
14	415	168	247	1698	987	199	0.42	25.8	-	-	-
15	418	163	244	1725	974	199	0.42	25.6	5	59	8.0
16	416	164	245	1708	976	199	0.42	25.6	-	-	-
17	415	166	246	1723	966	203	0.42	25.7	-	-	-
18	417	163	247	1727	966	201	0.43	25.7	-	-	-
19	419	164	246	1702	972	201	0.42	25.7	4½	67	8.7
20	415	165	245	1708	976	199	0.42	25.6	-	-	-
21	418	163	244	1706	972	199	0.42	25.6	-	-	-
22	419	168	245	1710	964	199	0.42	25.8	-	-	-
23[b]	-								-	-	-
24	419	163	246	1717	972	199	0.42	25.7	-	-	-
25[b]	-								-	-	-
26	416	167	249	1676	1022	202	0.43	25.9	-	-	-
27	418	165	243	1703	972	200	0.42	25.6	4½	60	8.4
28	417	164	242	1697	968	200	0.42	25.5	-	-	-
29	415	164	243	1701	970	200	0.42	25.5	-	-	-
30	417	163	243	1697	966	202	0.42	25.5	-	-	-
31	415	165	245	1699	970	200	0.42	25.6	-	-	-
32	415	166	244	1709	968	200	0.42	25.6	5½	58	9.5
33	413	163	245	1701	970	200	0.43	25.5	-	-	-
34	416	164	246	1705	970	200	0.42	25.7	-	-	-
35	417	166	247	1703	968	200	0.42	25.8	-	-	-
36	415	168	247	1716	968	200	0.42	25.8	-	-	-
37	419	163	247	1705	966	202	0.42	25.8	-	-	-
38	416	163	246	1709	968	200	0.42	25.7	-	-	-
39	415	166	244	1703	968	200	0.42	25.6	-	-	-
40	415	166	244	1703	968	200	0.42	25.6	-	-	-

[a] Air content measured twice
[b] Trip ticket not available

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.7: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-5

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	416	163	239	1706	938	214	0.41	25.3	4½	78	8.4
2	418	166	240	1715	952	214	0.41	25.4	-	-	-
3	415	165	238	1712	948	214	0.41	25.2	4	75	7.5[a]
4	415	163	240	1685	950	214	0.42	25.3	-	-	-
5	416	164	239	1704	938	214	0.41	25.3	-	-	-
6	417	163	239	1712	953	214	0.41	25.2	4	-	6.6[a]
7	415	166	240	1687	942	218	0.41	25.3	3¼	78	7.2
8	417	165	241	1687	963	214	0.41	25.5	-	-	-
9	415	163	238	1691	946	214	0.41	25.2	-	-	-
10	416	166	242	1687	946	214	0.42	25.5	4	77	6.7
11	416	165	241	1685	959	214	0.41	25.4	3¾	78	-

[a] Air content measured twice

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.8: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-6

Truck	Material Proportions, SSD/PSD Basis (lb/yd³)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
1	406	178	228	1630	1081	121	0.39	24.9	3	70	7.6[a]
2	406	174	229	1632	1097	117	0.40	24.8	-	-	-
3	406	174	231	1630	1101	115	0.40	25.0	-	-	-
4	406	172	225	1634	1097	121	0.39	24.5	-	-	-
5	406	173	225	1628	1087	119	0.39	24.6	-	-	-
6	406	174	225	1634	1079	121	0.39	24.6	-	-	-
7	406	172	225	1630	1085	117	0.39	24.6	3	65	6.8
8	406	174	233	1626	1079	121	0.40	25.1	-	-	-
9	406	172	230	1630	1091	126	0.40	24.8	-	-	-
10	406	171	234	1632	1093	123	0.41	25.1	-	-	-
11	406	173	235	1632	1083	126	0.41	25.2	-	-	-
12	406	173	233	1636	1076	121	0.40	25.1	-	-	-
13	406	176	232	1628	1083	117	0.40	25.1	-	-	-
14	406	178	233	1632	1078	123	0.40	25.2	-	-	-
15	406	178	234	1632	1083	119	0.40	25.2	-	-	-
16	406	174	233	1632	1085	119	0.40	25.1	3¾	72	8
17	406	176	234	1630	1085	123	0.40	25.2	-	-	-
18	406	175	233	1633	1082	125	0.40	25.1	-	-	-
19	406	172	234	1633	1079	125	0.41	25.1	-	-	-
20	406	175	234	1631	1086	126	0.40	25.1	-	-	-
21	406	174	234	1635	1082	125	0.40	25.2	-	-	-
22	406	174	233	1631	1081	123	0.40	25.1	-	-	-
23	406	175	234	1635	1082	123	0.40	25.2	-	-	-
24	406	176	234	1627	1077	121	0.40	25.1	-	-	-
25	406	175	233	1631	1084	125	0.40	25.1	-	-	-

[a] Air content measured twice; Note: 1 lb/yd³ = 0.593 kg/m³; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.8: (con't) Trip tickets and plastic concrete properties for MN-IC-LC-HPC-6

Truck	Material Proportions, SSD/PSD Basis (lb/yd³)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	FLWA			Slump (in.)	Temp. (°F)	Air (%)
26	406	171	234	1631	1081	121	0.41	25.1	-	-	-
27	406	172	232	1627	1081	123	0.40	25.0	-	-	-
28	406	172	234	1631	1086	121	0.41	25.1	-	-	-
29	406	174	233	1635	1082	123	0.40	25.1	-	-	-
30	406	174	233	1633	1081	123	0.40	25.1	-	-	-
31	406	176	235	1627	1088	125	0.40	25.2	-	-	-
32	406	174	233	1629	1088	125	0.40	25.1	-	-	-
33	406	172	233	1629	1081	123	0.40	25.0	-	-	-
34	406	174	235	1631	1084	123	0.41	25.2	-	-	-
35	406	173	233	1629	1086	130	0.40	25.0	-	-	-
36	406	174	234	1633	1079	123	0.40	25.1	3½	78	9.2
37	406	173	234	1625	1079	125	0.40	25.1	-	-	-
38	406	173	225	1629	1082	126	0.39	24.6	-	-	-
39	406	173	234	1635	1088	125	0.40	25.1	-	-	-
40	406	171	235	1637	1086	122	0.41	25.1	-	-	-
41	406	173	234	1631	1086	120	0.40	25.1	-	-	-
42	406	173	234	1631	1082	120	0.40	25.1	-	-	-
43	406	174	233	1631	1077	118	0.40	25.1	-	-	-

Note: 1 lb/yd³ = 0.593 kg/m³; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.9: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-7-P1

Truck	Material Proportions, SSD/PSD Basis (lb/yd³)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	409	174	244	1629	1094	213	0.42	25.7	4¾	72	10[a]
2	403	174	245	1630	1095	238	0.43	25.7	-	-	10
3	409	173	242	1673	1093	153	0.42	25.6	-	-	7.5
4	404	173	236	1640	1097	155	0.41	25.1	4½	71	8.5
5	402	175	237	1640	1097	153	0.41	25.2	-	-	-
6	410	174	240	1632	1095	153	0.41	25.6	-	-	-
7	412	175	236	1632	1095	153	0.40	25.4	-	-	-
8	405	173	237	1638	1095	153	0.41	25.3	-	-	-
9	407	176	237	1638	1095	153	0.41	25.3	4	75	8.5
10	406	174	238	1634	1095	155	0.41	25.3	-	-	-
11	408	175	238	1636	1093	155	0.41	25.4	-	-	-
12	405	172	240	1636	1095	155	0.42	25.4	-	-	-
13	407	173	239	1636	1095	155	0.41	25.4	-	-	-
14	407	173	242	1634	1095	157	0.42	25.6	-	-	-
15	403	174	239	1636	1092	156	0.41	25.3	-	-	-
16	406	174	238	1636	1095	158	0.41	25.4	-	-	-

[a] Air content measured twice; Note: 1 lb/yd³ = 0.593 kg/m³; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.9: (con't) Trip tickets and plastic concrete properties for MN-IC-LC-HPC-7-P1

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
17	402	174	240	1638	1100	169	0.42	25.4	-	-	-
18	408	173	242	1636	1097	166	0.42	25.6	-	-	-
19	402	173	240	1640	1095	173	0.42	25.4	-	-	-
20	410	173	241	1638	1093	175	0.41	25.6	4½	74	9
21	403	173	239	1634	1093	171	0.42	25.4	-	-	-
22	407	173	240	1637	1091	181	0.41	25.5	-	-	-
23	403	173	239	1637	1099	172	0.42	25.3	-	-	-
24	406	173	240	1637	1093	168	0.41	25.4	-	-	-
25	406	173	242	1635	1097	160	0.42	25.5	-	-	-
26	406	174	238	1637	1093	157	0.41	25.3	-	-	-
27	404	174	238	1635	1097	157	0.41	25.3	-	-	-
28	407	172	235	1643	1095	157	0.41	25.1	-	-	-
29	404	174	233	1641	1093	157	0.40	25.0	-	-	-
30	407	173	234	1639	1099	157	0.40	25.1	-	-	-
31	406	173	241	1637	1093	157	0.42	25.5	4¼	72	-
32	405	174	235	1643	1095	153	0.41	25.1	-	-	-
33	407	174	234	1637	1095	155	0.40	25.1	-	-	-
34	405	172	235	1635	1091	155	0.41	25.1	-	-	-
35	407	174	239	1637	1095	166	0.41	25.4	-	-	-
36	402	174	238	1635	1093	157	0.41	25.3	-	-	-
37	406	174	238	1635	1093	157	0.41	25.3	-	-	-
38	407	174	237	1635	1093	157	0.41	25.3	-	-	-
39	406	175	237	1626	1095	153	0.41	25.3	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.10: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-7-P2

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	408	174	235	1633	1100	156	0.40	25.2	4¼	74	8.5
2	403	172	237	1637	1102	168	0.41	25.2	-	-	-
3	407	174	229	1631	1098	155	0.39	24.9	3¾	76	8.5
4	406	173	235	1635	1102	154	0.41	25.1	-	-	-
5	405	172	234	1637	1098	154	0.41	25.0	-	-	-
6	408	173	239	1633	1104	155	0.41	25.4	-	-	-
7	408	174	234	1637	1104	155	0.40	25.1	-	-	-
8	405	173	234	1635	1100	154	0.40	25.1	-	-	-
9	402	174	234	1637	1102	154	0.41	25.0	-	-	-
10	404	172	233	1639	1104	154	0.41	25.0	-	-	-
11	404	173	235	1639	1102	154	0.41	25.1	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.10: (con't) Trip tickets and plastic concrete properties for MN-IC-LC-HPC-7-P2

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
12	409	173	234	1637	1102	154	0.40	25.1	4¼	75	8.5
13	412	174	234	1644	1106	157	0.40	25.2	-	-	-
14	408	173	238	1637	1118	157	0.41	25.4	-	-	-
15	408	174	239	1639	1113	155	0.41	25.4	-	-	-
16	403	175	240	1640	1109	155	0.41	25.4	-	-	-
17	403	174	239	1635	1109	155	0.41	25.3	-	-	-
18	402	174	239	1630	1106	152	0.41	25.3	-	-	-
19	412	174	239	1635	1102	152	0.41	25.5	-	-	-
20	403	174	237	1627	1102	156	0.41	25.2	-	-	-
21	404	173	239	1638	1101	151	0.41	25.3	4	70	8.0
22	403	174	238	1638	1102	156	0.41	25.3	-	-	-
23	405	174	238	1645	1104	153	0.41	25.4	-	-	-
24	403	175	238	1638	1101	153	0.41	25.3	-	-	-
25	406	175	238	1636	1101	155	0.41	25.4	-	-	-
26	403	175	237	1636	1104	151	0.41	25.2	-	-	-
27	404	174	237	1641	1099	156	0.41	25.2	-	-	-
28	410	174	237	1639	1099	151	0.41	25.3	-	-	-
29	412	173	237	1639	1101	155	0.40	25.4	-	-	-
30	422	174	236	1636	1104	153	0.40	25.5	1	69	8
31	408	174	239	1636	1104	156	0.41	25.5	-	-	-
32	412	174	238	1638	1102	153	0.41	25.5	-	-	-
33	405	172	238	1638	1106	155	0.41	25.3	4	76	7.5
34	403	170	239	1639	1099	155	0.42	25.3	-	-	-
35	410	176	238	1639	1102	171	0.41	25.5	-	-	-
36	406	175	238	1638	1101	158	0.41	25.4	-	-	-
37	404	168	238	1629	1097	180	0.42	25.2	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.11: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-8

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1[a]	400	175	236	1580	1073	193	0.41	25.1	4½	76	9.4
2	400	169	232	1578	1075	193	0.41	24.7	-	-	-
3	400	170	239	1578	1073	193	0.42	25.2	-	-	-
4	400	172	244	1582	1073	193	0.43	25.6	-	-	-
5	400	172	235	1582	1075	193	0.41	25.0	5¼[b]	-	9.5
6	400	172	242	1578	1070	193	0.42	25.4	-	-	-
7	400	173	234	1580	1070	193	0.41	25.0	-	-	-
8	400	169	240	1580	1075	191	0.42	25.2	-	-	-
9	400	170	232	1578	1072	193	0.41	24.8	-	-	-
10	404	169	230	1582	1072	188	0.40	24.7	4½	-	8.6
11	401	170	234	1580	1073	191	0.41	25.0	-	-	-
12	400	175	236	1580	1073	193	0.41	25.1	-	-	-

[a] Rejected; [b] Slump measured twice; Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.11: (con't) Trip tickets and plastic concrete properties for MN-IC-LC-HPC-8

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
13	407	169	232	1578	1073	191	0.40	24.9	-	-	-
14	400	169	230	1580	1070	193	0.41	24.7	-	-	-
15	400	169	244	1578	1066	197	0.43	25.5	-	-	-
16	400	172	244	1586	1073	193	0.43	25.5	-	-	-
17	400	172	247	1580	1072	193	0.43	25.7	-	-	-
18	402	169	244	1578	1072	191	0.43	25.5	-	-	-
19	399	170	241	1578	1072	191	0.42	25.3	-	-	-
20	399	171	242	1578	1070	191	0.43	25.4	-	-	-
21	400	170	240	1578	1070	193	0.42	25.3	4	74	9.0
22	401	169	236	1578	1075	191	0.41	25.0	-	-	-
23	400	169	236	1580	1066	195	0.42	25.0	-	-	-
24	401	173	235	1582	1066	195	0.41	25.1	-	-	-
25	400	178	235	1578	1068	195	0.41	25.2	-	-	-
26	400	173	253	1576	1070	195	0.44	26.1	-	-	-
27	400	175	245	1582	1070	193	0.43	25.6	-	-	-
28	400	175	244	1580	1070	193	0.43	25.6	-	-	-
29	400	172	240	1576	1070	193	0.42	25.3	-	-	-
30	402	169	240	1580	1073	191	0.42	25.3	4	78	7.4
31	400	174	244	1578	1066	195	0.42	25.6	-	-	-
32	400	175	236	1578	1072	188	0.41	25.1	-	-	-
33	401	170	247	1578	1072	195	0.43	25.7	-	-	-
34	400	170	241	1578	1068	195	0.42	25.3	-	-	-

Table D.12: Trip tickets and plastic concrete properties for MN-IC-LC-HPC-9

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1[a]	400	171	230	1581	1113	173	0.40	24.7	6¾[b]	67	7.8
2	400	171	224	1583	1106	177	0.39	24.3	3	73	6.2
3	400	169	227	1573	1110	170	0.40	24.5	-	-	-
4	401	171	229	1577	1110	168	0.40	24.6	-	-	-
5	399	174	228	1577	1110	170	0.40	24.6	-	-	-
6	401	169	216	1575	1110	168	0.38	23.8	-	-	-
7	400	171	218	1575	1106	166	0.38	24.0	-	-	-
8	400	172	215	1575	1108	172	0.38	23.8	3	73	9.0
9	401	171	220	1577	1106	170	0.38	24.1	-	-	-
10	401	170	215	1581	1106	173	0.38	23.8	-	-	-
11	406	170	219	1577	1108	168	0.38	24.2	-	-	-
12	401	172	215	1575	1108	172	0.38	23.8	-	-	-

[a] Rejected; [b] Slump measured twice; Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table D.12: (con't) Trip tickets and plastic concrete properties for MN-IC-LC-HPC-9

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
13	401	170	215	1577	1110	170	0.38	23.8	-	-	-
14	405	171	215	1581	1108	168	0.37	23.9	-	-	-
15	400	170	226	1583	1112	168	0.40	24.4	-	-	-
16	402	170	216	1581	1112	168	0.38	23.9	-	-	-
17	399	169	224	1581	1106	177	0.39	24.3	-	-	-
18	400	171	215	1585	1112	168	0.38	23.8	-	-	-
19	401	170	219	1581	1108	168	0.38	24.1	3½	73	7.7
20	401	172	216	1579	1110	172	0.38	23.9	-	-	-
21	400	171	215	1577	1106	173	0.38	23.8	4	-	8.8
22	400	170	215	1581	1106	170	0.38	23.8	-	-	-
23	400	170	216	1583	1110	170	0.38	23.8	-	-	-
24	401	171	216	1583	1110	170	0.38	23.9	-	-	-

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

APPENDIX E: KANSAS DEPARTMENT OF TRANSPORTATION SPECIFICATIONS FOR LOW-CRACKING HIGH-PERFORMANCE CONCRETE (LC-HPC)-GENERAL, AGGREGATES, CONCRETE, AND CONSTRUCTION

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, EDITION 2015

For Low-Cracking High-Performance Concrete – Concrete, delete SECTION 401 and replace with the following:

GENERAL LOW-CRACKING HIGH-PERFORMANCE CONCRETE - CONCRETE

401.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.
See **15-PS0167** for specific requirements for Structural Concrete.
See **SECTION 403** for specific requirements for On Grade Concrete.
See **SECTION 404** for specific requirements for Prestressed Concrete.

401.2 MATERIALS

Provide materials that comply with the applicable requirements.

Aggregate **15-PS0168**
Admixtures and Plasticizers .... **DIVISION 1400**
Grade 2 Calcium Chloride .... **DIVISION 1700**
Cement, Fly Ash, Silica Fume, Slag Cement and Blended Supplemental
Cementitious.. **DIVISION 2000**
Water .... **DIVISION 2400**

401.3 CONCRETE MIX DESIGN

a. General. Design the concrete mixes specified in the Contract Documents.
Do not place any concrete on the project until the Engineer approves the concrete mix designs.
Take full responsibility for the actual proportions of the concrete mix, even if the Engineer assists in the design of the concrete mix.
Provide aggregate gradations that comply with **DIVISION 1100** and Contract Documents.
Admixture dosage rate requirements for mix design approval and field production are provided in **subsection 401.3l**.
If desired, contact the DME for available information to help determine approximate proportions to produce concrete having the required characteristics on the project.
Submit all concrete mix designs to the Engineer for review and approval. Submit completed volumetric mix designs on KDOT Form No. 694 and all required attachments at least 60 days prior to placement of concrete on the project. The Engineer will provide an initial review of the design within 5 business days following submittal.
Include the following information:
(1) Test data from KT-73 tested at 28 days, KT-79 tested at 28 days **or** AASHTO T-277 tested at 56 days. Provide test results on a minimum of 1 set of 3 cylinders for each mix, tested at the highest water to cementitious material ratio that meets **subsections 401.3e.** and **401.3i**. Submit accelerated cure procedures for the Engineer's approval.
(2) Test data from ASTM C 1567 for blended cements meeting **subsection 401.3k.** for all concrete utilizing all actual materials proposed for use on the project at designated percentages.

(3) Single point grading for the combined aggregates along with a plus/minus tolerance for each sieve. Use plus/minus tolerances to perform quality control checks and by the Engineer to perform aggregate grading verification testing. The tests may be performed on the combined materials or on individual aggregates, and then theoretically combined to determine compliance.
(4) Laboratory 28-day compressive strength test results on a minimum of 1 set of 3 cylinders produced from the mix design with the highest water to cementitious ratio for the project, utilizing all actual materials proposed for use on the project at designated percentages. The average compressive strength shall exceed the strength requirements for the Grade (see **subsection 401.3e.** for Grade definitions) specified in the Contract Documents as determined by **subsection 401.3b**. Perform compressive strength tests according to KT-76.
(5) Historical mix production data for the plant producing concrete for the project to substantiate the standard deviation selected for use in **subsection 401.3b.**, if applicable.
(6) Necessary materials to enable the Engineer to test the mix properties, if applicable.
(7) Batching sequence. Consider the location of the concrete plant in relation to the job site, and identify when and at what location the water reducer or plasticizer is added to the concrete mixture.

Submit complete mix design data including proportions and sources of all mix ingredients, and the results of strength and permeability tests representing the mixes proposed for use. The data may come from previous KDOT project records or a laboratory regularly inspected by Cement and Concrete Reference Laboratory (CCRL). Data from other sources will only be accepted if testing was conducted by personnel certified in Hardened Concrete Properties (HCP) according to the Policy and Procedures Manual for The Certified Inspection and Testing (CIT) Training Program.
After initial review, the Engineer will perform any testing necessary to verify the design. This may include a 3 cubic yard test batch at the producing plant. Do not make changes to the Approved Concrete Mix Design without the Engineer's approval. Limited adjustments may be made to admixture dosages and aggregate proportions in accordance with **subsection 401.3j.** and **subsection 403.4e**.
Mix designs will remain approved when verification testing for strength and permeability conducted within the last 12 months indicate continued compliance with the specifications and percentages of constituents including aggregate and cementitious materials and product, type and supplier of admixtures remain the same. Test results on the same mix from other sources are acceptable.
Improvements in concrete strength, workability, durability and permeability are possible if the combined aggregate grading is optimized. Procedures found in ACI 302.1 or other mix design techniques, approved by the Engineer, are acceptable in optimizing the mix design.
Delay the commencement of tests for temperature, slump, and air content and molding of field cylinders from 4 to 4½ minutes after the sample has been taken from a continuous mixer. If a batch type mixer is used, take the tests at the point of placement and begin testing immediately.

b. Required Compressive Strength For Mix Design. The required compressive strength for mix design approval shall be based on previous data or **subsection 401.3b.(2)**.
(1) Concrete Mix Design Based on Previous Data. Provide concrete mix designs based on previous 28-day compressive strength test data from similar concrete mixtures. Similar mixtures are within 1000 psi of the specified 28-day compressive strength, and are produced with the same type and sources of cementitious materials, admixtures and aggregates.
Consider sand sources the same, provided they are not more than 25 miles apart on the same river and no tributaries enter the river between the 2 points. Consider crushed locations similar if they are mined in one continuous operation, and there is no significant change in geology. Mixes that have changes of more than 10% in proportions of cementitious materials, aggregates or water content are not considered similar.
Air entrained mixes are not considered similar to non-air entrained mixes.
Mixes tested with admixtures are not the same as mixes tested without those admixtures.
Test data should represent at least 30 separate batches of the mix. One set of data is the average of at least 2 cylinders from the batch. The data shall represent a minimum of 45 days of production within the past 12 months.
Do not include data over 1 year old. When fewer than 30 data sets are available, the standard deviation of the data must be corrected to compensate for the fewer data points.
Provide a concrete mix design that will permit no more than 5% of the 28-day compressive strength tests to fall below the specified 28-day compressive strength (*f'c*) based on equation A, and no more than 1% of the 28-day compressive strength tests to fall below the specified 28-day compressive strength (*f'c*) by more than 500 psi based on equation B.

Equation A: $f'cr = f'c + 1.62 * k * s$

Equation B: $f'cr = (f'c\text{-}500) + 2.24 * k * s$

Where: $f'cr$ = average 28-day compressive strength required to meet the above criteria.
$f'c$ = specified 28-day compressive strength
s = standard deviation of test data
k = constant based on number of data points
n = number of data points
$k = 1.3 - n / 100$, where $15 < n < 30$
$k = 1$, where $n > 30$

Provide a concrete mix design that has an average compressive strength that is equal to the larger of Equation A or Equation B. Submit all supporting test data with the mix design.
(2) All other concrete mix designs. For concrete mixes that have fewer than 15 data points, or if no statistical data is available, use Equations A and B to calculate $f'cr$ using the following values.

s = 20% of the specified 28-day compressive strength ($f'c$)
$k = 1$

c. Portland Cement and Blended Hydraulic Cement. Unless specified otherwise in the Contract Documents, select the type of portland cement or blended hydraulic cement according to **TABLE 401-1**.

TABLE 401-1: PORTLAND CEMENT & BLENDED HYDRAULIC CEMENT

Concrete for:	**Type of Cement Allowed**
On Grade Concrete	Type IP(x) Portland-Pozzolan Cement Type IS(x) Portland- Slag Cement Type IT(Ax)(By) Ternary Blended Cement Type IL(x) Portland-Limestone Cement Type II Portland Cement
All Concrete other than On Grade Concrete.	Type I Portland Cement Type IP(x) Portland-Pozzolan Cement Type IS(x) Portland- Slag Cement Type IT(Ax)(By) Ternary Blended Cement Type IL(x) Portland Limestone Cement Type II Portland Cement
High Early Strength Concrete	Type III Portland Cement Type I, IP(x), IS(x), IT(Ax)(By), Type IL(x) or II Cement may be used if strength and time requirements are met.

d. Blended Cement Concrete. When approved by the Engineer, the concrete mix design may include SCMs such as fly ash, slag cement, silica fume or blended SCM from an approved source as a partial replacement for portland cement or blended hydraulic cement except where controlled by **15-PS0167 and SECTIONS 403** and **404**. Obtain the Engineer's approval before substituting SCMs for Type III cement. Changes in SCM or cement will require a new mix design approval.
(1) Cements meeting **SECTION 2001** are not field blended cements.
(2) Cements with SCMs added at the concrete mixing plant are field blended cements.
(3) Supplementary materials can be combined with cement to create field blended cements. Do not exceed allowable substitution rates noted in **TABLE 401-2**. Substitute 1 pound of SCM for 1 pound of cement.
(4) SCMs in prequalified cements are to be included in the total combined substitution rate.

TABLE 401-2: ALLOWABLE SUBSTITUTION RATE FOR SUPPLEMENTARY CEMENTITIOUS MATERIAL.	
Material	**Substitution Rate***
Slag Cement	40% Maximum
Fly Ash	25% Maximum
Blended SCM	25% Maximum
Limestone	10% Maximum
Silica Fume	5% Maximum
Total Combined	50%

* Total Substitution Rate includes material in preblended cements and blended SCMs.

(5) When used, add silica fume with other cementitious materials during batching procedures. If the silica fume cannot be added to the cementitious materials, add the loose silica fume to the bottom of the stationary drum that is wet, but has no standing water, before adding the dry materials. The Engineer may approve shreddable bags on a performance basis and only when a central batch mixing process is used. If so, add the bags to half of the mixing water and mix before adding cementitious materials, aggregate and remainder of water.
Mix silica fume modified concrete for a minimum of 100 mixing revolutions.

e. Strength. Design concrete to meet **TABLE 401-3**.

TABLE 401-3: CONCRETE STRENGTH REQUIREMENTS	
Specified 28-Day Compressive Strengths, minimum, psi ***f'c***	
Grade of Concrete:	**Non-Air Entrained/Air Entrained Concrete**
Grade 7.0	7,000
Grade 6.0	6,000
Grade 5.0	5,000
Grade 4.5	4,500
Grade 4.0	4,000
Grade 3.5	3,500
Grade 3.0	3,000
Grade 2.5	2,500

f. High Early Strength Concrete (HESC). Design the high early strength concrete mix to comply with strength and time requirements specified in the Contract Documents.
Unless otherwise specified, design high early strength concrete for pavement at a minimum of 1 of the Contractor's standard deviations above 2400 psi (cylinders) at 24 hours. If no statistics are available, design a HESC with a compressive strength greater or equal to 2880 psi.
Submit complete mix design data including proportions and sources of all mix ingredients, and the results of time and strength tests representing the mixes proposed for use. The strength and time data may come from previous KDOT project records or from an independent laboratory, and shall equal or exceed the strength and time requirements listed in the Contract Documents.

g. Internally Cured Concrete (IC). The proportions of the internally cured concrete mix shall be determined by modifying the proportions of a conventional normal weight concrete mix. Replace a portion of the normal weight fine aggregate with prewetted lightweight fine aggregate. The weight of prewetted lightweight aggregate (W_{LWA}) required to supply internal curing water shall be calculated using equation C.

Equation C: $W_{LWA} = 0.07\times(\text{total weight of cementitious material})\times(1+\text{absorption})/((\text{absorption})\times(\text{desorption}))$

Where: the total weight of cementitious materials is expressed in pounds,
the absorption and desorption values are expressed as decimal fractions, and

the absorption and desorption values used to compute WLWA shall be for the specific source of aggregate selected for use in the internally cured concrete. Absorption and Desorption Values to be determined and supplied by aggregate producer.

For guidance on computing W_{LWA}, see the ESCSI Guide for Calculating the Quantity of Prewetted ESCS Lightweight Aggregates for Internal Curing (IC Calculator) at escsi.org. The volume of prewetted lightweight aggregate that corresponds to W_{LWA} shall replace an equal volume of normal weight fine aggregate.
Submit the internally cured concrete mix designs in accordance with **subsection 401.3a** including the absorption and desorption values for the selected source of lightweight aggregate. Mix designs for internally cured concrete shall be considered as approximate until verifying the absorption of the lightweight aggregate (to establish the amount of internal curing water) 24 hours prior to batching.
Changes in mixture proportions for lightweight aggregate based on the absorption measured 24 hours prior to batching shall be made as a replacement of normal weight fine aggregate. Samples shall be obtained in accordance with KT-01. Use a centrifuge to place the lightweight aggregate in a pre-wetted surface dry condition for testing.

h. Slump. Designate a slump for each concrete mix design that is required for satisfactory placement of the concrete application not to exceed 5 inches except where controlled by maximum allowable slumps stated in **15-PS0167 and SECTIONS 403** and **404**. Reject concrete with a slump that limits the workability or placement of the concrete.

i. Permeability. Supply concrete meeting the permeability requirements specified in **15-PS0167** for structural concrete and **SECTION 403** for on grade concrete. Permeability testing from KT-73 tested at 28 days, KT-79 tested at 28 days **or** AASHTO T-277 tested at 56 days is required for all bridge overlays, Moderate Permeability Concrete, and any project with over 250 cubic yards of concrete (this includes structural concrete, on grade concrete etc.). The field verification test procedure must be the same test procedure as the mix design approval test.
There are no permeability requirements for concrete for prestressed concrete members as specified in **SECTION 404**.

j. Air Content. Determine air content by KT-18 (Pressure Method) or KT-19 (Volumetric Method). With **the exception of LC-HPC** as shown in **15-PS0167** and pavement as shown in **SECTION 403**, use the middle of the specified air content range of 6.5 ± 1.5% for the design of air entrained concrete. Maximum air content is 10%. Take immediate steps to reduce the air content whenever the air content exceeds 8%.

k. Alkali Silica Reactivity. If the concrete mix design includes supplemental cementitious materials (SCMs), provide mortar expansion test results from ASTM C 1567 as part of mix design approval unless meeting the minimum requirements shown in **TABLE 401-4**. Use the project's mix design concrete materials at their designated percentages. Provide a mix with a maximum expansion of 0.10% at 16 days after casting. Provide ASTM C 1567 results on an annual basis.

TABLE 401-4: MINIMUM SCM CONTENT REQUIRED TO WAIVE ASTM C 1567 TESTING

Type of Coarse Aggregate Sweetener	**Proportion Required by Percent Weight of Total Cementitious Material**			
	Slag Cement	**Class C Fly Ash**	**Class F Fly Ash**	**Silica Fume**
Crushed Sandstone	ASTM C 1567 Testing Required		25%	Any*
Crushed Limestone or Dolomite			25%	Any*
Siliceous Aggregate Meeting **subsection 1102.2a.(2) or 1116.2a.(2)**			25%	Any*
Any combination of Limestone (or Dolomite or Sandstone) and Siliceous Aggregate meeting **subsection 1102.2a.(2) or 1116.2a.(2) or any TMA**	Any*	≥15%	Any*	Any*

*Subject to the maximum allowable percentages in **TABLE 401-2**.

ASTM C 1567 Testing can be waived for ternary mix designs with approval of the KDOT Bureau of Research.

l. Admixtures for Acceleration, Air-Entraining, Plasticizing, Set Retardation and Water Reduction. Verify that the admixtures used are compatible and will work as intended without detrimental effects. Use the dosages recommended by the admixture manufacturers. Incorporate and mix the admixtures into concrete mixtures according to the manufacturer's recommendations. Determine the quantity of each admixture for the concrete mix design.

(1) Accelerating Admixture. When specified in the Contract Documents, or in situations that involve contact with reinforcing steel and require early strength development to expedite opening to traffic, a non-chloride accelerator may be approved. The Engineer may approve the use of a Type C or E accelerating admixture. A Grade 2 calcium chloride accelerator may be used when patching an existing pavement more than 10 years old.

Add the calcium chloride by solution (the solution is considered part of the mixing water).

- For a minimum cure of 4 hours at 60°F or above, use 2% (by dry weight of cement) calcium chloride.
- For a minimum cure of 6 hours at 60°F or above, use 1% (by dry weight of cement) calcium chloride.

(2) Air-Entraining Admixture. When specified, use an air-entraining admixture in the concrete mixture. If another admixture is added to an air-entrained concrete mixture, determine if it is necessary to adjust the air-entraining admixture dosage to maintain the specified air content.

(3) Water-Reducers and Set-Retarders. A water-reducing admixture for improving workability may be required. If unfavorable weather or other conditions adversely affect the placing and finishing properties of the concrete mix, the Engineer may allow the use of water-reducers and set-retarders. Verify that the admixtures will work as intended without detrimental effects. If the Engineer approves the use of water-reducers and set-retarders, their continued use depends on their performance.

(4) Plasticizer Admixture. A plasticizer is defined as an admixture that produces flowing concrete, without further addition of water, and/or retards the setting of concrete. Flowing concrete is defined as having a slump equal to or greater than 7 ½ inches while maintaining a cohesive nature.

Manufacturers of plasticizers may recommend mixing revolutions beyond the limits specified in **subsection 401.8**. If necessary, address the additional mixing revolutions in the concrete mix design. The Engineer may allow up to 60 additional revolutions when plasticizers are designated in the mix design.

Before the concrete mixture with a slump equal to or greater than 7 ½ inches is used on the project, conduct tests on at least 1 full trial batch of the concrete mix design in the presence of the Engineer to determine the adequacy of the dosage and the batching sequence of the plasticizer to obtain the desired properties. Determine the air content of the trial batch both before and after the addition of the plasticizer. Monitor the slump, air content, temperature and workability at regular intervals of the time period from when the plasticizer is added until the estimated time of completed placement. At the discretion of the Engineer, if all the properties of the trial batch remain within the specified limits, the trial batch may be used in the project.

Do not add water after plasticizer is added to the concrete mixture.

(5) Field Adjustment to Admixtures. Limited adjustments to the dosage rate of accelerators, set-retarders, water reducers, and air-entraining admixtures are permitted to compensate for environmental changes during placement without a new concrete mix design or trial batch. Test the concrete for temperature, air content, and slump whenever changes are made to the dosage rates to ensure continued compliance with the specifications. The allowable adjustments are based on the dose used in the Approved Concrete Mix Design and according to the following:

- Do not exceed the accelerator dosage used in the Approved Mix Design. The accelerator dosage may be reduced or eliminated as needed. Redosing accelerators is not permitted.
- The water reducer dosage used in the Approved Mix Design sets the minimum permitted dose for use in the field. The water reducer dose may be increased from that shown in the Approved Mix Design provided that the slump does not to exceed the maximum designated slump. Slump reduction may be obtained by withholding a portion of the mix water as specified in **subsection 401.8a**.
- Redosing of water reducers and air-entraining admixtures is permitted to control slump or air content in the field, when approved by the Engineer, time and temperature limits are not exceeded, and at least 30 mixing revolutions remain before redosing. Redose according to manufacturer's recommendations.
- Set retarders may be added as needed during production. Do not include set retarders in the mix submitted for Mix Design Approval. Redosing retarders is not permitted. Paperwork for submitted mix designs (Form 694) with no (zero) water reducer and/or set retarder in the original Concrete submitted for Mix Design Approval must show the manufacturer of the admixtures that may be included in the Project Concrete.

401.4 REQUIREMENTS FOR COMBINED MATERIALS

a. Measurements for Proportioning Materials.

(1) Cement. Measure cement as packed by the manufacturer. A sack of cement is considered as 0.04 cubic yards weighing 94 pounds net. Measure bulk cement by weight. In either case, the measurement must be accurate to within 0.5% throughout the range of use.

(2) Supplemental Cementitious Materials. Supplemental cementitious materials proportioning and batching equipment is subject to the same controls as required for cement. Provide positive cut off with no leakage from the cut off valve. Cementitious materials may be weighed accumulatively with the cement or separately. If weighed accumulatively, weigh the cement first.

(3) Water. Measure the mixing water by weight or by volume accurate to within 1% throughout the range of use.

(4) Aggregates. Measure the aggregates by weight, accurate to within 0.5% throughout the range of use.

(5) Admixtures. Measure liquid admixtures by weight or volume, accurate to within 3% of the quantity required. If liquid admixtures are used in small quantities in proportion to the cement as in the case of air-entraining agents, use readily adjustable mechanical dispensing equipment capable of being set to deliver the required quantity and to cut off the flow automatically when this quantity is discharged.

b. Testing of Aggregates.

(1) Production of On Grade Concrete Aggregate (OGCA). If OGCA is required, notify the Engineer in writing at least 2 weeks in advance of producing the aggregate. Include the source of the aggregate and the date production will begin. Failure to notify the Engineer, as required, may result in rejection of the aggregate for use as OGCA. Maintain separate stockpiles for OGCA at the quarry and at the batch site and identify them accordingly.

(2) Testing Aggregates at the Batch Site. Provide the Engineer with reasonable facilities at the batch site for obtaining samples of the aggregates. Provide adequate and safe laboratory facilities at the batch site allowing the Engineer to test the aggregates for compliance with the specified requirements.

KDOT will sample and test aggregates from each source to determine their compliance with specifications. Do not batch the concrete mixture until the Engineer has determined that the aggregates comply with the specifications. KDOT will conduct sampling at the batching site, and test samples according to the Sampling and Testing Frequency Chart in Part V. For QC/QA contracts, establish testing intervals within the specified minimum frequency.

After initial testing is complete, and the Engineer has determined that the aggregate process control is satisfactory, use the aggregates concurrently with sampling and testing as long as tests verify compliance with specifications. When batching, sample the aggregates as near the point of batching as feasible. Sample from the stream as the storage bins or weigh hoppers are loaded. If samples cannot be taken from the stream, take them from approved stockpiles, or use a template and sample from the conveyor belt. If test results indicate an aggregate does not comply with specifications, cease concrete production using that aggregate. Unless a tested and approved stockpile for that aggregate is available at the batch plant, do not use any additional aggregate from that source and specified grading until subsequent testing of that aggregate indicate compliance with specifications. When tests are completed and the Engineer is satisfied that process control is satisfactory, production of concrete using aggregates tested concurrently with production may resume.

c. Handling of Materials.

(1) Approved stockpiles are permitted only at the batch plant and only for small concrete placements or for maintaining concrete production. Mark the approved stockpile with an "Approved Materials" sign. Provide a suitable stockpile area at the batch plant so that aggregates are stored without detrimental segregation or contamination. At the plant, limit stockpiles of tested and approved coarse, fine and intermediate aggregate to 250 tons each, unless approved for more by the Engineer. If mixed aggregate is used, limit the approved stockpile to 500 tons, the size of each being proportional to the amount of each aggregate to be used in the mix.

Load aggregates into the mixer such that no material foreign to the concrete or material capable of changing the desired proportions is included.

(2) Segregation. Do not use segregated aggregates. Previously segregated materials may be thoroughly re-mixed and used when representative samples taken anywhere in the stockpile indicated a uniform gradation exists.

(3) Cement and Supplemental Cementitious. Protect cement and supplemental cementitious materials in storage or stockpiled on the site from any damage by climatic conditions which would change the characteristics or usability of the material.

(4) Moisture. Provide aggregate with a moisture content of ± 0.5% from the average of that day. If the moisture content in the aggregate varies by more than the above tolerance, take whatever corrective measures are necessary to bring the moisture to a constant and uniform consistency before placing concrete. This may be accomplished by handling or manipulating the stockpiles to reduce the moisture content, or by adding moisture to the stockpiles in a manner producing uniform moisture content through all portions of the stockpile.

Handheld moisture-determining devices are permitted. For plants equipped with an approved accurate moisture-determining device capable of continuously determining the free moisture in the aggregates, and provisions made for batch to batch correction of the amount of water and the weight of aggregates added, the requirements relative to manipulating the stockpiles for moisture control will be waived. Approval and accuracy of the moisture-determining device is based on daily comparisons with KT-24 or ASTM C 566 and at the discretion of the Engineer. Any procedure used will not relieve the producer of the responsibility for delivering concrete of uniform slump within the limits specified.

(5) Separation of Materials in Tested and Approved Stockpiles. Only use KDOT Approved Materials. Provide separate means for storing materials approved by KDOT. If the producer elects to use KDOT Approved Materials for non-KDOT work, during the progress of a project requiring KDOT Approved Materials, inform the Engineer and agree to pay all costs for additional material testing.

Clean all conveyors, bins and hoppers of any unapproved materials before beginning the manufacture of concrete for KDOT work.

(6) Prewetted Lightweight Fine Aggregate Stockpiles. The lightweight aggregate shall be stockpiled and handled in accordance with **DIVISION 1100** to ensure that the target absorbed moisture content has been achieved at the time of batching. Batch weights for lightweight aggregate shall be adjusted based on the amount of free moisture determined within one hour of batching.

401.5 MORTAR AND GROUT

a. General. Follow the proportioning requirements in **subsections 401.5b.** and **c.** for mortar and grout unless otherwise specified in the Contract Documents, including altering the proportions when a minimum strength is specified.

b. Mortar. Mortar is defined as a mixture of cementitious materials, FA-M aggregate and water, which may contain admixtures, and is typically used to minimize erosion between large stones or to bond masonry units.
Proportion mortar for laying stone for stone rip-rap, slope protection, stone ditch lining or pavement patching at 1 part of portland cement and 3 parts of FA-M aggregate by volume with sufficient water to make a workable and plastic mix.

Proportion mortar for laying brick, concrete blocks or stone masonry at ½ part masonry cement, ½ part portland cement and 3 parts FA-M aggregate, either commercially produced masonry sand or FA-M, by volume with sufficient water to make a workable and plastic mix.

Do not use air-entraining agents in mortar for masonry work.

The Engineer may visually accept the sand used for mortar. The Engineer may visually accept any recognized brand of portland cement or masonry cement that is free of lumps.

c. Grout. Grout is defined as a mixture of cementitious materials with or without aggregate or admixtures to which sufficient water is added to produce a pouring or pumping consistency without segregation of the constituent materials and meeting the applicable specifications.

401.6 COMMERCIAL GRADE CONCRETE

If the Contract Documents allow the use of commercial grade concrete for designated items, then use a commercial grade mixture from a ready mix plant approved by the Engineer.

The Engineer must approve the commercial grade concrete mixture. Approval of the commercial grade mixture is based on these conditions:

- All materials are those normally used for the production and sale of concrete in the vicinity of the project.
- The mixture produced is that normally used for the production and sale of concrete in the vicinity of the project.
- The mixture produced contains a minimum cementitious content of 6 sacks (564 lbs) of cementitious material per cubic yard of concrete.

- The water-cementitious ratio is as designated by the Engineer. The maximum water-cementitious ratio permitted may not exceed 0.50 pounds of water per pound of cementitious material including free water in the aggregate.
- Type I, II, III, IP, IS or IT cement may be used unless otherwise designated. Fly ash, slag cement and blended supplemental materials may be substituted for the required minimum cement content as specified in **subsection 401.3**. No additives other than air entraining agent will be allowed. The Contractor will not be required to furnish the results of strength tests when submitting mix design data to the Engineer.
- In lieu of the above, approved mix designs (including optimized) for all other grades of concrete, Grade 3.0 or above, are allowable for use as commercial grade concrete, at no additional cost to KDOT.

Exercise good engineering judgment in determining what equipment is used in proportioning, mixing, transporting, placing, consolidating and finishing the concrete.

Construct the items with the best current industry practices and techniques.

Before unloading at the site, provide a delivery ticket for each load of concrete containing the following information:

- Name and location of the plant.
- Time of batching concrete.
- Mix proportions of concrete (or a mix designation approved by the Engineer).
- Number of cubic yards of concrete batched.

Cure the various items placed, as shown in **DIVISION 700 and 15-PS0165**.

The Engineer may test commercial grade concrete by molding sets of 3 cylinders. This is for informational purposes only. No slump or unit weight tests are required.

401.7 CERTIFIED CONCRETE

If KDOT inspection forces are not available on a temporary basis, the Engineer may authorize the use of concrete from approved concrete plants. Approval for this operation is based on certification of the plant and plant personnel, according to KDOT standards. KDOT's approval may be withdrawn any time that certification procedures are not followed. Contact the DME for additional information.

The Engineer will not authorize the use of certified concrete for major structures such as bridges, RCB box bridges, RCB culverts, permanent main line and ramp pavement or other structurally, critical items.

Each load of certified concrete must be accompanied by a ticket listing mix proportions, time of batching and setting on revolution counter, total mixing revolutions and must be signed by certified plant personnel.

401.8 MIXING, DELIVERY AND PLACEMENT LIMITATIONS

a. Concrete Batching, Mixing and Delivery. Batch and mix the concrete in a central mix plant, in a truck mixer or in a drum mixer at the work site. Provide plant capacity and delivery capacity sufficient to maintain continuous delivery at the rate required. The delivery rate of concrete during concreting operations must provide for the proper handling, placing and finishing of the concrete.

Seek the Engineer's approval of the concrete plant/batch site before any concrete is produced for the project. The Engineer will inspect the equipment, the method of storing and handling of materials, the production procedures and the transportation and rate of delivery of concrete from the plant to the point of use. The Engineer will grant approval of the concrete plant/batch site based on compliance with the specified requirements. The Engineer may, at any time, rescind permission to use concrete from a previously approved concrete plant/batch site upon failure to comply with the specified requirements.

Clean the mixing drum before it is charged with the concrete mixture. Charge the batch into the mixing drum such that a portion of the water is in the drum before the aggregates and cementitious material. Uniformly flow materials into the drum throughout the batching operation. All mixing water must be in the drum by the end of the first 15 seconds of the mixing cycle. Keep the throat of the drum free of accumulations restricting the flow of materials into the drum.

Do not exceed the rated capacity (cubic yards shown on the manufacturer's plate on the mixer) of the mixer when batching the concrete. The Engineer may allow an overload of up to 10% above the rated capacity for central mix plants and drum mixers at the work site, provided the concrete test data for strength, segregation and uniform consistency are satisfactory, and no concrete is spilled during the mixing cycle.

Operate the mixing drum at the speed specified by the mixer's manufacturer (shown on the manufacturer's plate on the mixer).

Mixing time is measured from the time all materials, except water, are in the drum. If it is necessary to increase the mixing time to obtain the specified percent of air in air-entrained concrete, the Engineer will determine the mixing time.

If the concrete is mixed in a central mix plant or a drum mixer at the work site, mix the batch between 1 to 5 minutes at mixing speed. Do not exceed the maximum total 60 mixing revolutions. Mixing time begins after all materials, except water, are in the drum, and ends when the discharge chute opens. Transfer time in multiple drum mixers is included in mixing time. Mix time may be reduced for plants utilizing high performance mixing drums provided thoroughly mixed and uniform concrete is being produced with the proposed mix time. Performance of the plant must conform to Table A1.1 of ASTM C 94, Standard Specification for Ready Mixed Concrete. Five of the 6 tests listed in Table A1.1 must be within the limits of the specification to indicate that uniform concrete is being produced.

If the concrete is mixed in a truck mixer, mix the batch between 70 and 100 revolutions of the drum or blades at mixing speed. After the mixing is completed, set the truck mixer drum at agitating speed. Unless the mixing unit is equipped with an accurate device indicating and controlling the number of revolutions at mixing speed, perform the mixing at the batch plant and operate the mixing unit at agitating speed while travelling from the plant to the work site. Do not exceed 300 total revolutions (mixing and agitating). An additional 60 mixing revolutions may be allowed by the Engineer when plasticizers are designated in the mix design.

If a truck mixer or truck agitator is used to transport concrete that was completely mixed in a stationary central mixer, agitate the concrete while transporting at the agitating speed specified by the manufacturer of the equipment (shown on the manufacturer's plate on the equipment). Do not exceed 200 total revolutions (additional re-mixing and agitating).

Provide a batch slip including batch weights of every constituent of the concrete and time for each batch of concrete delivered at the work site, issued at the batching plant that bears the time of charging of the mixer drum with cementitious materials and aggregates. Include quantities, type, product name and manufacturer of all admixtures on the batch ticket.

On paving projects and other high volume work, the Engineer will evaluate the haul time, and whether tickets will be collected for every load. Thereafter, random checks of the loads will be made. Maintain all batch tickets when not collected.

When non-agitating equipment is used for transportation of concrete, place within 30 minutes of adding the cement to the water. Provide approved covers for protection against the weather when required by the Engineer.

When agitating equipment is used for transportation of the concrete, place concrete within the time and temperature conditions shown in **TABLE 401-5**.

TABLE 401-5: AMBIENT AIR TEMPERATURE AND AGITATED CONCRETE PLACEMENT TIME		
T = Ambient Air Temperature at Time of Batching (°F)	**Time limit agitated concrete must be placed within, after the addition of cement to water (hours)**	**Admixtures**
T < 75	1 ½	All Cases
75 ≤ T < 90	1	None
75 ≤ T < 90	1 ½	Set Retarder
90 ≤ T	¾ (45 minutes)	All Cases

Do not use concrete that has developed its initial set. Regardless of the speed of delivery and placement, the Engineer will suspend the concreting operations until corrective measures are taken, if there is evidence that the concrete cannot be adequately consolidated.

Weather conditions and the use of admixtures can affect the set times for the concrete. Do not use the time limits and total revolutions as the sole criterion for rejection of concrete. Exceed the time limits and total revolutions only after demonstrating that the properties of the concrete can be improved. Evaluation of the consistency and workability should be taken into consideration. Reject concrete that cannot be adequately consolidated.

Adding water to concrete after the initial mixing is prohibited, with this exception:

If the concrete is delivered to the work site in a truck mixer, the Engineer will allow water (up to 2 gallons per cubic yard) be withheld from the mixture at the batch site, and if needed, added at the work site to adjust the slump to the specified requirements. Determine the need for additional water as soon as the load arrives at the construction site. Use a calibrated water-measuring device to add the water, and add the water to the entire load. Do not add more water than was withheld at the batch site. After the additional water is added, turn the drum or blades an additional 20 to 30 revolutions at mixing speed. The Engineer will supervise the adding of water to the load, and will allow this procedure only once per load. Conduct all testing for acceptance and produce any required cylinders after all water or admixtures have been added.

Do not add water at the work site if the slump is within the designated slump tolerance, even if water was withheld.

Do not add water at the work site if the percent air is above 8%, regardless of the slump, even if water was withheld.

Do not withhold and add water if plasticizer is added to the concrete mixture at the batch site.

If at any time during the placement of concrete it is determined that redosing with water is adversely affecting the properties of the concrete, the concrete will be rejected and the Engineer will suspend the practice.

b. Placement Limitations.

(1) Concrete Temperature. Unless otherwise authorized by the Engineer, the temperature of the mixed concrete immediately before placement is a minimum of 50ºF and a maximum of 90ºF. The maximum concrete temperature for LC-HPC is 80ºF. Maintain the temperature of the concrete at time of placement within the specified temperature range by any combination of the following:

- Shading the materials storage areas or the production equipment.
- Cooling the aggregates by sprinkling with potable water.
- Cooling the aggregates or water by refrigeration or replacing a portion or all of the mix water with ice that is flaked or crushed to the extent that the ice will completely melt during mixing of the concrete.
- Liquid nitrogen injection.

(2) Qualification Batch. For LC-HPC, qualify a field batch (one truckload or at least 6 cubic yards) at least 60 days prior to commencement of placement of the bridge decks. Produce the qualification batch from the same plant that will supply the concrete for the job. Simulate haul time to the jobsite prior to discharge of the concrete for testing. Prior to placing concrete in the qualification slab and on the job, submit documentation to the Engineer verifying that the qualification batch concrete meets the requirements for air content, slump, temperature of plastic concrete, compressive strength, unit weight and other testing as required by the Engineer.

Before the concrete mixture with plasticizing admixture is used on the project, determine the air content of the qualification batch. Monitor the slump, air content, and temperature at initial batching and estimated time of concrete placement. If these properties are not adequate, repeat the qualification batch until it can be demonstrated that the mix is within acceptable limits as specified in this specification. Once the LC-HPC has passed these plastic requirements, 11 4 in. × 8 in. cylinders will be cast by KDOT to determine permeability (RCPT, surface resistivity, and volume of permeable pores) and spacing factor.

(1) Placing Concrete at Night. Do not mix, place or finish concrete without sufficient natural light, unless an adequate, artificial lighting system approved by the Engineer is provided.

(2) Placing Concrete in Cold Weather. Unless authorized by the Engineer, discontinue mixing and concreting operations when the descending ambient air temperature reaches 40°F. Do not begin concreting operations until an ascending ambient air temperature reaches 35°F and is expected to exceed 40ºF.

If the Engineer permits placing concrete during cold weather, aggregates may be heated by either steam or dry heat system before placing them in the mixer. Use an apparatus that heats the mass uniformly and is so arranged as to preclude the possible occurrence of overheated areas which might injure the materials. Do not heat aggregates directly by gas or oil flame or on sheet metal over fire. Aggregates that are heated in bins, by steam-coil or water-coil heating, or by other methods not detrimental to the aggregates may be used. The use of live steam on or through binned aggregates is prohibited. Unless otherwise authorized, maintain the temperature of the mixed concrete between 50 to 90°F at the time of placing. Do not, under any circumstances, continue concrete operations if the ambient air temperature is less than 20°F.

If the ambient air temperature is 35°F or less at the time the concrete is placed, the Engineer may require that the water and the aggregates be heated to between 70 and 150°F.

Do not place concrete on frozen subgrade or use frozen aggregates in the concrete.

Make adjustments for potential longer set time and slower strength gain for concrete with SCMs. Adjust minimum time requirements as stated in **15-PS0165** for concrete used in structures. For concrete paving, be aware of the effect that the use of SCMs (except silica fume) may have on the statistics and moving averages.

401.9 INSPECTION AND TESTING

Unless otherwise designated in the Contract Documents or by the Engineer, obtain samples of fresh concrete for the determination of slump, weight per cubic yard and percent of air from the final point of placement.

The Engineer will cast, store and test strength test specimens in sets of 3.

KDOT will conduct the sampling and test the samples according to **DIVISION 2500** and the Sampling and Testing Frequency Chart in Part V. For QC/QA contracts, establish testing intervals within the specified minimum frequency.

The Engineer will reject concrete that does not comply with specified requirements.

The Engineer will permit occasional deviations below the specified cementitious content, if it is due to the air content of the concrete exceeding the designated air content, but only up to the maximum tolerance in the air content.

Continuous operation below the specified cementitious content for any reason is prohibited.

As the work progresses, the Engineer reserves the right to require the Contractor to change the proportions if conditions warrant such changes to produce a satisfactory mix. Any such changes may be made within the limits of the specifications at no additional compensation to the Contractor.

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, EDITION 2015

For Low-Cracking High-Performance Concrete, delete SECTION 1102 and replace with the following:

SECTION 1102

LOW-CRACKING HIGH-PERFORMANCE CONCRETE-AGGREGATES

1102.1 DESCRIPTION

This specification is for coarse aggregates, intermediate aggregates, fine aggregates, mixed aggregates (coarse, intermediate and fine material) and miscellaneous aggregates for use in construction of concrete not placed on grade.

For Intermediate Aggregates and Mixed Aggregates, consider any aggregate with 30% or more retained on the No. 8 sieve to be Coarse Aggregate.

1102.2 REQUIREMENTS

a. Quality of Individual Aggregates.

(1) Provide Aggregates for Concrete that comply with **TABLE 1102-1**. Crushed Aggregates with less than 20% material retained on the 3/8" sieve must be produced from a source complying with these requirements prior to crushing. Fine Aggregates for Concrete have additional Quality Requirements stated in **subsection 1102.2e.(2).** Requirements for Lightweight Aggregates for Internally Cured Concrete are specified in **subsection 1102.2f.(2)(e).**

TABLE 1102-1: QUALITY REQUIREMENTS FOR CONCRETE AGGREGATES

Concrete Classification	Soundness (min.)	Wear (max.)	Absorption (max.)	Acid Insoluble[5] (min.)
Grade xx (AE)(SW)[1]	0.90	40	-	-
Grade xx (AE)(SA)[2]	0.90	40	2.0	-
Grade xx (AE)(AI)[3]	0.90	40	-	85
Grade xx (AE)(PB)[4]	0.90	40	3.0	-
Bridge Overlays	0.95	40	-	85
All Other Concrete	0.90	50	-	-

[1]Grade xx (AE)(SW) - Structural concrete with select coarse aggregate for wear.
[2]Grade xx (AE)(SA) - Structural concrete with select coarse aggregate for wear and absorption.
[3]Grade xx (AE)(AI) - Structural concrete with select coarse aggregate for wear and acid insolubility.
[4]Grade xx (AE)(PB) - Structural concrete with select aggregate for use in prestressed concrete beams.
[5]Acid Insoluble requirement does not apply to calcite cemented sandstone.

- Soundness (KTMR-21) requirements do not apply to aggregates having less than 10% material retained on the No. 4 sieve.
- Wear (AASHTO T 96) requirements do not apply to aggregates having less than 10% retained on the No. 8 sieve.
- Absorption KT-6 Procedure I for material retained on the No. 4 sieve. Apply the maximum absorption to the portion retained on the No. 4 sieve.

(2) All predominately siliceous aggregate must comply with the Wetting & Drying Test requirements, or be used with a Coarse Aggregate Sweetener, or will require Supplemental Cementitious Materials (SCM) to prevent Alkali Silica Reactions (ASR). Refer to **15-PS0166 TABLE 401-4** to determine the need for ASTM C 1567 Testing. When required, provide the results of mortar expansion tests of ASTM C 1567 using the project's mix design concrete materials at their designated percentages. Provide a mix with a maximum expansion of 0.10% at 16 days after casting. Provide the results to the Engineer at least 15 days before placement of concrete on the project.

Wetting & Drying Test of Siliceous Aggregate for Concrete (KTMR-23)

Concrete Modulus of Rupture:

- At 60 days, minimum .... 550 psi
- At 365 days, minimum .... 550 psi

Expansion:

- At 180 days, maximum 0.050%
- At 365 days, maximum 0.070%

Aggregates produced from the following general areas are exempt from the Wetting and Drying Test:

- Blue River Drainage Area.
- The Arkansas River from Sterling, west to the Colorado state line.
- The Neosho River from Emporia to the Oklahoma state line.

(3) Coarse Aggregate Sweetener. Types and proportions of aggregate sweeteners to be used with Mixed Aggregates are listed in **TABLE 1102-2**.

TABLE 1102-2: COARSE AGGREGATE SWEETENER	
Type of Coarse Aggregate Sweetener	**Proportion Required by Percent Weight**
Crushed Sandstone*	40 (minimum)
Crushed Limestone or Dolomite*	40 (minimum)
Siliceous Aggregates meeting **subsection 1102.2a.(2)**	40 (minimum)
Siliceous Aggregates not meeting **subsection 1102.2a.(2)** **	30 (maximum)

*Waive the minimum portion of Coarse Aggregate Sweetener for all intermediate and fine aggregates that comply with the wetting and drying requirements for Siliceous Aggregates. In this case, combine the intermediate, fine and coarse aggregate sweetener in proportions required to comply with the requirements of **subsection 1102.2a.(3)**

**To be used only with intermediate and fine aggregates that comply with the wetting and drying requirements of Siliceous Aggregates unless a Supplemental Cementitious Material is utilized.

(4) Deleterious Material. Maximum allowed deleterious substances by weight are:

- Clay lumps and friable particles (KT-7) 1.0%
- Coal (AASHTO T 113) 0.5%
- Shale or Shale-like material (KT-8) 0.5%
- Sticks (wet) (KT-35) 0.1%
- Total allowable deleterious 1.5%

b. Mixed Aggregates.

(1) Composition. Provide coarse, intermediate, and fine aggregates in a combination necessary to meet **subsection 1102.2b.(2)**. Use a proven optimization method such as ACI 302.1 or other method approved by the Engineer. Aggregates may be from a single source or combination of sources.

(2) Product Control.

(a) Gradations such as those shown in **TABLE 1102-3** have proven satisfactory in reducing water demand while providing good workability. Adjust mixture proportions whenever individual aggregate grading varies during the course of the work. Use the gradations shown in **TABLE 1102-3**, or other gradation approved by the Engineer.

Optimization is not required for Commercial Grade Concrete. The Engineer may waive the optimization requirements if the concrete meets all the requirements of **DIVISION 400, 15-PS0166 and 15-PS0167**.

Follow these guidelines:

1. Do not permit the percent retained on two adjacent sieve sizes to fall below 4%;

2. Do not allow the percent retained on three adjacent sieve sizes to fall below 8%; and

3. When the percent retained on each of two adjacent sieve sizes is less than 8%, the total percent retained on either of these sieves and the adjacent outside sieve should be at least 13%.

(for example, if both the No. 4 and No. 8 sieves have 6% retained on each, then:
1) the total retained on the 3/8 in. and No. 4 sieves should be at least 13%, and
2) the total retained on the No. 8 and No. 16 sieves should be at least 13%.)

TABLE 1102-3: ALLOWABLE GRADING FOR MIXED AGGREGATES FOR CONCRETE													
Type	Usage	Percent Retained - Square Mesh Sieves											
		1 ½"	1"	¾"	½"	⅜"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
MA-3	LC-HPC, and Optimized All Concrete		0	2-12	Note[1]	Note[1]	Note[1]	Note[1]	Note[2]	Note[2]	Note[2]	95-100[3]	98-100[4]
MA-4	Optimized All Concrete*	0	2-12	Note[1]	Note[1]	Note[1]	Note[1]	Note[1]	Note[2]	Note[2]	Note[2]	95-100[3]	98-100[4]
MA-5	Optimized Drilled Shafts		0	2-12	8 min	22-34		55-65		75 min		95-100	98-100
MA-6	Optimized for Bridge Overlays		0	0	2-12	Note[1]	Note[1]	Note[1]	Note[2]	Note[2]	Note[2]	95-100[3]	98-100[4]
MA-7	Contractor Design KDOT Approved	Proposed Grading that does not correspond to other limits in this table but meet the requirements for concrete in **DIVISION 400, 15-PS0166 and 15-PS0167**.											98-100

*MA-4 is allowable on structures if the maximum aggregate size for reinforcing steel spacing and minimum cover are adhered to.

[1]Retain a maximum of 22% (24% for MA-6) and a minimum of 6% of the material on each individual sieve.

[2]Retain a maximum of 15% and a minimum of 6% of the material on each individual sieve.

[3]Retain a maximum of 7% on the No. 100 sieve.

[4]Retain a maximum of 2% on the No. 200 sieve.

(b) Optimization Requirements for all Gradations except MA-7.

- Actual Workability must be within ± 5 of Target Workability.

Where: W_A = Actual Workability
W_T = Target Workability
CF = Coarseness Factor

1. Determine the Grading according to KT-2
2. Calculate the Coarseness Factor (CF) to the nearest whole number.

$$CF = \frac{+3/8\text{"Material\%Retained}}{+\#8\text{Material\%Retained}} x100$$

3. Calculate the Actual Workability (W_A) to the nearest whole number as the percent material passing the #8 sieve.

$$W_A = 100 - \%\text{ retained on \#8 sieve}$$

4. Calculate the Target Workability (W_T) to the nearest whole number where
For 517 lbs cement per cubic yard of concrete

$$W_T = 46.14 - (CF/6)$$

For each additional 1 lb of cement per cubic yard, subtract 2.5/94 from the Target Workability.

(c) Deleterious Substances. **Subsection 1102.2a.(4),** as applicable.

(d) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) for each aggregate according to the procedure listed Part V, Section 5.10.5-Fineness Modulus of Aggregates (Gradation Factor) before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

Provide a single point grading for the combined aggregates along with a plus/minus tolerance for each sieve. Use plus/minus tolerances to perform quality control checks and by the Engineer to perform aggregate grading verification testing. The tests may be performed on the combined materials or on individual aggregates, and then theoretically combined to determine compliance.

(3) Handling of All Aggregates.

(a) Segregation. Before acceptance testing, remix all aggregate segregated by transit or stockpiling.

(b) Stockpiling.

- Maintain separation between aggregates from different sources, with different gradings or with a significantly different specific gravity.
- Transport aggregate in a manner that promotes uniform grading.
- Do not use aggregates that have become mixed with earth or foreign material.
- Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.
- Provide additional stockpiling or binning in cases of high or non-uniform moisture.
- Stockpile accepted aggregates in layers 3 to 5 feet thick. Berm each layer so that aggregates do not "cone" down into lower layers.

c. Coarse Aggregates for Concrete.

(1) Composition. Provide coarse aggregate that is crushed or uncrushed gravel or crushed stone meeting the quality requirements of **subsection 1102.2a.** Consider limestone, calcite cemented sandstone, rhyolite, quartzite, basalt and granite as crushed stone.

Mixtures utilizing siliceous aggregate not meeting **subsection 1102.2a.(2)** will require supplemental cementitious materials to prevent Alkali Silica Reactions. Provide the results of mortar expansion tests of ASTM C 1567 using the project's mix design concrete materials at their designated percentages. Provide a mix with a maximum expansion of 0.10% at 16 days after casting. Provide the results to the Engineer at least 15 days before placement of concrete on the project.

(2) Product Control. Use gradations such as those in **TABLE 1102-4** which have been shown to work in Optimized Mixed Aggregates, or some other gradation approved by the Engineer that will provide a combined aggregate gradation meeting **subsection 1102.2b.**

TABLE 1102-4: ALLOWABLE GRADING FOR COARSE AGGREGATES

Type	Composition	Percent Retained - Square Mesh Sieves							
		1½"	1"	¾"	½"	⅜"	No. 4	No. 8	No. 200
SCA-1	Siliceous Gravel or Crushed Stone	0	0-10	14-35	-	50-75	-	95-100	98-100
SCA-2	Siliceous Gravel or Crushed Stone			0	0-35	30-70	75-100	95-100	98-100
SCA-4	Siliceous Gravel or Crushed Stone		0	0-20				95-100	98-100

d. Intermediate Aggregate for Concrete.

(1) Composition. Provide intermediate aggregate for mixed aggregates (IMA) that is crushed stone, natural occurring sand, or manufactured sand meeting the quality requirements of **subsection 1102.2a.**

(2) Product Control. Provide IMA grading when necessary to provide a combined aggregate gradation meeting **subsection 1102.2b.**

(3) Deleterious Substances. **Subsection 1102.2a.(4),** as applicable.

(4) Organic Impurities (AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

e. Fine Aggregates for Concrete.

(1) Composition.

(a) Type FA-A. Provide either singly or in combination natural occurring sand resulting from the disintegration of siliceous or calcareous rock, or manufactured sand produced by crushing predominately siliceous materials meeting the quality requirements of **subsection 1102.2a.** and **1102.2e.(2)**.

(b) Type FA-C. Provide crushed siliceous aggregate, steel slag, or chat that is free of dirt, clay, and foreign or organic material.

(2) Additional Quality Requirements for FA-A.

(a) Mortar strength and Organic Impurities. If the DME determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide fine aggregates that comply with the following:

- Mortar Strength (KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
  - At age 24 hours, minimum 100%*
  - At age 72 hours, minimum 100%*

  *Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.
- Organic Impurities (AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(b) Provide FA-C for Multi/Single-Layer and Slurry Polymer Concrete Overlay complying with **TABLE 1102-5**.

TABLE 1102-5: QUALITY REQUIREMENTS FOR MULTI/SINGLE-LAYER POLYMER CONCRETE OVERLAY		
Property	**Requirement**	**Test Method**
Soundness, minimum	0.92	KTMR-21
Wear, maximum	30%	AASHTO T 96
Acid Insoluble Residue, minimum	55%	KTMR-28
Uncompacted Voids Fine Aggregate, minimum	45	KT-50
Moisture Content, maximum	0.2%	KT-11

(3) Product Control.

(a) Size Requirements. Provide FA-C for Multi/Single-Layer and Slurry Polymer Concrete Overlay complying with **TABLE 1102-6**. Provide FA-A that comply with **TABLE 1102-6** or some other gradation approved by the Engineer that will provide a combined aggregate gradation meeting **subsection 1102.2.b.**

TABLE 1102-6: GRADING REQUIREMENTS FOR FINE AGGREGATES FOR CONCRETE								
Type	**Percent Retained-Square Mesh Sieves**							
	⅜"	**No. 4**	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**
FA-A	0	0-10	0-27	15-55	40-77	70-93	90-100	98-100
FA-C	0	0	25-70	95-100	98-100	98-100	98-100	98-100

(b) Deleterious Substances.

- Type FA-A: Maximum allowed deleterious substances by weight are:
  - Coal (AASHTO T 113).. 0.5%
  - Sticks (wet) (KT-35).. 0.1%
  - Sum of all deleterious 0.5%

f. Miscellaneous Aggregates for Concrete.

(1) Aggregates for Mortar Sand, Type FA-M.

(a) Composition. Provide aggregates for mortar sand, Type FA-M that is natural occurring sand.

(b) Quality.

- Mortar strength and Organic Impurities. If the DME determines it is necessary, because of unknown characteristics of new sources or changes in existing sources, provide aggregates for mortar sand, Type FA-M that comply with the following:
  - Mortar Strength (KTMR-26). Compressive strength when combined with Type III (high early strength) cement:
    - At age 24 hours, minimum 100%*

- At age 72 hours, minimum 100%*

* Compared to strengths of specimens of the same proportions, consistency, cement and standard 20-30 Ottawa sand.

- Organic Impurities (AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.

(c) Product Control.

- Size Requirements. Provide aggregates for mortar sand, Type FA-M that comply with **TABLE 1102-7**.

TABLE 1102-7: GRADING REQUIREMENTS FOR MORTAR SAND								
Type	**Percent Retained - Square Mesh Sieves**							**Gradation Factor**
	No. 4	**No. 8**	**No. 16**	**No. 30**	**No. 50**	**No. 100**	**No. 200**	
FA-M	0	0-2	0-30	20-50	50-75	90-100	98-100	1.70-2.50

Deleterious Substances. **Subsection 1102.2a.(4),** as applicable.

(2) Lightweight Aggregate.

(a) Composition. Provide a lightweight aggregate consisting of expanded shale, clay or slate produced from a uniform deposit of raw material.

(b) Quality.

- Soundness, minimum (KTMR-21) 0.90
- Loss on Ignition 5%

(c) Product Control.

- Size Requirements. Provide lightweight aggregate that complies with **TABLE 1102-8**.

TABLE 1102-8: GRADING REQUIREMENTS FOR LIGHTWEIGHT AGGREGATES								
Type	**Percent Retained - Square Mesh Sieves**							
	¾"	**½"**	**⅜"**	**No. 4**	**No. 8**	**No. 16**	**No. 50**	**No. 100**
Grade 1	0	0-10	30-60	85-100	95-100			
Grade 2		0-2	0-30	20-50	50-75	90-100		
Grade 3			0	0-15		20-60	65-90	75-100

- Deleterious Substances. **Section 1102.2a.(4)** as applicable.
- Organic Impurities (AASHTO T 21). The color of the supernatant liquid is equal to or lighter than the reference standard solution.
- Unit Weight (dry, loose weight) (max.) .... 1890 lbs/cu yd

(d) Modified Lightweight Aggregate. Lightweight aggregate produced from a uniform deposit of raw material combined with FA-A **subsection 1102.2c**. Provide lightweight aggregate that meets the Grade 1 or Grade 2 requirements in **TABLE 1102-8**.

(e) Lightweight Fine Aggregate for Internally Cured Concrete. Provide lightweight aggregate that meets the Grade 3 requirements in **TABLE 1102-8**. Internally cured concrete shall have lightweight fine aggregate proportions calculated per **15-PS0166 subsection 401.3g**. Submit lightweight fine aggregate properties for absorption, desorption, and specific gravity along with the concrete mix design to Construction and Materials for approval prior to use.

(f) Concrete Making Properties. Drying shrinkage of concrete specimens prepared with lightweight aggregate proportioned as shown in the Contract Documents cannot exceed 0.07%.

(g) Uniformity of Supply. Designate or determine the fineness modulus (grading factor) according to procedure listed in Part V, Section 5.10.5-Fineness Modulus of Aggregates (Gradation Factor) before delivery, or from the first 10 samples tested and accepted. Provide aggregate that is within ±0.20 of the average fineness modulus.

(h) Proportioning Materials. Submit mix designs for concrete using lightweight aggregate to Construction and Materials for approval prior to use.

(i) Lightweight Stockpile Management. Lightweight aggregate stockpiles shall be limited to 5 ft in height to promote even distribution of moisture and particle size. Use sprinklers to uniformly apply water to soak the stockpile(s) for a minimum of 72 hours or until a constant absorption is achieved. If steady rain of comparable intensity occurs, the sprinkler system may be turned off, if approved by the Engineer. Turning the stockpiles daily and immediately prior to sampling and batching concrete will be necessary to assure uniform pre-wetting and drainage and care should be taken to prevent segregation. Pre-wetting of lightweight aggregate shall stop 24 hours prior to batching to allow the stockpile to drain. As placement proceeds turn the pile as necessary to equalize the moisture content of the aggregate.

(j) Determining moisture contents for proportioning and batching. Turn the stockpile to equalize the moisture content and measure the absorption of the lightweight aggregate (to establish the amount of internal curing water) 24 hours prior to batching Turn the stockpile to equalize the moisture content and determine the aggregate surface moisture not more than 1 hour before batching concrete. In both cases, samples shall be obtained in accordance with KT-01.

1102.3 TEST METHODS

Test aggregates according to the applicable provisions of **SECTION 1115**.

1102.4 PREQUALIFICATION

Aggregates for concrete must be prequalified according to **subsection 1101.4**.

1102.5 BASIS OF ACCEPTANCE

The Engineer will accept aggregates for concrete based on the prequalification required by this specification and **subsection 1101.5**.

09-05-19 R (DAM)

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, EDITION 2015

For Low-Cracking High-Performance Concrete, delete SECTION 402 and replace with the following:

SECTION 402

STRUCTURAL LOW-CRACKING HIGH-PERFORMANCE CONCRETE

402.1 DESCRIPTION

Provide the grades of concrete specified in the Contract Documents.

This specification is specific to Structural Concrete. See **SECTION 401** for general concrete requirements.

402.2 MATERIALS

Provide materials that comply with the applicable requirements.

General Concrete... **15-PS0166**
Aggregate **15-PS0168**
Admixtures, and Plasticizers ....**DIVISION 1400**
Cement, Fly Ash, Silica Fume, Slag Cement and Blended Supplemental
Cementitious.. **DIVISION 2000**
Water ....**DIVISION 2400**

402.3 CONCRETE MIX DESIGN

a. General. Structural LC-HPC mix designs shall include internal curing. Design structural concrete mixes as specified in the Contract Documents.

b. Concrete Mix Design. Two options are available for mix design procedures. Use the procedures outlined in **15-PS0166** to design structural concrete mixes.

c. Concrete Strength Requirements. Design concrete to meet the strength requirements of **15-PS0166**.

d. Portland Cement, Blended Hydraulic Cement, and Individual and Blended Supplemental Cementitious Materials. Unless specified otherwise in the Contract Documents, select the type of portland cement, blended hydraulic cement and individual and blended supplemental cementitious materials according to **15-PS0166**.

e. Structural Concrete Specific Requirements. Design air-entrained concrete to meet the requirements shown in **TABLE 402-1** for the type of concrete specified in the Contract Documents.

TABLE 402-1: AIR ENTRAINED CONCRETE FOR BRIDGE DECKS				
Grade of Concrete	**lb of Cementitious per cu yd of Concrete**	**lb of Water per lb of Cementitious[1]**	**Designated Air Content Percent by Volume**	**Supplementary Cementitious Material (by weight of cementitious materials)**
LC-HPC	500 min. / 560 max	0.43 – 0.45	8.0 ± 1.5[2]	Max 30% Slag Cement and Max 2% Silica Fume
All other concrete	480 min.	0.45 max	**15-PS0166 subsection 401.3j**	See **15-PS0166 subsection 401.3c** or **401.3d**

[1]Limits of lb. of water per lb. of cementitious material as designed. Includes free water in aggregates, but excludes water of absorption of the aggregates.
[2]Use the middle of the specified range of 8.0 ± 1.5% for the design of the LC-HPC concrete. Maximum air content is 10%. Concrete with an air content less than 6.5% or greater than 10 % shall be rejected. Take immediate steps to reduce the air content whenever the air content exceeds 9.5%. The Engineer will sample concrete for tests at the discharge end of the conveyor, bucket, or end of the placement hose.

(1) Determine the air loss due to pumping operations once in the AM and once in the PM. Determine the difference between the air content from concrete sampled before the pump, and concrete sampled after pumping. Make adjustment to the mix to compensate for the pumping of the concrete.

(2) Concrete permeability requirements according to **TABLE 402-2**.

(3) For non-LC-HPC Concrete, test data from KT-73 tested at 28 days, KT-79 tested at 28 days, or AASHTO T-277 tested at 56 days. For LC-HPC Concrete, submit results from KT-79 tested at 28 days or AASHTO T-277 at 56 days. Provide test results on a minimum of 1 set of 3 cylinders for each mix, tested at the highest water to cementitious ratio that meets **15-PS0166 subsections 401.3e.** and **401.3j**. Submit accelerated cure procedures for the Engineer's approval. The use of supplemental cementitious materials may be necessary to meet permeability requirements. See **15-PS0166.**

(4) Use quality and gradation requirements for Structural Aggregates as listed in **15-PS0168**, Aggregates For Concrete Not Placed on Grade.

(5) Use MA-6 optimized gradation for Low Permeability Concrete for Bridge Overlays.

(6) ASTM C-1567 is required for some combinations of aggregate and supplementary cementitious materials (SCMs). See **15-PS0166 subsection 401.3k.** for requirements.

TABLE 402-2: PERMEABILITY REQUIREMENTS FOR STRUCTURAL CONCRETE			
	Volume of Permeable Voids, maximum	**Surface Resistivity, minimum**	**Rapid Chloride Permeability, maximum**
Use Low Permeability Concrete (LPC) for Bridge Overlays	9.5%	27.0 kΩ-cm	1000 Coulombs
Use Low-Cracking High Performance Concrete (LC-HPC) if specified in the Contract Documents.	Not Permitted	19.0 kΩ-cm	1500 Coulombs
Use Moderate Permeability Concrete (MPC) for specified Full Depth Bridge Decks.	11.0%	13.0 kΩ-cm	2000 Coulombs
Use Standard Permeability Concrete (SPC) for all other structural concrete not specified as LC-HPC, Low or Moderate Permeability.	12.5%	9.0 kΩ-cm	3000 Coulombs

f. Slump.

(1) Designate a slump for each concrete mix design that is required for satisfactory placement of the concrete application. Reject concrete with a slump that limits the workability or placement of the concrete.

(2) If the designated slump is 3 inches or less, the tolerance is ±3/4 inch, or limited by the maximum allowable slump for the individual type of construction.

(3) If the designated slump is greater than 3 inches the tolerance is ±25% of the designated slump.

(4) For drilled shafts the target slump just prior to being pumped into the drilled shaft is 9 inches. If the slump is less than 8 inches, redose the concrete with admixtures as permitted in **15-PS0166 subsection 401.3l**.

(5) Do not designate a slump in excess of 4 inches for LC-HPC and 5 inches for all other structural concrete.

09-05-19 R (DAM)

KANSAS DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION TO THE
STANDARD SPECIFICATIONS, EDITION 2015

For Low-Cracking High-Performance Concrete, delete SECTION 710 and replace with the following:

SECTION 710

LOW-CRACKING HIGH-PERFORMANCE CONCRETE-CONSTRUCTION

710.1 DESCRIPTION

Construct concrete structures according to the Contract Documents. When Bridge Deck Grooving is a bid item in the contract, perform the grooving as shown in the Contract Documents.

BID ITEMS	UNITS
Concrete (*) (**) (***) (****)	Cubic Yard
Bridge Deck Grooving	Square Yard

*Grade of Concrete
**AE (air-entrained), if specified
***Aggregate, if specified
****MPC (Moderate Permeability Concrete), if specified

710.2 MATERIALS

Provide materials that comply with the applicable requirements.

Concrete+	**15-PS0166 and 15-PS0167**
Aggregates for Concrete Not On Grade	**15-PS0168**
Concrete Curing Materials	**DIVISION 1400**
Joint Sealing Compounds	**DIVISION 1500**
Type B Preformed Expansion Joint Filler	**DIVISION 1500**
Preformed Elastomeric Compression Joint Seals	**DIVISION 1500**
Bridge Number Plates	**DIVISION 1600**

+ If Moderate Permeability Concrete (MPC) is not specified, the concrete shall meet the requirements for Standard Permeability Concrete.

710.3 CONSTRUCTION REQUIREMENTS

a. Qualification Batch for LC-HPC. For each bridge deck containing LC-HPC, produce a qualification batch of at least 6 cubic yards using concrete that is to be placed in the deck and complies with **15-PS0166 subsection 401.8b(2)**. A representative from the lightweight aggregate supplier must be present for the qualification batch. This representative shall have the necessary technical expertise to understand the properties of lightweight fine aggregate for internal curing in structural concrete.

The Engineer will be in attendance. Do not commence placement of concrete in the deck until approval is given by the Engineer. Approval to place concrete on the deck will be based on satisfactory compliance with the specification and will be given or denied within 24 hours of the qualification batch.

a. Falsework and Forms. Construct falsework and forms according to **SECTION 708**.

b. Handling and Placing Concrete. At a progress project meeting prior to placing concrete, discuss with the Engineer the method and equipment used for deck placement; include the equipment for controlling the evaporation rate and concrete temperature, procedures used to minimize the evaporation rate, method to place saturated burlap within the specified 15 minute limit, and plans to maintain a continuous supply of concrete throughout placement with an adequate quantity of concrete to complete the deck and filling diaphragms and end walls in advance of deck placement.

Fogging using hand-held equipment may be required by the Engineer during unanticipated delays in the placing, finishing or curing operations. If fogging is required by the Engineer, do not allow water to drip, flow or puddle on the concrete surface during fogging, placement of absorptive material, or at any time before the concrete has achieved final set.

When needed, produce a fog spray from nozzles that atomize the droplets and a system capable of keeping a large surface area damp without depositing excess water. Use high pressure equipment that generates a minimum of 1200 psi at 2.2 gpm, or low pressure equipment having nozzles capable of supplying a maximum flow rate of 1.6 gpm.

Use a method and sequence of placing concrete approved by the Engineer. Do not place concrete until the forms and reinforcing steel have been checked and approved. Before placing concrete, clean all forms of debris. Drive all foundation piling in any one pier or abutment before concrete is poured in any footing or column of that pier or abutment.

On bridges skewed greater than 10º, place concrete on the deck forms across the deck on the same skew as the bridge, unless approved otherwise by State Bridge Office (SBO). Operate the bridge deck finishing machine on the same skew as the bridge, unless approved otherwise by the SBO.

Maintain environmental conditions on the entire bridge deck such that the evaporation rate is less than 0.2 lb/sq ft/hr. This may require placing the deck at night, in the early morning or on another day. The evaporation rate (as determined in the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2) is a function of air temperature, concrete temperature, wind speed and humidity.

Just prior to and at least once per hour during placement of the concrete, the Engineer will measure and record the air temperature, concrete temperature, wind speed and humidity on the bridge deck. The Engineer will take the air temperature, wind and humidity measurements approximately 12 inches above the surface of the deck. With this information, the Engineer will determine the evaporation rate by using KDOT software or by using **FIGURE 710-1** (Figure 2.1.5 from the American Concrete Institute Manual of Concrete Practice 305R, Chapter 2).

When the evaporation rate is equal to or above 0.2 lb/ft^2/hr, take actions (such as cooling the concrete, installing wind breaks, sun screens etc.) to create and maintain an evaporation rate less than 0.2 lb/ft^2/hr on the entire bridge deck.

Place concrete to avoid segregation of the materials and displacement of the reinforcement. Do not deposit concrete in large quantities at any point in the forms, and then run or work the concrete along the forms.

Deposit the concrete in the forms in horizontal layers. Perform the work rapidly and continuously between predetermined planes. Vibrate through each plane.

Fill each part of the form by depositing the concrete as near to the final position as possible. If the chutes for placement of concrete are on steep slopes, equip them with baffle boards or assemble in short lengths that reverse the direction of movement. Do not drop concrete in the forms a distance of more than 5 feet, unless confined by clean, smooth, closed chutes or pipes.

Work the coarse aggregate back from the forms and around the reinforcement without displacing the bars. After initial set of the concrete, do not disturb the forms, or place any strain on the ends of projecting reinforcement.

If placing concrete by pumping, place the concrete in the pipeline to avoid contamination or separation of the concrete, or loss of air by fitting the pump with a concrete brake (e.g. french horn or bladder valve) at the end of the pump boom. Obtain sample concrete for slump and air test requirements at the discharge end of the piping.

Do not use chutes, troughs or pipes made of aluminum.

Uniformly consolidate the concrete without voids. In case voids are present after consolidation, the vibrator shall be reinserted near within one-half of the radius of action to remove the hole and fully reconsolidate the concrete.

Accomplish consolidation of the concrete on all span bridges that require finishing machines by means of a mechanical device on which internal (spud or tube type) concrete vibrators of the same type and size are mounted (**subsection 154.2**). Workers shall not walk in concrete that has been consolidated by this method. Vibrators and finishing equipment shall be as close to each other as possible to prevent workers from walking in the concrete after consolidation. Observe special requirements for vibrators in contact with epoxy coated reinforcing steel as specified in **subsection 154.2**. Provide stand-by vibrators for emergency use to avoid delays in case of failure.

Operate the mechanical device so vibrator insertions are made on a maximum spacing of 12-inch centers over the entire deck surface. Provide a uniform time per insertion of all vibrators of 3 to 15 seconds, or until the course aggregate settles below the surface of the concrete, unless otherwise designated by the Engineer. Provide positive control of vibrators using a timed light, buzzer, automatic control. The vibrators shall be removed slowly enough to allow the concrete to close in around the vibrator heads as they are removed so that no voids are left at the concrete surface. Do not drag the vibrators horizontally through the concrete.

Use hand held vibrators (**subsection 154.2**) in inaccessible and confined areas such as along hubguards. When required, supplement vibrating by hand spading with suitable tools to provide required consolidation.

Reconsolidate any voids left by workers by reinserting the vibrator within one-half of the radius of action.

Deposit concrete in water, only with approval from the Engineer. Do not place concrete in running water.

Use forms that are reasonably watertight to hold concrete deposited under water. Increase the minimum cement factor of the grade of concrete being deposited in water by 10%, obtaining approximately a 6-inch slump. Carefully deposit the concrete in place, in a compact mass, using a tremie pumped through piping, bottom-dumping bucket or other approved method that does not permit the concrete to fall through the water. Do not pump water from the inside of the foundation forms while concrete is being placed. Do not disturb the concrete after being deposited. If necessary to prevent flooding, place a seal of concrete through a closed chute or tremie, and allow it to set.

Continuously place concrete in any floor slab until complete, unless shown otherwise in the Contract Documents.

The method used for transporting concrete batches, materials or equipment over previously placed single pour (non-overlaid) floor slabs or floor units, or over units of structures of continuous design types is subject to approval by the Engineer.

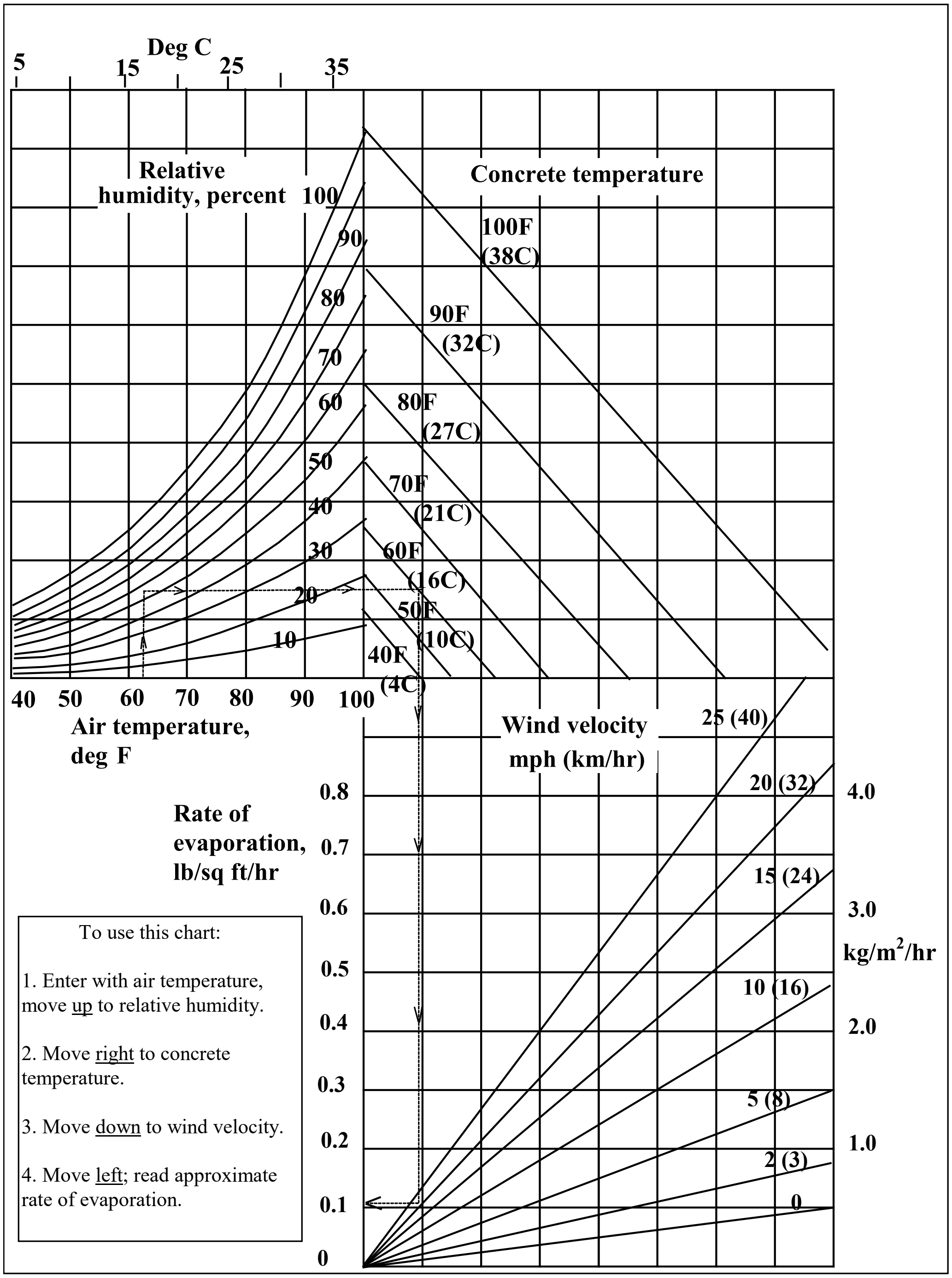
Do not operate bridge deck finishing equipment on previously placed concrete spans until:

- A minimum of 72 hours on structures that are fully supported with falsework;
- A minimum of 72 hours on structures with concrete girder spans with concrete decks; and
- A minimum of 96 hours on structures with steel girder spans with concrete decks.

The time delays begin after the day's pour has been completed.

Follow **TABLE 710-2** for load limitations after concrete placement. Prior to permitting approved traffic on the bridge deck, construct temporary bridge approaches and maintain them in a condition to prevent damage to the bridge ends.

FIGURE 710-1: STANDARD PRACTICE FOR CURING CONCRETE



Effect of concrete and air temperatures, relative humidity, and wind velocity on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use the chart, follow the four steps outlined above. When the evaporation rate exceeds 0.2 lb/ft^2/hr (1.0 kg/ m^2/hr), measures shall be taken to prevent excessive moisture loss from the surface of unhardened concrete; when the rate is less than 0.2 lb/ft^2/hr (1.0 kg/m^2/hr) such measures may be needed. When excessive moisture loss is not prevented, plastic cracking is likely to occur.

c. Construction Joints, Expansion Joints and End of Wearing Surface (EWS) Treatment. Locate the construction joints as shown in the Contract Documents. If construction joints are not shown in the Contract Documents, submit proposed locations for approval by the Engineer.

If the work of placing concrete is delayed and the concrete has taken its initial set, stop the placement, saw the nearest construction joint approved by the Engineer and remove all concrete beyond the construction joint. On post-tensioned structures construct a stepped joint as shown in the Contract Documents.

When the Contract Documents show a construction joint in the wall of the RCB 3 inches above the floor, the Contractor has the option of constructing the joint as shown on the Contract Documents, or constructing the joint level with the floor of the RCB. When the Contract Documents show a construction joint in the wall of the RFB 2 inches above the floor haunch, the Contractor has the option of constructing the joint as shown on the Contract Documents, or even with the top of the floor haunch of the RFB.

If dowels, reinforcing bars or other tie devices are not required by the Contract Documents, make a key in the construction joint. Construct keyed joints by embedding water-soaked beveled timbers of a size shown on the Contract Documents, into the soft concrete. Remove the timber when the concrete has set. When resuming work, thoroughly clean the surface of the concrete previously placed, and when required by the Engineer roughen the key with a steel tool. Before placing concrete against the keyed construction joint, the joint shall be cleaned of surface laitance, curing compound, and all other foreign material, use of abrasive blasting may be required to achieve the level of cleanliness required. Thoroughly wash the surface of the keyed joint with clean water, and allow the joint to dry to a saturated surface dry condition immediately prior to placing fresh concrete against the joint key.

(1) Bridges With Tied Approaches. When concrete is placed at the bridge EWS, embed 3 (½-inch by 8-inch) bolts to hold a header board for each traffic lane into the vertical surface of the EWS. Finish the surface of the EWS using an edging tool with a ¼ inch radius. Immediately after the vertical forms on the EWS are removed, protect the exposed EWS by bolting a wooden header (minimum dimension of 2 ⅝ inches by 7 ½ inches) to the exposed vertical surface of the EWS. Extend the header board the full width of the EWS, or use 1 section of header board for each lane of traffic. Shape the header board to comply with the crown of the bridge surface, and install it flush with the concrete wearing surface. Do not bend the reinforcing steel which will tie the approach slab to the EWS or damage the concrete at the EWS.

(2) Bridges Without Tied Approaches. Place the concrete for the approach slab, and at the end of the approach slab away from the EWS place bolts and attach a header board in the same manner required for bridges with tied approaches. If the Contractor needs to drive on the bridge before the approach slabs can be placed and cured construct a temporary bridge from the approach over the EWS capable of supporting the anticipated loads. The method of bridging must be approved by the Engineer.

d. Finishing. Finish all top surfaces, such as the top of retaining walls, curbs, abutments and rails, with a wooden float by tamping and floating, flushing the mortar to the surface and provide a uniform surface, free from pits or porous places. Trowel the surface producing a smooth surface, and brush lightly with a damp brush to remove the glazed surface.

Strike off bridge decks with a self-propelled finishing machine, which may be manually operated by winches to reach a temporary bulkhead when approved by the Engineer. The screed on the finish machine must be self-oscillating, and operate or finish from a position either on the skew or transverse to the bridge roadway centerline.

On decks skewed greater than 10º, operate the finishing machine on the same skew as the bridge, unless approved otherwise by the SBO. Before placing concrete, position the finisher throughout the proposed placement area allowing the Engineer to verify the reinforcing steel positioning.

Irregular sections may be finished by other methods approved by the Engineer. Reinforced concrete box bridges that will be under fill may be struck off by other approved methods.

Finish the surface using one or more metal pans or burlap drag or a combination mounted to the finishing equipment. Do not add water or other finishing aids to the surface of concrete.

Secure a smooth riding bridge deck, correcting surface variations exceeding ⅛ inch in 10 feet by use of an approved profiling device, or other method approved by the Engineer.

Straightedge decks that are to receive an overlay, leaving them with an acceptable float or machine pan finish.

For decks not receiving an overlay, and without the bid item Bridge Deck Grooving, finish the deck with the rough burlap drag.

For decks not receiving an overlay, and with the bid item Bridge Deck Grooving, see **subsection 710.3f.** for grooving requirements.

After finishing operations are complete on a section, workers shall not disturb that section of concrete.

Obtain reasonably true and even concrete surfaces, free from stone pockets, excessive depressions or projections on the surface. Strike off with a straightedge and float the concrete in bridge seats and walls flush with the finished top surface.

As soon as the forms are removed and the concrete is ready to hone, rub the concrete surfaces that are not in an acceptable condition, or are designated in the Contract Documents to be surface finished to a smooth and uniform texture with a carborundum brick and clean water. Remove the loose material formed on the surface, due to the rubbing with a carborundum brick as soon as it dries. The finished surface shall be free from all loose material. Do not use a neat cement wash.

Give handrails, handrail posts, the deck side, and the top and end of all curbs, except curbs of structures having the top of curb below the final shoulder elevation of the road, an acceptable troweled or floated finish. This includes the back of the inside rails of side by side structures, or any rails easily viewed by the traveling public.

Remove the forms as early as possible, and perform the float finish while the concrete is still green. Use mortar during the float finish operation to fill in air and water voids and supplement the float finish. Keep surfaces requiring a rubbed finish moist before and during the rubbing. Do not use a mortar coating after the concrete has cured.

Unless otherwise provided in the Contract Documents, all reasonably true and even surfaces, obtained by use of a form lining, which are of a uniform color, free from stone pockets, honeycomb, excessive depressions or projections beyond the surface, are considered as acceptable surfaces, and a rubbed surface finish is not required.

The Engineer may require the use of a dry carborundum brick for straightening moulding lines, removing fins or requiring a rubbed surface finish on all portions of the structure that do not present an acceptable surface even though a form lining is used.

e. Curing and Protection.

(1) General. Cover concrete surfaces according to **TABLE 710-1**. Cure all pedestrian walkway surfaces in the same manner as the bridge deck. The determination of the time requirement for curing commences after all the concrete for the placement is in place and finished. During cold weather, the specified time limits may be increased at the discretion of the Engineer, based upon the amount of protection and curing afforded the concrete.

Maintain a damp surface until the wet burlap is placed. Fully saturate burlap before placing on concrete surface. Soak the burlap for a minimum of 12 hours prior to placement on the deck. Re-wet the burlap if it has dried for more than one hour before it is applied to the surface of bridge deck. Apply 1 layer of wet burlap within 15 minutes of strike-off from the screed, followed by a second layer of wet burlap within 10 minutes. Do not allow the surface to dry after the strike-off, or at any time during the cure period. Do not mar concrete during placement of the wet burlap. Maintain the curing so that moisture is always present at the concrete surface.

Place and weight down the burlap so it will remain in intimate contact with the surface covered.

When an impermeable sheeting material is used, lap each unit 18 inches with the adjacent unit. Place and weight down the impermeable sheeting material so it will remain in intimate contact with the surface covered. When any burlap or impermeable sheeting material becomes perforated or torn, immediately repair it, or discard and replace it with acceptable material.

TABLE 710-1: MINIMUM CURE TIMES AND CURING MEDIUMS		
Type of Work	**Minimum Cure Time (days)**	**Curing Medium and Use**
Bridge decks (full-depth decks with multi-layer polymer overlays) Bridge subdecks (decks with overlays)	14 Wet	Wet burlap covered with white polyethylene sheeting during the 14-day period.
Bridge decks (full-depth decks with no overlay) Bridge Overlays	14 Wet Plus 7 Curing Membrane	Wet burlap covered with white polyethylene sheeting during the 14-day period. After the wet cure period, apply 2 coats of Type 2 white liquid membrane forming compound. Place the first coat within 30 minutes of removing the sheeting and burlap. Spray the second coat immediately after and at right angles to the first application. Protect the curing membrane against marring for a minimum of 7 days. The Engineer may limit work during this 7-day period.
Other unformed or exposed surfaces	7 Curing Membrane	Apply 2 coats of Type 2 white liquid membrane forming compound. Place the first coat immediately after completion of the concrete finish just as the surface water disappears. Spray the second coat immediately after and at right angles to the first application. Protect the curing membrane against marring for a minimum of 7 days. The Engineer may limit work during this 7-day period. Should the compound be subjected to continuous damage, the Engineer will require wet burlap, white polyethylene sheeting or other approved impermeable material to be applied at once for the remainder of the cure time.
Formed sides and ends of bridge wearing surfaces and bridge curbs Other formed surfaces	4 Formed	Formed surfaces will be considered completely cured upon the Engineer's permission to remove the forms, providing the forms have been in place for a minimum of 4 days. If forms are removed before the end of the 4-day cure period, cure the surface with an application of Type 1-D liquid membrane forming compound.

(2) Liquid Membrane Forming Compounds. Use spraying equipment capable of supplying a constant and uniform pressure to provide uniform distribution at the rates required. Agitate the liquid membrane forming compound continuously during application. The surface must be kept wet from the time it is finished until the liquid membrane forming compound is applied. Apply liquid membrane forming compound at a minimum rate per coat of 1 gallon per 200 square feet of concrete surface.

Give marred or otherwise damaged applications an additional coating.

If rain falls on the newly coated concrete before the film has dried sufficiently to resist damage from the rain, or if the film is damaged by any other means, apply a new coat of the membrane to the affected portion equal in curing value to the original application.

(3) Bridge Subdecks and Decks. Provide a work bridge to facilitate application of all curing materials. Maintain the curing so that moisture is always present at the concrete surface.

Maintain the wet burlap in a fully wet condition using misting hoses, self-propelled, machine-mounted fogging equipment with effective fogging area spanning the deck width, moving continuously across the entire burlap-covered surface, or other approved devices until the concrete has set sufficiently to allow foot traffic. At that time, place soaker hoses on the burlap, and supply running water continuously to maintain continuous saturation of all burlap material to the entire concrete surface. For bridge decks with superelevation, place a minimum of 1 soaker hose along the high edge of the deck to keep the entire deck wet during the curing period.

If the concrete surface temperature is above 90ºF, do not use polyethylene sheeting in direct sunshine during the day for the first 24 hours of the specified curing period (**TABLE 710-1**). White polyethylene sheeting may be used at night to maintain the required damp condition of the burlap. When polyethylene sheeting is used over the burlap at night during the first 24 hours and the concrete surface temperature is above 90ºF, place the polyethylene sheeting a maximum of 1 hour before sunset, and remove the polyethylene sheeting within 1 hour after sunrise. After the first 24 hours, the polyethylene sheeting may be left in place continuously for the remainder of the curing period provided the burlap is kept damp.

Construction loads on the new bridge subdeck, new one-course deck or any concrete overlay are subject to the limitations in **TABLE 710-2**. The use of supplemental cementitious materials will require additional time before specified loading is allowed.

TABLE 710-2: CONCRETE LOAD LIMITATIONS ON BRIDGE DECKS		
Days after concrete is placed	**Element**	**Allowable Loads**
1*	Subdeck, one-course deck or concrete overlay	Foot traffic only.
3*	One-course deck or concrete overlay	Work to place reinforcing steel or forms for the bridge rail or barrier.
7*, Δ	Concrete overlays	Legal Loads; Heavy stationary loads with the Engineer's approval.***
10 *, Δ (15)**, Δ	Subdeck, one-course deck or post-tensioned haunched slab bridges	Light truck traffic (gross vehicle weight less than 5 tons).****
14 *, Δ (21)**, Δ	Subdeck, one-course deck or post-tensioned haunched slab bridges	Legal Loads; Heavy stationary loads with the Engineer's approval.***Overlays on new decks.
28	Bridge decks	Overloads, only with the State Bridge Engineer's approval.***

*Maintain the specified wet cure at all times (**TABLE 710-1**).

** All haunched slab structures.

*** Submit the load information to the appropriate Engineer. Information that will be required is the weight of the material and the footprint of the load, or the axle (or truck) spacing and the width, the size of each tire (or track length and width) and their weight.

****An overlay may be placed using pumps or conveyors until legal loads are allowed on the bridge.

Δ Increase time period by 3 days when supplemental cementitious materials are used October 1 thru April 30.

(4) Surfaces Requiring Rubbed Finish. Apply Type 1-D liquid membrane-forming compound immediately after the surface is completed, and while the concrete is still damp.

(5) Cold Weather Curing. If concrete is placed in cold weather, comply with **15-PS0166**.

If concrete is placed and the ambient air temperature is expected to drop below 40ºF during the entire specified curing period or when the ambient air temperature is expected to drop more than 25ºF below the temperature of the concrete during the first 24 hours after placement, provide suitable measures such as straw, additional burlap or other suitable blanketing materials or housing and artificial heat to maintain the concrete temperature between 40 and 90ºF as measured on the surface of the concrete. Keep the surface of the concrete moist by the use of an approved moisture barrier such as wet burlap or polyethylene sheeting or both as defined in **TABLE 710-1**. Maintain the moisture barrier in intimate contact with the concrete during the entire specified curing period. For every day the ambient air temperature is below 40ºF, an additional day of curing with a minimum ambient air temperature of 50ºF will be required. After completion of the required curing period, remove the curing and protection so that the temperature of the LC-HPC during the first 24 hours does not fall more than 25°F.

(6) If concrete is placed in cofferdams and subsequently flooded with ground water, the specified curing conditions are waived providing the surface of the water does not freeze.

f. Grinding and Grooving. Correct surface variations exceeding ⅛ inch in 10 feet by use of an approved profiling device, or other methods approved by the Engineer after the curing period. Perform grinding on hardened concrete after the specified curing membrane period (**TABLE 710-1**) to achieve a plane surface and grooving of the final wearing surface as shown in the Contract Documents. Apply the corrective measure to the full width of the lane. The corrected areas shall have uniform texture and appearance. The beginning and ending of the corrected areas shall be squared normal to centerline of the paved surface.

If at least 25% of the traveled way of the deck needs ground to correct surface variations, grind the entire deck.

Use a self-propelled grinding machine with diamond blades mounted on a multi-blade arbor. Avoid using equipment that causes excessive ravels, aggregate fractures or spalls. Remove from the project and properly dispose of the material. Do not allow the grinding slurry to flow across lanes being used by traffic, onto shoulder slopes, into streams, lakes, ponds or other bodies of water, or gutters or other drainage facilities. Do not place grinding slurry on foreslopes.

After any required grinding is complete and after the specified curing membrane period (**TABLE 710-1**), give the surface a suitable texture by transverse grooving. Use diamond blades mounted on a self-propelled machine that is designed for texturing pavement. Transverse grooving of the finished surface may be done with equipment that is not self-propelled providing that the Contractor can show proficiency with the equipment. Use equipment that does not cause strain, excessive raveling, aggregate fracture, spalls, disturbance of the transverse or longitudinal joint, or damage to the existing concrete surface. Make the grooving approximately $^{3}/_{16}$ inch in width at ¾ inch centers and the groove depth approximately ⅛ inch. Terminate the transverse bridge deck grooving approximately 2 feet in from the base of the rail, and 1 foot from any deck drains or other appurtenances.

If after corrective measures are made, more than ½ inch of the deck was ground at any location, the Engineer may require a multi-layer polymer concrete overlay over the whole deck, according to **SECTION 729**, at no additional cost to KDOT.

g. Removal of Forms and Falsework. Do not remove forms and falsework without the Engineer's approval. During cold weather, the specified time limits may be increased at the discretion of the Engineer, based upon the amount of protection and curing afforded the concrete.

Do not remove forms and falsework until the minimum amount of time required for strength gain has elapsed regardless if the concrete is fully cured per **TABLE 710-1**.

If forms are removed before expiration of the cure period, maintain the cure as provided in **DIVISION 700**. Remove forms on handrails, ornamental work and other vertical surfaces that require a rubbed finish as soon as the concrete has hardened sufficiently that it shall not be damaged.

Under normal conditions, the Engineer will allow removal of forms and falsework according to **TABLE 710-3**. The determination of the time requirement for the removal of forms commences after all the concrete for the placement is in place and finished. If high early strength concrete is used, the specified time limits may be decreased as determined by the Engineer, and agreed upon before placing the concrete.

TABLE 710-3: MINIMUM STRENGTH GAIN TIME BEFORE REMOVAL OF FORMS & FALSEWORK (DAYS)

Type of Work	Span Length (feet)						
	Less than 10	10 or less	Greater than 10	10 to 20	20 + to 30	Greater than 20	Greater than 30
Cantilevered Piers - Formwork (supporting the pier beam) supported on column		7^{Δ} [4]*	10^{Δ} [6]*				
Column Bent Piers - Falsework supporting pier beam**	4^{Δ}			7^{Δ} [4]*		10^{Δ} [6]*	
Forms and Falsework under slabs, beams, girders, arches and brackets***	4^{Δ}			7^{Δ} $[4]^{+}$	10^{Δ} $[6]^{+}$		15^{Δ} $[10]^{+}$
RCB and RFB top slabs not re-shored		7^{Δ} $[4]^{+}$		7^{Δ} $[4]^{+}$		10^{Δ} $[6]^{+}$	

Type of Work	Time (Days)
Walls, Wing Walls and vertical sides of RCB and RFB structures Do not backfill according to **SECTION 204**, until 3 days after forms are removed.	4^{Δ} [3]*
Footing Supported on Piles - minimum cure before erecting forms and reinforcing steel for columns	4^{Δ} [2]*
Spread Footing founded in rock – minimum before erecting forms and reinforcing steel for columns	2^{Δ}
Footing supported on piles - minimum cure before erecting forms and reinforcing steel for columns	4^{Δ} [2]*
Columns for cantilevered piers - 1. minimum before supporting forms and reinforcing steel for the pier beam on the column. 2. minimum before placing concrete for the pier beam	4^{Δ} $[2]^{+}$ 7^{Δ} $[4]^{+}$
Columns for bent piers - 1. minimum before erecting formwork and reinforcing steel for the pier beam 2. minimum before placing concrete for the pier beam	2^{Δ} 4^{Δ} [2]*
Drilled shafts - minimum before erecting forms and reinforcing steel for the columns	2^{Δ}
Floors for RCB and RFB structures on rock or a seal course - minimum before erecting forms and reinforcing steel	2^{Δ}
Floors for RCB and RFB structures on soil or foundation stabilization - minimum before erecting forms and reinforcing steel	4^{Δ} [2]*
Do not remove forms or falsework from post tensioned elements until all applied post tensioning forces are transferred.	NA

* Contractors may reduce the time required before form removal to the number of days shown in brackets, provided the concrete is shown to have attained a minimum strength of 65% of the specified f'_c. To accomplish this, prepare the necessary cylinders, obtain the services of an approved laboratory to break them at the appropriate time and provide a report to the Engineer. Field cure the cylinders alongside and under the same curing conditions, as the concrete they represent.

** Do not set girders or beams on the pier beams until the falsework under the pier beams is removed.

*** Remove the formwork from subdecks or one-course decks within 6 weeks after the deck has been placed.

$^{+}$ Contractors may reduce the time required before form removal to the number of days shown in brackets, provided the concrete is shown to have attained a minimum strength of 75% of the specified f'_c. To accomplish this, prepare the necessary cylinders, obtain the services of an approved laboratory to break them at the appropriate time and provide a report to the Engineer. Field cure the cylinders alongside and under the same curing conditions, as the concrete they represent.

$^{\Delta}$ Increase the time period 3 days when supplemental cementitious materials are used October 1 thru April 30.

Reshoring of RCB and RFB (classified as culverts or bridges) top slab will be permitted if the Contractor uses traveling forms or to reduce the minimum time shown in **TABLE 710-2**. At the Preconstruction Conference, submit calculations, sealed by a Professional Engineer, to the Engineer that show that the concrete tensile stress is below $0.23 \sqrt{f'_c}$ (ksi) and the shoring has sufficient capacity.

In determining the time for the removal of forms, give consideration to the location and character of the structure, weather and other conditions influencing the setting of concrete. If forms are removed before expiration of the cure period, maintain the cure as provided in **DIVISION 700**.

For additional requirements regarding forms and falsework, see **SECTION 708**.

h. Bridge Number Marking. When designated in the Contract Documents, place bridge numbers on bridges by the use of plates recessed in the concrete during construction, using plates constructed as shown in the Contract Documents. The date placed on the plates is the year in which the structure is completed.

710.4 MEASUREMENT AND PAYMENT

The Engineer will measure the various grades of concrete placed in the structure by the cubic yard. No deductions are made for reinforcing steel and pile heads extending into the concrete. When shown as a bid item in the contract, the Engineer will measure for payment bridge deck grooving by the square yard.

Payment for the various grades of "Concrete" and "Bridge Deck Grooving" at the contract unit prices is full compensation for the specified work.

09-05-19 R (DAM)

APPENDIX F: TRIP TICKETS AND PLASTIC CONCRETE TEST RESULTS FOR KDOT IC-LC-HPC DECK PLACEMENTS

Table F.1: Trip tickets and plastic concrete properties for KS-IC-LC-HPC-1

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)								*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Silica Fume	Water	Coarse Agg. A	Coarse Agg. B	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	355	159	16	228	1194	285	1104	303	0.43	23.9	4¼[b]	68[b]	6.4[b]
2	354	159	16	229	1197	289	1102	310	0.43	24.0	-	-	-
3	354	159	16	233	1188	289	1101	306	0.44	24.2	-	-	-
4	354	159	16	233	1183	289	1101	304	0.44	24.2	-	-	-
5	354	160	16	232	1183	287	1103	304	0.44	24.2	-	-	-
6	354	160	16	234	1189	286	1101	304	0.44	24.3	-	-	-
7	354	158	16	233	1191	289	1101	304	0.44	24.2	-	-	-
8	354	158	16	234	1185	289	1101	306	0.44	24.2	-	-	-
9	354	159	16	232	1194	287	1103	304	0.44	24.2	4[c]	70[c]	6.2[c]
10	354	161	16	234	1187	287	1103	304	0.44	24.3	-	-	-
11	354	159	16	233	1183	287	1101	304	0.44	24.2	-	-	-
12	354	160	16	234	1191	291	1101	304	0.44	24.3	-	-	-
13	354	159	16	233	1187	289	1101	304	0.44	24.2	-	-	-
14	355	162	16	233	1194	289	1101	304	0.44	24.3	5	66	5.8
15	354	159	16	233	1182	287	1103	304	0.44	24.2	-	-	-
16	354	161	16	233	1186	287	1101	304	0.44	24.3	-	-	-
17	354	161	16	234	1194	289	1101	306	0.44	24.3	-	-	-
18	354	158	16	233	1192	289	1101	304	0.44	24.2	-	-	-
19	355	159	16	233	1186	291	1101	304	0.44	24.2	-	-	-
20	354	158	16	234	1190	289	1101	304	0.44	24.2	-	-	-
21	356	159	16	234	1186	293	1101	306	0.44	24.3	-	-	-
22	354	161	16	233	1184	289	1103	304	0.44	24.2			
23	358	160	16	233	1194	293	1101	306	0.44	24.3	5[d]	68[d]	5.5[d]
24	354	159	16	233	1194	293	1101	308	0.44	24.2	-	-	-
25	355	159	16	233	1184	291	1101	304	0.44	24.2	-	-	-
26	355	160	16	233	1186	289	1101	304	0.44	24.2	-	-	-
27	354	161	16	233	1182	289	1101	304	0.44	24.2	-	-	-
28	355	158	16	234	1186	289	1101	312	0.44	24.3	-	-	-
29	354	159	16	233	1188	289	1101	304	0.44	24.2	-	-	-
30	355	158	16	233	1188	291	1101	304	0.44	24.2	-	-	-
31	354	158	16	233	1182	289	1101	304	0.44	24.2	4¾	69	6.3
32	354	159	16	233	1196	289	1101	304	0.44	24.2	-	-	-
33	356	159	16	233	1186	293	1101	304	0.44	24.2	-	-	-
34	355	158	16	234	1186	289	1101	304	0.44	24.3	-	-	-
35	354	158	16	233	1190	291	1101	303	0.44	24.2	-	-	-

[a] Values after pumping; [b] 4 in. 60 °F, and 6.8%, respectively, before pumping; [c] 4 in., 62 °F, and 6.8%, respectively, before pumping; [d] 5 in., 62 °F, and 6.5%, respectively, before pumping;
Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.1: (con't) Trip tickets and plastic concrete properties for KS-IC-LC-HPC-1

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)								*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Silica Fume	Water	Coarse Agg.		Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
36	354	158	16	233	1196	293	1101	303	0.44	24.2	5½	68	5.7
37	354	159	16	234	1184	291	1101	303	0.44	24.3	-	-	-
38	355	158	16	233	1194	293	1101	303	0.44	24.2	-	-	-
39	355	158	16	233	1188	289	1101	303	0.44	24.2	-[b]	-[b]	-[b]
40	355	158	16	233	1182	289	1101	303	0.44	24.2	-	-	-
41	354	158	16	233	1190	291	1101	303	0.44	24.2	-	-	-
42	355	159	16	233	1196	289	1101	303	0.44	24.3	-	-	-
43	354	158	16	233	1188	289	1101	303	0.44	24.2	-	-	-
44	356	161	16	234	1192	289	1103	309	0.44	24.3	5½	70	6.7
45	354	157	16	233	1184	289	1101	303	0.44	24.2	5	68	5.7
46	354	159	16	233	1182	293	1101	303	0.44	24.2	-	-	-
47	354	162	16	233	1188	293	1101	303	0.44	24.3	-	-	-
48	354	163	16	233	1190	289	1101	303	0.44	24.3	-	-	-
49	354	162	16	233	1188	291	1103	303	0.44	24.3	-	-	-
50	354	159	16	233	1188	291	1103	303	0.44	24.2	-	-	-
51	354	161	16	234	1192	291	1101	303	0.44	24.3	-	-	-
52	355	158	16	233	1194	293	1101	303	0.44	24.2	-	-	-
53	354	161	16	233	1190	291	1101	303	0.44	24.3	5	68	6.2
54	355	158	16	233	1188	291	1101	303	0.44	24.2	-	-	-
55	362	162	16	232	1188	289	1101	303	0.43	24.4	-	-	-
56	355	160	16	234	1190	291	1101	303	0.44	24.3	-	-	-
57	354	159	16	232	1192	289	1101	303	0.44	24.2	-	-	-
58	356	158	16	233	1182	291	1101	303	0.44	24.2	-	-	-
59	355	158	16	233	1184	289	1101	303	0.44	24.2	-	-	-
60	354	158	16	233	1186	293	1101	303	0.44	24.2	7	70	7.6
61	354	159	16	233	1190	291	1101	311	0.44	24.3	-	-	-
62	354	159	16	234	1188	298	1103	303	0.44	24.3	-	-	-

[a] Values after pumping; [b] 6 in. 62 °F, and 6.3%, respectively, before pumping;
Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.2: Trip tickets and plastic concrete properties for KS-IC-LC-HPC-2-P1

Truck	Material Proportions, SSD/PSD Basis (lb/yd³)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[b]		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1[a]	378	162	214	1689	840	281	0.40	23.1	1½	61	4.2
2	377	161	215	1680	843	283	0.40	23.1	10½[c]	61	9.9
3	378	161	213	1680	841	278	0.40	23.1	-	-	-
4	377	161	214	1680	839	276	0.40	23.1	4[d]	60	6.8[d]
5	378	162	214	1682	841	276	0.40	23.1	-	-	-
6	377	162	230	1680	839	276	0.43	24.1	-[e]	-	-[e]
7	378	162	231	1680	839	286	0.43	24.1	-	-	-
8	377	163	232	1680	839	276	0.43	24.2	-	65	8.7
9	377	161	229	1685	842	277	0.43	24.0	7¼	65	8.8
10	380	163	231	1681	842	280	0.43	24.2	-	68	9.2
11	378	161	231	1680	847	282	0.43	24.1	-	-	-
12	378	161	231	1680	839	280	0.43	24.1	-	67	8.3
13	378	161	231	1684	841	280	0.43	24.1	-	-	-
14	377	162	230	1680	839	276	0.43	24.1	-	-	-

[a] Rejected; [b] Before pumping values; [c] First test showed 4¼ in.; [d] 3 in. and 8%, respectively, after pumping; [e] 3½ in. and 6.2%, respectively, after pumping;
Note: 1 lb/yd³ = 0.593 kg/m³; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.3: Trip tickets and plastic concrete properties for KS-IC-LC-HPC-2-P2

Truck	Material Proportions, SSD/PSD Basis (lb/yd³)						*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[b]		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	378	161	214	1688	841	276	0.40	23.1	6½	-[b]	-[b]
2	377	162	214	1675	838	276	0.40	23.1	9	54	8.25
3	377	162	218	1693	838	280	0.41	23.4	10¼	60	9.25
4	377	161	233	1682	847	276	0.43	24.2	-	-	-
5	378	161	231	1680	845	276	0.43	24.1	-[c]	-[c]	-[c]
6	380	161	230	1680	838	276	0.42	24.1	-	-	-
7	378	174	231	1682	838	276	0.42	24.4	4½	60	-
8	379	161	231	1675	839	282	0.43	24.1	6¾	60	6.0
9	377	161	230	1675	841	285	0.43	24.1	-	-	-
10	377	161	233	1675	838	280	0.43	24.2	-	70	8.5
11	378	163	228	1682	838	282	0.42	24.0	-[d]	-[d]	-[d]
12	377	161	231	1678	841	280	0.43	24.1	-	65	8.6
13	378	162	231	1682	841	276	0.43	24.1	-	65	9.5
14	378	164	232	1678	838	280	0.43	24.2	-	65	8.0

[a] Before pumping values; [b] 71°F and 7.1%, respectively, after pumping; [c] 7 in., 68°F, and 10.0%, respectively, after pumping; [d] 3¼ in., 68°F, and 6.1%, respectively, after pumping;
Note: 1 lb/yd³ = 0.593 kg/m³; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.3: (con't)Trip tickets and plastic concrete properties for KS-IC-LC-HPC-2-P2

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)						w/c Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Water	Coarse Agg.	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
15	378	163	231	1678	849	276	0.43	24.2	-	67	9.6
16	377	162	230	1680	841	276	0.43	24.1	-	-	-
17	377	162	230	1681	837	278	0.43	24.1	-	-	-
18	378	163	230	1682	838	278	0.43	24.1	-[b]	-[b]	-[b]
19	377	163	232	1682	838	282	0.43	24.2	-	-	-
20	377	162	230	1684	841	276	0.43	24.1	5½	65	6.1
21	377	162	231	1680	841	276	0.43	24.1	-	61	-
22	377	162	231	1675	838	278	0.43	24.1	-	-	-
23	378	162	231	1678	849	276	0.43	24.2	-[c]	-[c]	-[c]
24	377	163	230	1675	838	280	0.43	24.1	-	-	7.3
25	379	161	231	1680	843	287	0.43	24.2	-	67	-
26	377	162	231	1681	839	280	0.43	24.1	-	67	7.4
27	380	162	231	1680	843	276	0.43	24.2	-	69	7.9
28	380	162	230	1680	838	276	0.42	24.1	-[d]	-[d]	-[d]
29	378	161	231	1680	838	278	0.43	24.1	-	-	-
30	378	161	232	1686	838	287	0.43	24.2	-	-	-
31	378	162	229	1682	838	278	0.42	24.0	-	-	-
32	377	162	231	1682	838	280	0.43	24.1	-	-	-
33	378	162	230	1680	838	280	0.43	24.1	-	72	10.0
34	379	161	231	1678	843	276	0.43	24.1	-	71	7.3
35	379	163	232	1677	839	286	0.43	24.2	-	-	-
36	378	162	230	1680	838	276	0.43	24.1	-	72	8.0
37	377	161	228	1678	838	276	0.42	23.9	-	-	-
38	378	163	231	1686	841	278	0.43	24.2	-	-[e]	-[e]
39	380	161	230	1682	841	285	0.43	24.1	-	70	6.2
40	378	162	230	1682	847	280	0.43	24.1	-	-	-
41	380	161	230	1675	837	278	0.43	24.1	-	-	-
42	378	162	231	1675	843	285	0.43	24.2	-	-	-

[a] Before pumping values; [b] 4 in., 71°F, and 9.1%, respectively, after pumping; [c] 4½ in., 72°F, and 8.0%, respectively, after pumping; [d] 7¼ in., 73°F, and 6.9%, respectively, after pumping; [e] 5 in., 75°F, and 11.0%, respectively, after pumping;
Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.4: Trip tickets and plastic concrete properties for KS-IC-LC-HPC-3

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)								*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Silica Fume	Water	Coarse Agg. A	Coarse Agg. B	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
1	360	160	10	233	1298	275	1096	160	0.44	24.1	6	71	6.2
2	361	160	10	235	1303	275	1096	162	0.44	24.2	-	-	-
3	360	159	10	235	1309	277	1099	160	0.44	24.2	6	74	7.0
4	361	159	10	235	1311	275	1097	160	0.44	24.2	-	-	-
5	361	160	10	235	1305	279	1097	160	0.44	24.2	-	-	-
6	360	160	10	235	1296	281	1101	160	0.44	24.2	-	-	-
7	360	160	10	233	1294	277	1095	162	0.44	24.1	5½	76	7.8
8	361	159	10	236	1296	279	1098	161	0.44	24.2	-	-	-
9	360	165	10	235	1303	277	1098	162	0.44	24.3	-	-	-
10	361	160	10	235	1301	277	1097	160	0.44	24.2	-	-	-
11	360	159	10	236	1294	275	1096	160	0.45	24.2	5	76	6.4
12	360	160	10	236	1307	275	1099	160	0.45	24.3	-	-	-
13	362	159	10	235	1296	275	1097	160	0.44	24.2	-	-	-
14	360	162	10	235	1296	277	1095	160	0.44	24.3	-	-	-
15	361	163	10	235	1301	275	1097	160	0.44	24.2	-	-	-
16	361	160	10	235	1296	279	1096	160	0.44	24.2	6	76	6.4
17	361	163	10	234	1303	279	1096	160	0.44	24.2	-	-	-
18	361	159	10	235	1296	277	1095	160	0.44	24.2	-	-	-
19	361	160	10	234	1308	277	1096	164	0.44	24.2	-	-	-
20	361	161	10	235	1308	275	1097	160	0.44	24.3	-	-	-
21	361	159	10	236	1308	279	1099	181	0.45	24.3	6	78	8.0
22	361	161	10	236	1302	281	1096	160	0.44	24.3	-	-	-
23	361	159	10	234	1304	279	1096	170	0.44	24.2	-	-	-
24	361	159	10	234	1298	279	1096	164	0.44	24.2	-	-	-
25	360	159	10	235	1304	277	1095	160	0.44	24.2	-	-	-
26	360	159	10	235	1304	279	1097	160	0.44	24.2	-	-	-
27	361	159	10	243	1306	277	1095	164	0.46	24.7	-	-	-
28	360	159	10	235	1306	275	1098	166	0.44	24.2	-	-	-
29	362	160	10	244	1302	277	1096	164	0.46	24.8	5	76	6.4
30	360	161	10	234	1308	277	1096	164	0.44	24.2	-	-	-
31	361	159	10	236	1304	275	1095	177	0.45	24.3	-	-	-
32	361	159	10	236	1308	277	1097	168	0.45	24.2	-	-	-
33	361	159	10	235	1298	293	1096	160	0.44	24.2	-	-	-
34	360	159	10	198	1314	293	1096	160	0.37	22.0	5	75	7.6
35	361	159	10	219	1298	289	1095	160	0.41	23.2	-	-	-

[a] Values after pumping

Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.4: (con't) Trip tickets and plastic concrete properties for KS-IC-LC-HPC-3

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)								*w/c* Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Silica Fume	Water	Coarse Agg. A	Coarse Agg. B	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
36	360	159	10	221	1308	289	1096	160	0.42	23.3	-	-	-
37	361	159	10	223	1300	277	1096	161	0.42	23.5	-	-	-
38	361	159	10	220	1305	275	1096	161	0.41	23.3	5	72	7.2
39	360	159	10	220	1303	275	1096	161	0.42	23.3	-	-	-
40	361	159	10	220	1305	277	1096	161	0.41	23.3	-	-	-
41	361	159	10	221	1301	275	1097	168	0.42	23.4	-	-	-
42	360	159	10	220	1309	275	1097	161	0.41	23.3	-	-	-
43	360	159	10	220	1305	275	1097	161	0.42	23.3	-	-	-
44	361	160	10	221	1303	283	1095	176	0.42	23.4	-	-	-
45	361	159	10	220	1303	281	1097	161	0.42	23.3	5¼	75	6.8
46	361	159	10	220	1309	279	1096	161	0.41	23.3	-	-	-
47	360	159	10	220	1317	275	1096	161	0.42	23.3	-	-	-
48	360	159	10	221	1311	275	1099	162	0.42	23.3	-	-	-
49	361	159	10	219	1301	275	1098	160	0.41	23.2	-	-	-
50	360	159	10	220	1309	275	1096	160	0.41	23.3	5	78	8
51	361	159	10	220	1309	277	1096	160	0.41	23.3	-	-	-
52	361	159	10	221	1303	279	1098	160	0.42	23.4	-	-	-
53	361	159	10	220	1305	281	1099	160	0.41	23.3	-	-	-
54	360	159	10	220	1311	275	1096	160	0.42	23.3	-	-	-
55	361	159	10	220	1301	275	1096	160	0.41	23.3	5	81	6.5
56	361	159	10	220	1301	285	1097	160	0.42	23.3	-	-	-
57	360	159	10	219	1309	279	1098	160	0.41	23.2	-	-	-
58	361	159	10	220	1315	275	1096	162	0.42	23.3	-	-	-
59	360	159	10	220	1313	275	1096	160	0.42	23.3	9	76	6.5
60	360	159	10	220	1301	277	1095	162	0.42	23.3	-	-	-
61	360	159	10	244	1309	275	1096	166	0.46	24.7	-	-	-
62	361	159	10	243	1305	277	1097	160	0.46	24.6	5½	78	7.4
63	361	159	10	244	1301	281	1097	164	0.46	24.7	-	-	-
64	361	159	10	245	1301	275	1097	168	0.46	24.8	-	-	-
65	361	159	10	242	1301	281	1097	160	0.46	24.6	-	-	-
66	360	159	10	243	1303	277	1095	166	0.46	24.7	-	-	-
67	360	159	10	243	1311	275	1096	160	0.46	24.6	-	-	-
68	360	159	10	242	1303	279	1096	170	0.46	24.6	-	-	-
69	361	159	10	241	1309	281	1097	162	0.46	24.6	-	-	-
70	361	159	10	242	1309	277	1096	162	0.46	24.6	6½	80	7.8

[a] Values after pumping

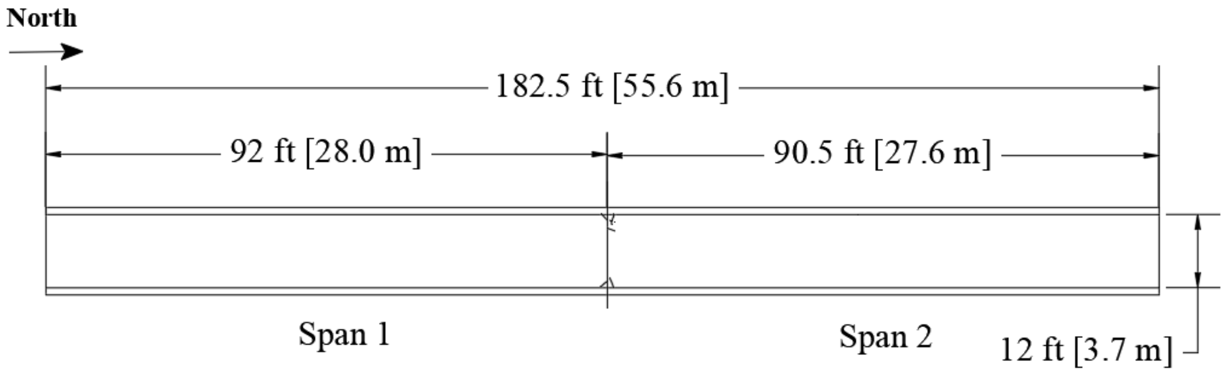
Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

Table F.4: (con't) Trip tickets and plastic concrete properties for KS-IC-LC-HPC-3

Truck	Material Proportions, SSD/PSD Basis (lb/yd^3)								w/c Ratio	Paste Content (%)	Plastic Concrete Properties[a]		
	Type I/II Cement	Slag Cement	Silica Fume	Water	Coarse Agg. A	Coarse Agg. B	Fine Agg.	LWA			Slump (in.)	Temp. (°F)	Air (%)
71	361	159	10	243	1311	279	1096	164	0.46	24.7	-	-	-
72	361	159	10	237	1303	279	1097	162	0.45	24.4	-	-	-
73	361	159	10	237	1301	283	1098	162	0.45	24.3	-	-	-
74	361	159	10	238	1311	281	1096	160	0.45	24.4	-	-	-
75	361	159	10	238	1311	279	1096	160	0.45	24.4	6	78	7.2
76	362	159	10	239	1307	277	1096	160	0.45	24.4	-	-	-
77	361	159	10	239	1303	275	1096	160	0.45	24.4	-	-	-
78	361	159	10	224	1311	277	1096	162	0.42	23.5	-	-	-
79	361	159	10	234	1303	275	1096	176	0.44	24.1	-	-	-
80	360	159	10	233	1313	275	1096	164	0.44	24.1	-	-	-
81	360	159	10	234	1305	277	1096	162	0.44	24.1	-	-	-
82	361	159	10	233	1301	281	1095	162	0.44	24.1	-	-	-
83	360	159	10	233	1301	277	1099	160	0.44	24.1	6	79	8.8
84	361	159	10	233	1305	279	1096	160	0.44	24.1	-	-	-
85	360	159	10	233	1296	295	1095	160	0.44	24.1	-	-	-
86	360	159	10	234	1307	291	1097	160	0.44	24.1	-	-	-
87	361	159	10	234	1298	275	1096	160	0.44	24.1	-	-	-
88	360	159	10	232	1307	281	1096	160	0.44	24.0	-	-	-

[a] Values after pumping
Note: 1 lb/yd^3 = 0.593 kg/m^3; 1 in. = 25.4 mm; °C = (°F-32)×5/9

APPENDIX G: PREVIOUS DATA FOR EVALUATION OF CRACKING PERFORMANCE OF BRIDGE DECKS IN CHAPTER 5

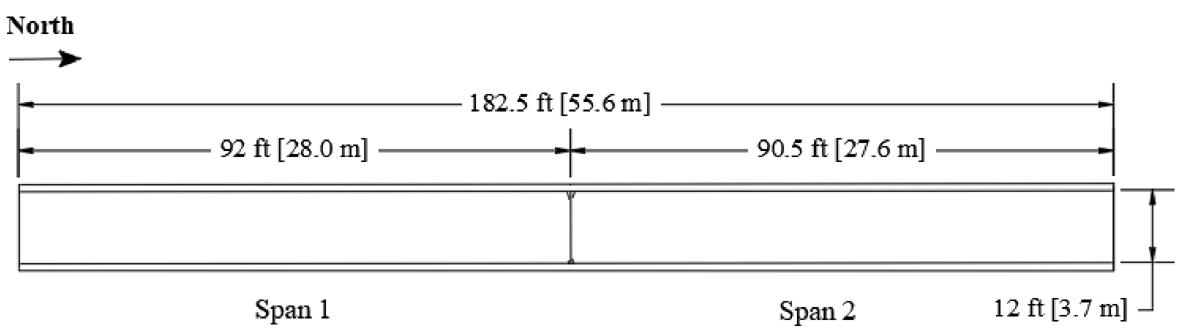


Birdge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 6/27/2017

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 9.2 months
Crack Density: 0.013 m/m^2
Span 1: 0.010 m/m^2
Span 2: 0.016 m/m^2

Figure G.1: Crack Map for MN-IC-LC-HPC-1 (Survey 1)

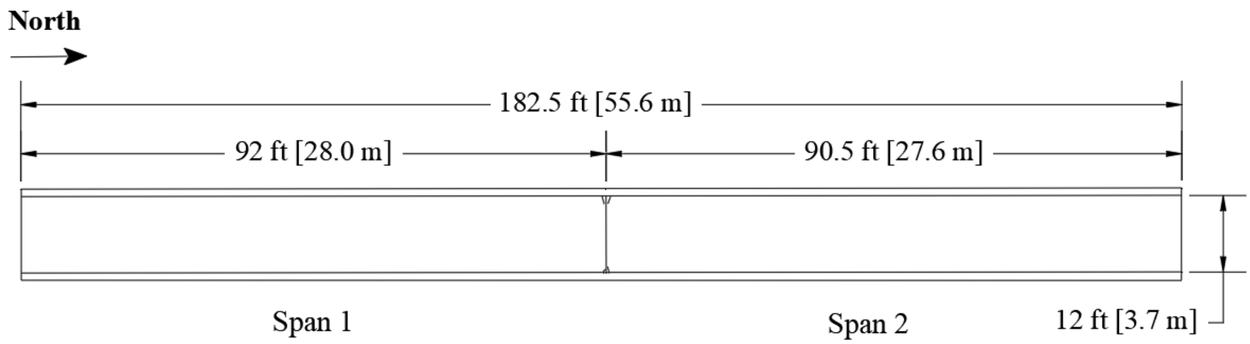


Bridge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 5/8/2018

Bridge Length: 185.2 ft (56.4 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 19.6 months
Crack Density: 0.007 m/m^2
Span 1: 0.006 m/m^2
Span 2: 0.009 m/m^2

Figure G.2: Crack Map for MN-IC-LC-HPC-1 (Survey 2)

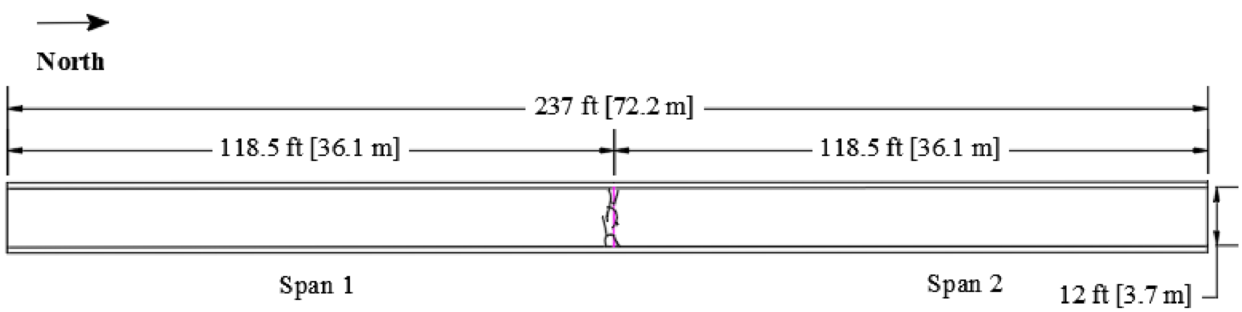


Bridge ID: MN-IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 6/3/2019

Bridge Length: 182.5 ft (55.6 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 32.4 months
Crack Density: 0.007 m/m^2
Span 1: 0.007 m/m^2
Span 2: 0.007 m/m^2

Figure G.3: Crack Map for MN-IC-LC-HPC-1 (Survey 3)

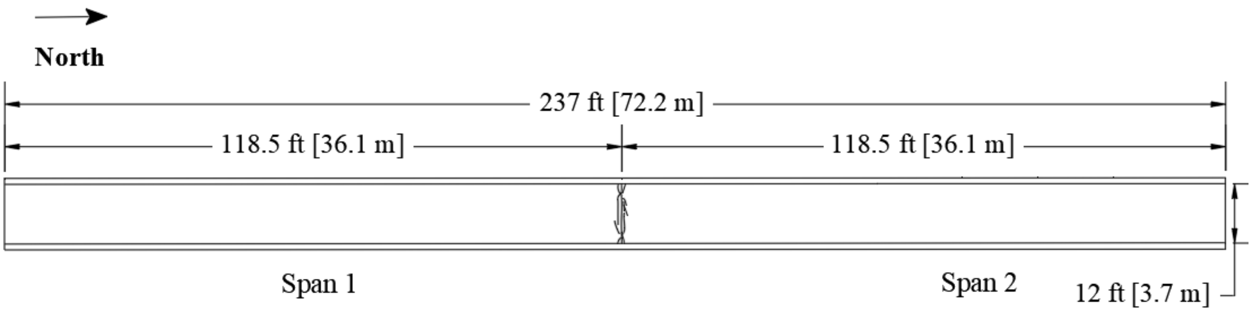


Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94, St. Paul, MN
Construction Date: 9/28/2016
Crack Survey Date: 6/27/2017

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0°
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 9.0 months
Crack Density: 0.034 m/m^2
Span 1: 0.037 m/m^2
Span 2: 0.030 m/m^2

Figure G.4: Crack Map for MN-Control-1 (Survey 1)

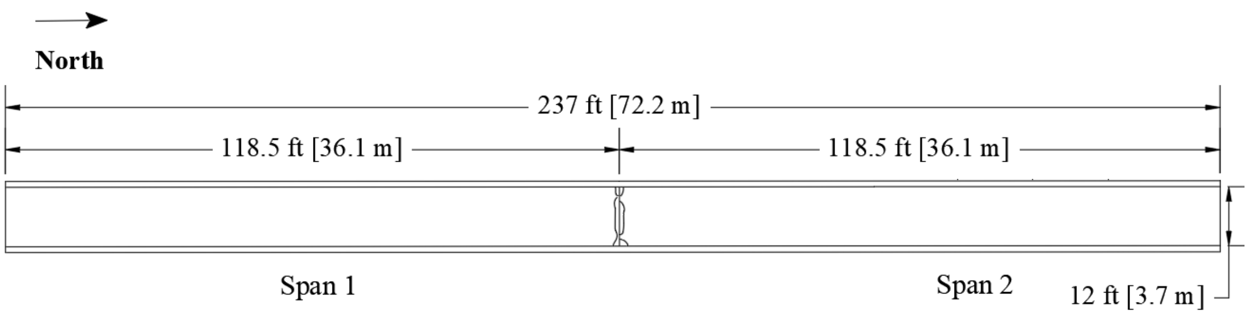


Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 5/8//2018

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 19.4 months
Crack Density: 0.032 m/m^2
Span 1: 0.031 m/m^2
Span 2: 0.034 m/m^2
Crack Length: 28.1 ft
Span 1: 13.5 ft
Span 2: 14.6 ft

Figure G.5: Crack Map for MN-Control-1 (Survey 2)

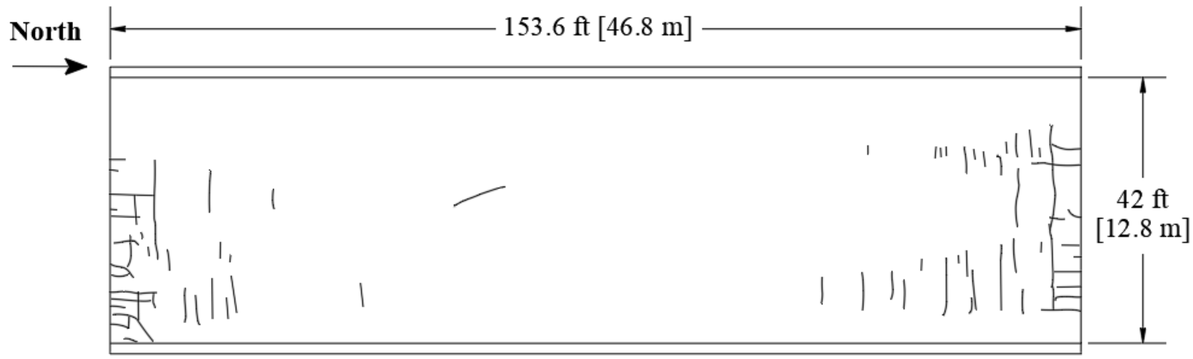


Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 6/3/2019

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

Bridge Age: 32.2 months
Crack Density: 0.029 m/m^2
Span 1: 0.029 m/m^2
Span 2: 0.028 m/m^2

Figure G.6: Crack Map for MN-Control-1 (Survey 3)

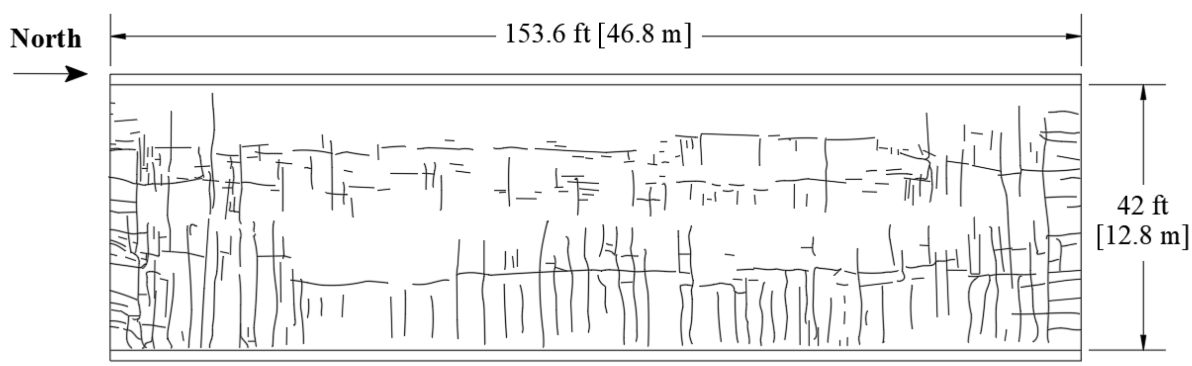


Bridge ID: MN-IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over Little Cannon River
Construction Date: 7/6/2017
Crack Survey Date: 5/10/2018

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 10.2 months
Crack Density: 0.165 m/m²

Figure G.7: Crack Map for MN-IC-LC-HPC-2 (Survey 1)

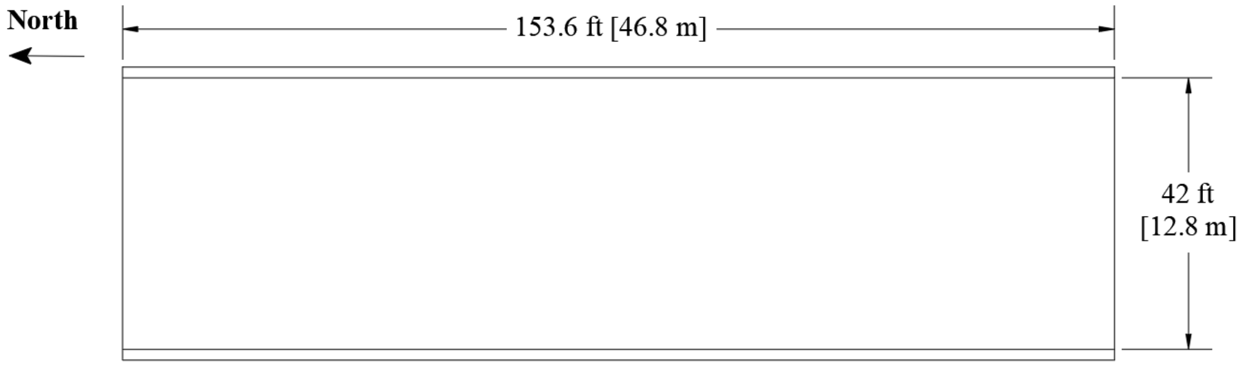


Bridge ID: MN-IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over Little Cannon River
Construction Date: 7/6/2017
Crack Survey Date: 6/3/2019

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 22.9 months
Crack Density: 0.896 m/m²

Figure G.8: Crack Map for MN-IC-LC-HPC-2 (Survey 2)

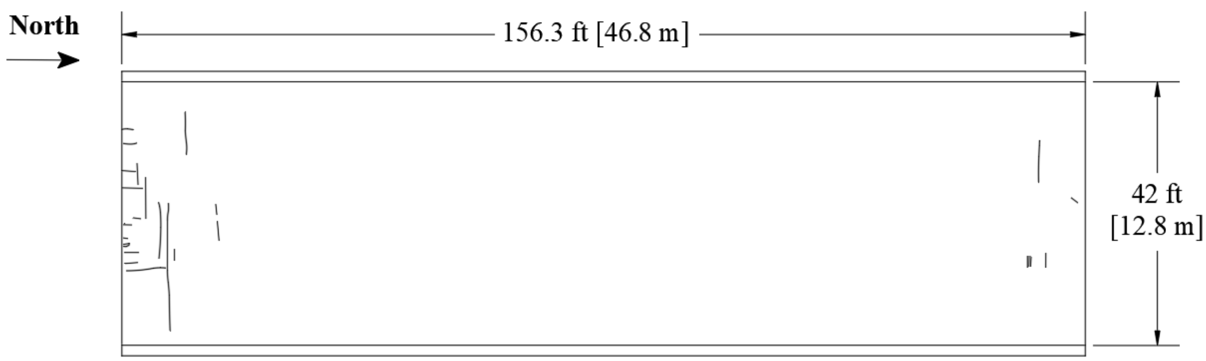


Bridge ID: MN-Control-2
Bridge Number: 25032
Bridge Location: N.B TH 52 over Little Cannon River
Construction Date: 9/15/2017
Crack Survey Date: 5/10/2018

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

Bridge Age: 7.8 months
Crack Density: 0 m/m^2
Crack Length: 0 ft

Figure G.9: Crack Map for MN-Control-2 (Survey 1)

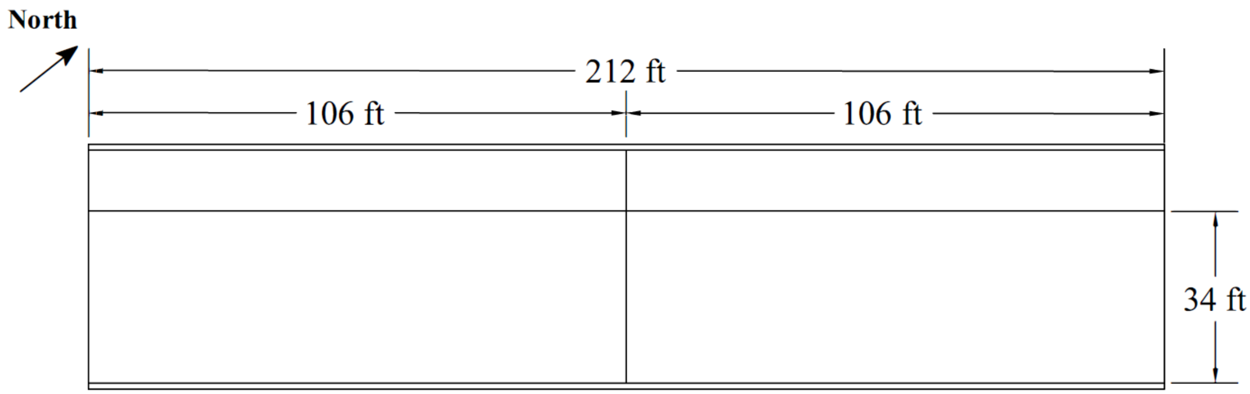


Bridge ID: MN-Control-2
Bridge Number: 25032
Bridge Location: S.B TH 52 over Little Cannon River
Construction Date: 9/15/2017
Crack Survey Date: 6/3/2019

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

Bridge Age: 20.6 months
Crack Density: 0.050 m/m^2
Crack Length: 98.4 ft

Figure G.10: Crack Map for MN-Control-2 (Survey 2)



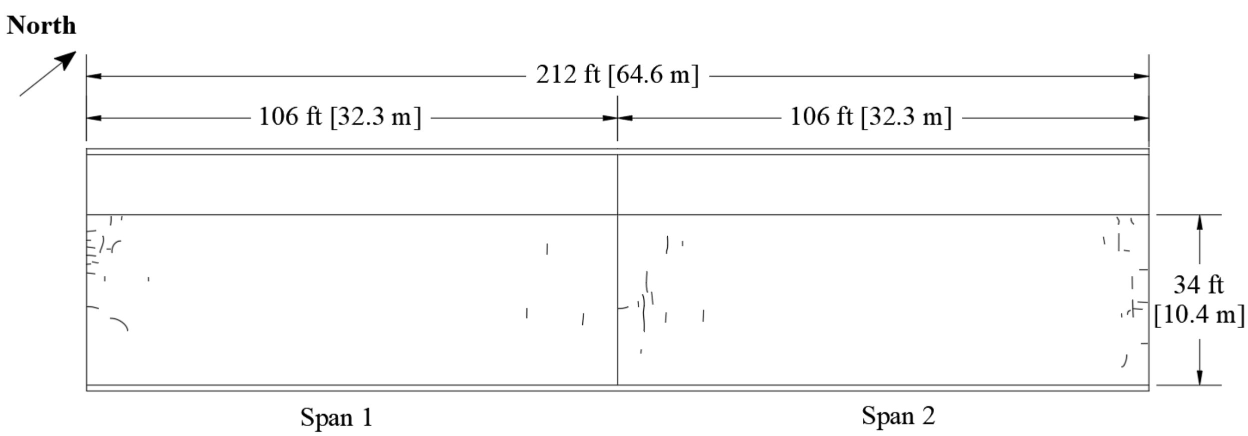
Bridge IC: MN-IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52
Construction Date: 6/29/2017
Crack Survey Date: 5/10/2018

Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)

Skew: 0
Number of Spans: 1
Number of Placements: 1

Bridge Age: 10.4 months
Crack Density: 0 m/m^2

Figure G.11: Crack Map for MN-IC-LC-HPC-1 (Survey 1)

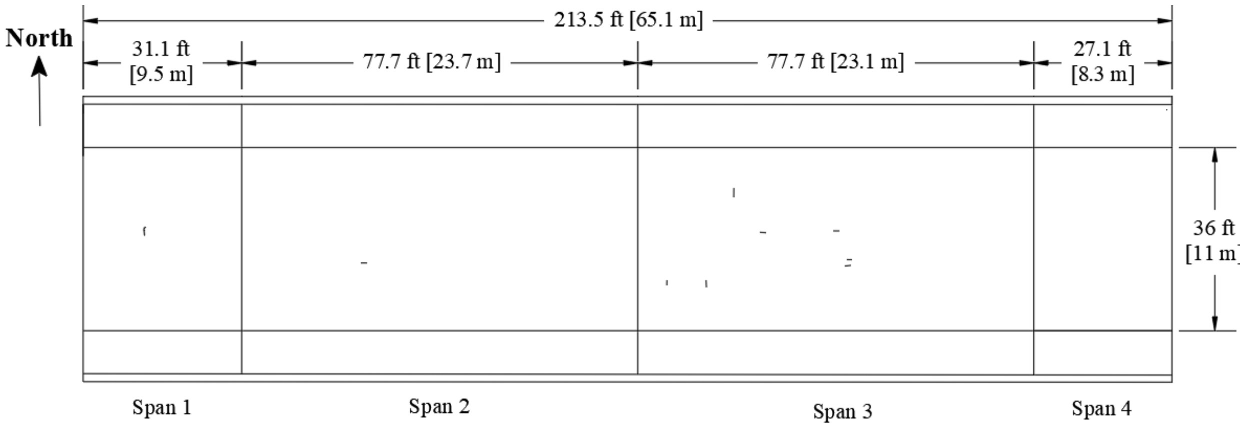


Bridge ID: MN-IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52
Construction Date: 6/29/2017
Crack Survey Date: 6/3/2019

Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)
Skew: 0°
Number of Spans: 2
Span 1: 106 ft (32.3 m)
Span 2: 106 ft (32.3 m)
Number of Placements: 1

Bridge Age: 23.2 months
Crack Density: 0.042 m/m^2
Span 1: 0.033 m/m^2
Span 2: 0.050 m/m^2
Crack Length: 92.0 ft
Span 1: 36.7 ft
Span 2: 55.3 ft

Figure G.12: Crack Map for MN-IC-LC-HPC-3 (Survey 2)



Bridge Number: MN-IC-LC-HPC-4
Bridge Number: 9619
Bridge Location: 38th St. over I-35W
Construction Date: 5/16/2018
Crack Survey Date: 9/16/2019

Bridge Length: 213.5 ft (65.1 m)
Bridge Width: 36.0 ft (11.0 m)
Skew: 0°
Number of Spans: 4
- **Span 1:** 31.1 ft (9.5 m)
- **Span 2:** **77.7** ft (23.1 m)
- **Span 3:** 77.7 ft (23.1 m)
- **Span 4:** 27.1 ft (8.3 m)

Number of Placements: 1

Bridge Age: 16.0 months
Crack Density: 0.005 m/m^2
- **Span 1:** 0.005 m/m^2
- **Span 2:** 0.001 m/m^2
- **Span 3:** 0.009 m/m^2
- **Span 4:** 0.000 m/m^2

Figure G.13: Crack Map for MN-IC-LC-HPC-4 (Survey 1)

APPENDIX H: BRIDGE DECK SURVEY SPECIFICATIONS

H.1 DESCRIPTION.

This specification covers the procedures and requirements to perform bridge deck surveys of reinforced concrete bridge decks.

H.2 SURVEY REQUIREMENTS.

H.2.1 Pre-Survey Preparation.

(1) Prior to performing the crack survey, related construction documents need to be gathered to produce a scaled drawing of the bridge deck. The scale must be exactly 1 in. = 10 ft (for use with the scanning software), and the drawing only needs to include the boundaries of the deck surface.

NOTE 1 – In the event that it is not possible to produce a scaled drawing prior to arriving at the bridge deck, a hand-drawn crack map (1 in.= 10 ft) created on engineering paper using measurements taken in the field is acceptable.

(2) The scaled drawing should also include compass and traffic directions in addition to deck stationing. A scaled 5 ft by 5 ft grid is also required to aid in transferring the cracks observed on the bridge deck to the scaled drawing. The grid shall be drawn separately and attached to the underside of the crack map such that the grid can easily be seen through the crack map.

NOTE 2 – Maps created in the field on engineering paper need not include an additional grid.

(3) For curved bridges, the scaled drawing need not be curved, i.e., the curve may be approximated using straight lines.

(4) Coordinate with traffic control so that at least one side (or one lane) of the bridge can be closed during the time that the crack survey is being performed.

H.2.2 Preparation of Surface.

(1) After traffic has been closed, station the bridge in the longitudinal direction at ten feet intervals. The stationing shall be done as close to the centerline as possible. For curved bridges, the stationing shall follow the curve.

(2) Prior to beginning the crack survey, mark a 5 ft by 5 ft grid using lumber crayons or chalk on the portion of the bridge closed to traffic corresponding to the grid on the scaled drawing. Measure and document any drains, repaired areas, unusual cracking, or any other items of interest.

(3) Starting with one end of the closed portion of the deck, using a lumber crayon or chalk, begin tracing cracks that can be seen while bending at the waist. After beginning to trace cracks, continue to the end of the crack, even if this includes portions of the crack that were not initially seen while bending at the waist. Cracks not attached to the crack being traced must not be marked unless they can be seen from waist height. Surveyors must return to the location where they started tracing a crack and continue the survey. Areas covered by sand or other debris need not be surveyed. Trace the cracks using a different color crayon than was used to mark the grid and stationing.

(4) At least one person shall recheck the marked portion of the deck for any additional cracks. The goal is not to mark every crack on the deck, only those cracks that can initially be seen

while bending at the waist.

NOTE 3 – An adequate supply of lumber crayons or chalk should be on hand for the survey. Crayon or chalk colors should be selected to be readily visible when used to mark the concrete.

H.2.3 Weather Limitations.

(1) Surveys are limited to days when the expected temperature during the survey will not be below 60 °F.

(2) Surveys are further limited to days that are forecasted to be at least mostly sunny for a majority of the day.

(3) Regardless of the weather conditions, the bridge deck must be completely dry before the survey can begin.

H.3 BRIDGE SURVEY.

H.3.1 Crack Surveys.

Using the grid as a guide, transfer the cracks from the deck to the scaled drawing. Areas that are not surveyed should be marked on the scaled drawing. Spalls, regions of scaling, and other areas of special interest need not be included on the scale drawings but should be noted.

H.3.2 Delamination Survey.

At any time during or after the crack survey, bridge decks shall be checked for delamination. Any areas of delamination shall be noted and drawn on a separate drawing of the bridge. This second drawing need not be to scale.

H.3.3 Under Deck Survey.

Following the crack and delamination survey, the underside of the deck shall be examined and any unusual or excessive cracking noted.

APPENDIX I: ESTIMATED 36-MONTH CRACK DENSITIES FOR USE IN ANALYSIS IN CHAPTER 6

In this section, the survey results of the 74 deck placements, as well as MnDOT and KDOT IC-LC-HPC placements as presented in Tables I.1 through I.6, are converted to equivalent crack densities at 36 months of age to allow a fair comparison between decks introduced in Chapter 6.

I.1 Crack Densities at 36 Months

The crack density of bridge decks increases over time (Yuan et al. 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018, Feng and Darwin 2019 to name just a few). To eliminate the variable of age and compare bridge deck cracking on an equal-age basis, the crack density at 36 months after construction is chosen for the analyses in this study. An age of 36 months is selected because the tendency to exhibit cracking over the long term becomes apparent at this age (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass and Darwin 2014).

The primary assumption made in determining the 36-month crack density based on previous survey data is that a linear relationship exists between crack density and deck age. For bridge decks with survey data available at dates both before and after 36 months, the 36-month crack density is determined by linearly interpolating between the two data points. If the latest survey data of a deck was obtained before 36 but no earlier than 30 months of age, the last survey data point is taken as an approximation of the 36-month crack density. Similarly, if the earliest survey data of a deck was obtained after 36 but no later than 42 months, the first survey data point is taken as an approximation for the 36-month crack density. In bridge decks with the first available survey data point taken after 42 months of age or with the latest available survey data point taken before 30 months of age, the 36-month crack density is linearly extrapolated using the two available consecutive survey data points nearest to 36 months.

Exceptions for Fiber 1 NB-P1 (S-F) and Fiber 1 NB-P2 (S-F), Fiber 2 SB-P1 (S-F), and Fiber 2 SB-P2 (S-F) decks (Table 6.10) were made due to a reduction in the measurable crack density caused by scaling of the deck. For these decks, the crack densities obtained in the third crack survey (at ages of 33.7 and 31.7, and 34 and 32.4, respectively) are treated as the crack densities at 36 months. Additionally, for the MN-IC-LC-HPC-8 and MN-IC-LC-HPC-9 with significantly high crack densities exhibited in less than 24 months of age, the crack densities obtained in the second crack survey (at ages of 21.2 and 20.6 months, respectively) are treated as the crack densities at 36 months.

The crack survey results of the two available consecutive survey data points used in calculation of 36-month crack densities of the 74 deck placements, as well as MnDOT and KDOT IC-LC-HPC placements described in Chapter 6, are presented in Tables I.1 through I.6.

Table I.1: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for Fiber, Control, and SRA Decks

Bridge Deck	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
Fiber 1 NB-P1 (S-F)	33.7	0.112	-	-	0.112
Fiber 1 NB-P2 (S-F)	31.7	0.220	-	-	0.220
Fiber 2 SB-P1 (S-F)	34.0	0.127	-	-	0.127
Fiber 2 SB-P2 (S-F)	32.4	0.456	-	-	0.456
Topeka Fiber 1 (S-F)	26.8	0.272	37.8	0.287	0.284
Topeka Fiber 2-P1 (S-F)	24.0	0.300	33.6	0.709	0.709
Topeka Fiber 2-P2 (S-F)	24.0	0.645	33.4	0.431	0.431
Topeka Control-P1 (S-F)	27.0	0.725	35.8	0.766	0.766
Topeka Control-P2 (S-F)	27.0	0.411	35.6	0.393	0.393
Fiber 5 WB (S-F)	31.1	0.044	44.7	0.091	0.061
Control 5 (Eastbound) (S)	31.2	0.038	44.8	0.077	0.052
Fiber 6 WB (S-F)	25.0	0.005	38.6	0.013	0.011
Control 6 (Eastbound) (S)	25.3	0.002	38.9	0.013	0.011
Fiber 7 WB (S-F)	24.6	0.001	38.0	0.005	0.004
Control 7 (Eastbound) (S)	25.8	0.014	38.3	0.037	0.033
VA-SRA 4 (S-SRA)	10.5	0.027	33.9	0.083	0.083
VA-SRA 8 (S-SRA)	10.5	0.025	34.0	0.056	0.056
VA Control (S)	31.0	0.222	54.1	0.266	0.232

Table I.2: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for IC and Control Decks in Indiana

Placements	**Survey A**		**Survey B**		**Crack Density Used for Analysis (m/m^2)**
	Deck Age (month)	**Crack Density (m/m^2)**	**Deck Age (month)**	**Crack Density (m/m^2)**	
IN-Control (PS Box)	71.6	0.507	93.0	0.670	0.236
IN-IC (PS Box-IC)	71.6	0.347	93.0	0.447	0.181
IN-IC-HPC-2 (S-IC)	34.8	0.003	56.8	0.033	0.003
IN-IC-HPC-3 (S-IC)	21.6	0.016	43.8	0.086	0.061
IN-IC-HPC-4-P1 (S-IC)	15.6	0.021	35.4	0.214	0.214
IN-IC-HPC-4-P2 (S-IC)	10.5	0.005	32.8	0.032	0.032

Table I.3: Crack Densities at the Time of Survey and Crack Densities Used for Analysis for Conventional Decks in Kansas

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
Conv. 3-046 East Deck (S)	102	0.402	210	0.418	0.392
Conv. 3-046 West Deck (S)	102	0.362	210	0.539	0.254
Conv. 3-046 Ctr. Deck (S)	102	0.153	210	0.334	0.042
Conv. 75-044 Deck (S)	48	0.179	155	0.304	0.165
Conv. 89-204 Deck (S)	34	0.732	82	0.825	0.736
Conv. 3-045 West Deck (S)	112	0.122	223	0.192	0.074
Conv. 3-045 East Deck (S)	112	0.196	223	0.368	0.078
Conv. 3-045 W. Ctr. Deck (S)	112	0.188	223	0.203	0.178
Conv. 3-045 Ctr. Deck (S)	112	0.215	220	0.273	0.174
Conv. 3-045 E. Ctr. Deck (S)	112	0.163	220	0.333	0.043
Conv. 56-142 Pos. Moment (S)	80	0.108	189	0.200	0.071
Conv. 56-142 Neg. Moment (S)	80	0.093	188	0.163	0.064
Conv. 56-148 Deck (S)	36	0.259	133	0.486	0.259
Conv. 70-095 Deck (S)	106	0.069	212	0.136	0.025
Conv. 70-103 Right (S)	102	0.395	219	0.647	0.253
Conv. 70-103 Left (S)	102	0.557	219	0.852	0.391
Conv. 70-104 Deck (S)	106	0.083	212	0.104	0.069
Conv. 70-107 Deck (S)	34	0.322	82	0.417	0.322
Conv. 99-076-P4 (S)	42	0.872	163	1.022	0.872
Conv. 99-076-P5 (S)	42	0.861	163	1.052	0.861
Conv. 99-076 North (West Ln.) (S)	42	0.801	161	0.947	0.801
Conv. 99-076 North (East Ln.) (S)	42	0.412	157	0.663	0.412
Conv. 99-076-P3 (S)	42	0.739	164	0.881	0.739
Conv. 89-208 Deck (S)	36	0.009	73	0.106	0.009

Table I.4: Crack densities at the Time of Survey and Crack Densities Used for Analysis for LC-HPC Decks, Control 8/10, and Extra Control

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
LC-HPC 1-P1 (S)	32.1	0.044	44.1	0.060	0.049
LC-HPC 1-P2 (S)	31.5	0.024	55.0	0.023	0.024
LC-HPC 2 (S)	21.2	0.028	44.5	0.059	0.048
LC-HPC 4-P2 (S)	32.7	0.094	44.9	0.080	0.090
LC-HPC 5 (S)	31.1	0.128	43.0	0.190	0.154
LC-HPC 6 (S)	31.4	0.231	43.4	0.336	0.271
LC-HPC 7 (S)	24.2	0.019	34.8	0.012	0.012
LC-HPC 8 (PS)	31.8	0.348	45.0	0.380	0.358
LC-HPC 9 (S)	26.5	0.248	38.3	0.344	0.325
LC-HPC 10 (PS)	36.2	0.029	49.6	0.088	0.029
LC-HPC 11 (S)	36.2	0.165	48.4	0.269	0.163
LC-HPC 12-P1 (S)	26.8	0.256	38.8	0.313	0.300
LC-HPC 12-P2 (S)	27.3	0.268	38.1	0.375	0.354
LC-HPC 13 (S)	24.8	0.129	37.1	0.364	0.344
LC-HPC 14-P1 (S)	30.0	0.502	42.2	0.585	0.543
LC-HPC 14-P2 (S)	25.5	0.727	37.7	1.304	1.223
LC-HPC 14-P3 (S)	24.9	0.871	37.1	0.678	0.695
LC-HPC 15 (S)	30.8	0.161	43.0	0.316	0.227
LC-HPC 16 (S)	31.2	0.211	43.5	0.311	0.250
LC-HPC 17 (S)	32.5	0.274	45.5	0.308	0.283
Control 8/10 (PS)	25.5	0.127	37.2	0.137	0.136
Extra Control (S)	37.0	0.219	48.0	0.265	0.215

Table I.5: Crack densities at the Time of Survey and Crack Densities Used for Analysis for US-59 Decks

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
US-59 1 (S)	31.0	0.385	45.0	0.403	0.391
US-59 2 (S)	32.0	0.217	46.0	0.306	0.242
US-59 10 (PS-F)	31.0	0.150	43.0	0.217	0.178
US-59 12 (PS-F)	30.0	0.022	42.6	0.075	0.047

Table I.6: Crack densities at the Time of Survey and Crack Densities Used for Analysis for Minnesota and Kansas IC-LC-HPC Decks

Placements	Survey A		Survey B		Crack Density Used for Analysis (m/m^2)
	Deck Age (month)	Crack Density (m/m^2)	Deck Age (month)	Crack Density (m/m^2)	
MN-IC-LC-HPC-1	32.4	0.007	45.0	0.007	0.007
MN-IC-LC-HPC-4	37.0	0.045	48.3	0.046	0.045
MN-IC-LC-HPC-5	-	-	34.0	0.153	0.153
MN-IC-LC-HPC-6	-	-	32.2	0.011	0.011
MN-IC-LC-HPC-7-P1	11.7	0.018	23.0	0.037	0.059
MN-IC-LC-HPC-7-P2	8.8	0.014	20.1	0.024	0.038
MN-IC-LC-HPC-8	9.9	0.013	21.2	0.671	0.671
MN-IC-LC-HPC-9	9.5	0.004	20.6	0.788	0.788
KS-IC-LC-HPC-1	-	-	30.9	0.019	0.019
KS-IC-LC-HPC-2-P1	8.6	0.004	19.7	0.004	0.004
KS-IC-LC-HPC-2-P2	8.4	0.002	19.4	0.003	0.005

APPENDIX J: IC-LC-HPC CONSTRUCTION EVALUATION SPREADSHEET

No.	VARIABLE* (in order of completion)		Notes
1	Even sprinkling of FLWA	☐	
2	FLWA sprinkled for at least 72 hours or until moisture content becomes constant	☐	
3	Sprinkling of FLWA stopped 24 hours prior to batching to allow drainage	☐	
4	Absorption of FLWA is tested within 24 hours of batching	☐	
5	Mix proportions are modified based on absorption measurement	☐	
6	FLWA Free-surface moisture is tested within 1 hour of batching	☐	
7	Admixtures are added per manufacturer's suggestions / at time of batching	☐	
8	Tracking the quantity of water withheld on trip tickets at the job site	☐	
9	Time between batching and discharge less than 90 minutes	☐	
10	Good communication between KU, DOT, and the contractor personnel	☐	
11	Forms and reinforcement are uniformly wet	☐	
12	Pumpable concrete	☐	
13	Slump within specification	☐	

No.	VARIABLE* (in order of completion)		Notes
14	Air content within specification	☐	
15	Temperature within specification	☐	
16	Evaporation rate below specification limit	☐	
17	Adequate consolidation	☐	
18	No disturbance of concrete after consolidation	☐	
19	Minimized finishing (no overfinishing)	☐	
20	Time between placing and finishing less than 15 minutes	☐	
21	Time between finishing and first layer of burlap less than 15 minutes	☐	
22	Time between first and second layers of burlap less than 15 minutes	☐	
23	Burlap fully saturated for a minimum of 12 hours prior to placement on the deck	☐	
24	Concrete completely covered with burlap	☐	
25	Soaker hoses uniformly wet the burlap	☐	
26	Proper curing conditions through 14 days after placement	☐	
27	Formwork removed within 4 weeks of end of curing	☐	

28	Concrete compressive strength within specification	☐	
Total	Number of "Selected Checkboxes" for Project	**0**	

* Concrete Supplier Variable

CONCRETE SUPPLIER	**0**	out of 13
CONTRACTOR	**0**	out of 15