EFFECTS OF TOTAL INTERNAL WATER CONTENT ON FREEZE-THAW DURABILITY AND SCALING RESISTANCE OF INTERNALLY-CURED CONCRETE

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A Report on Research Sponsored by

Construction of Low-Cracking High-Performance
Bridge Decks Incorporating New Technology
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Structural Engineering and Engineering Materials
SM Report No. 154
July 2023

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

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ABSTRACT

The effects of total internal (TI) water, provided by normalweight coarse and fine aggregates and pre-wetted fine lightweight aggregate (LWA), in the range of 6.8 to 17.3%, corresponding to internal curing (IC) water in the LWA ranging from 0 to 15.1%, by weight of cementitious materials, on the freeze-thaw durability and scaling resistance of 12 concrete mixtures are evaluated. Cementitious materials consist of portland cement only or portland cement with a 30% weight replacement by slag cement. The coarse aggregate consists of limestone (with an oven-dry absorption of 1.8%) or granite (with an oven-dry absorption of 0.6%), which provide 5.5 to 5.6% or 1.9% internal curing water by the weight of cementitious materials, respectively.

All of the mixtures with the limestone coarse aggregate failed the test, with the average dynamic modulus of elasticity (E_{DYN}) dropping below 95% of the initial value well before the 660 freeze-thaw cycles specified by the Kansas Department of Transportation, demonstrating that the limestone itself is susceptible to freeze-thaw damage. The mixtures containing granite coarse aggregate had an average relative E_{DYN} above 95% of the initial value at 660 freeze-thaw cycles in the test of freeze-thaw durability at TI water contents up to 15.7% (corresponding to an IC water content of 13.4% from the LWA) by the weight of cementitious materials. The only mixture with granite coarse aggregate that failed the test had a 30% weight replacement of portland cement with slag cement and a TI water content of 17.3% by weight of the cementitious materials (corresponding to 15.1% IC water from LWA). This result indicates that it is possible to have too much internal curing water. In the scaling test, the mixtures with granite coarse aggregate, all of which contained LWA, had lower mass losses than mixtures with limestone coarse aggregate, although all but one of the 12 mixtures passed the test with a cumulative 56-day mass loss below 0.1 lb/ft^2. For concrete with granite coarse aggregate, the mass loss increased slightly with increased TI water content when portland cement was used as the only cementitious material. When a 30% weight replacement of portland cement with slag cement was used, the mass loss increased for a TI water content above 12.5% (corresponding to 9.9% IC water from LWA), but remained below the failure limit, suggesting no benefits for a TI water content above 12.5% by the weight of cementitious materials. The mixtures with portland cement as the only cementitious material had lower mass losses than the mixtures with a 30% weight replacement of portland cement with slag cement for the same coarse aggregate. Pre-wetted fine lightweight aggregate (LWA) for internal curing (IC) should equal 7 to 8% by weight of cementitious materials. The results provide no evidence that it would be advantageous to stray much above these values and demonstrate that high TI/IC water contents can be deleterious.

Keywords: bridge decks, freeze-thaw durability, internal curing, lightweight aggregate, low-cracking high-performance concrete, scaling resistance, slag cement, specifications, total internal water.

ACKNOWLEDGEMENTS

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CHAPTER 1 – INTRODUCTION

1.1 GENERAL

Bridges are a crucial element of US infrastructure, enabling the transportation of people and goods throughout the country. However, issues with cracking and durability of concrete in bridge decks have resulted in significant costs and rehabilitation efforts. Among the 617,000 bridges in the National Bridge Inventory (NBI) as of 2021, 7.5% of the bridges were considered to be structurally deficient and in need of replacement or rehabilitation (ASCE 2021). These bridges pose higher risks for potential closure or weight restrictions in the future.

Since concrete bridge decks are prone to cracking, weathering action, and other durability issues, finding ways to reduce cracking and improve the durability of concrete can help reduce maintenance and repair costs (ACI Committee 201.2R-16). The University of Kansas has developed specifications for low-cracking high-performance concrete (LC-HPC) for use in bridge decks (Lindquist, Darwin, and Browning 2008, McLeod, Darwin, and Browning 2009, Yuan, Darwin, and Browning 2011, Pendergrass and Darwin 2014, Khajehdehi and Darwin 2018) with the goal of reducing cracking and improving their durability. The original specifications included requirements for aggregates, concrete mixtures with low paste contents, low slump, limitations on compressive strength, and construction practices, such as concrete temperature, thorough consolidation, minimal finishing, and early and extended curing.

In recent years, state departments of transportation (DOTs) and the University of Kansas have investigated a number of techniques to reduce cracking and improve the longevity of bridge decks, including the use of internal curing (IC), fiber-reinforced concrete, and shrinkage-reducing admixtures with or without supplementary cementitious materials (SCMs) as partial substitutes for portland cement (Bitnoff 2014, Barrett et al. 2015, Rupnow et al. 2016, Lafikes et al. 2020, Feng and Darwin 2020, Bahadori et al. 2023). Internal curing using pre-wetted fine lightweight aggregate (LWA) has shown promising results on reducing cracking in bridge decks, but some negative effects on the freeze-thaw durability of bridge decks have also been observed (Lafikes et al. 2020, Bahadori et al. 2023). Lafikes et al. (2020) suggested that the total absorbed water or total internal (TI) water content (consisting of the water in both the fine lightweight and normalweight aggregates) is a better indicator of concrete durability than just the amount of IC water from LWA alone, a factor that becomes more important when a high-absorption normalweight aggregates are used.

The current study aims to further examine the effects of TI water, including water in both normalweight and pre-wetted fine lightweight aggregate (LWA) on the durability of concrete mixtures with different compositions of cementitious materials. Concrete mixtures with limestone (absorption of 1.8%), providing an additional 5.5 to 5.6% IC water by the weight of cementitious materials, are compared with mixtures with granite (absorption of 0.6%), providing an additional 1.9% IC water. The concrete mixtures contained either portland cement as the only cementitious material or a 30% weight replacement of portland cement with slag cement. The freeze-thaw durability and scaling resistance of the paired concrete mixtures with these coarse aggregates proportioned to provide similar TI water contents in the range of 6.8 to 17.3% by the weight of cementitious materials, are evaluated.

This chapter presents the background, objective, and scope of this research.

1.2 INTERNAL CURING

For concrete with a low *w/cm* ratio and low permeability, external curing water may not penetrate the interior of the concrete to aid in hydration of the cementitious materials (Powers et al. 1959, ACI Committee 308 2013). One of the ways to maintain a saturated cement paste and higher hydration of cementitious materials is to provide internal curing (IC) through the replacement of a portion of normalweight aggregate with pre-wetted absorptive material that can provide water to the hydrating cementitious materials (ACI Committee 308 2013). The application of internal curing using absorptive materials can be attained through the use of pre-wetted fine lightweight aggregate (LWA), super-absorbent polymers (SAPs), and absorbent limestone aggregate (Jensen and Lura 2006, Kovler and Jensen 2007). Multiple studies have been conducted on the use of LWA to provide internal curing (Villareal 2008). For the LWA to be used for internal curing, it must be saturated, usually using a water sprinkler system or by submerging the LWA in water (Villareal 2008).

The amount of LWA used in a concrete mixture depends on the target quantity of IC water, the absorption, and the desorption of LWA, where desorption is the loss of water from the LWA pores as a function of relative humidity at a constant temperature (Castro 2011). Equation (1.1) was proposed by Bentz and Snyder (1999) to define the design quantity of LWA per yd^3 of concrete:

$$W_{LWA}=\frac{C_f \times IC}{\alpha \times \beta} \tag{0.1}$$

where C_f = Amount of Cementitious Materials (lb/yd^3)
IC = Desired percentage of internal curing water from LWA
α = LWA absorption (oven-dry basis, based on pre-wetting method and duration)
β = LWA desorption at specified RH

An IC water content of 7 or 8% by weight of cementitious material is often used for concrete mixtures (Bentz and Weiss 2011, Bitnoff 2014, Barrett et al. 2015, Kansas Department of Transportation 2015, Lafikes et al. 2018).

Concrete with internal curing (IC) through the use of LWA has higher strength, lower permeability, and improved cement hydration than concrete without IC (Bentz and Weiss 2011). Villarreal and Crocker (2007) observed that the addition of IC added about 1000 psi (6.8 MPa) to the compressive strength similar concretes without IC with compressive strengths in the range of 5100 to 5800 psi (35.2 to 40.0 MPa). This increase in strength was attributed to additional hydration of cement made possible by the availability of internal curing water. Bentz (2009) reported that for mortars with 8% IC water by the weight of cementitious materials, the measured penetration depths for chloride ingress were significantly less than that of similar mortars without IC. The decrease in permeability was also attributed to improved hydration in the mortar with IC. Cusson and Margeson (2010) cast air-entrained concrete mixtures with IC, a water-to-cement ratio (*w/cm*) of 0.35, and performed compressive strength and chloride permeability tests. The concrete mixtures with IC had a 10% average increase in 28-day compressive strength and a 25% decrease in chloride ion permeability compared to concrete without IC.

The effects of internal curing using LWA on freeze-thaw durability and scaling resistance is a concern that is often mentioned due to the presence of additional water in the highly porous LWA structure. The effects can be prominent if the LWA is not allowed to fully desorb before exposing to freezing-and-thawing conditions (Bentz and Weiss 2011). The effects on freeze-thaw durability and scaling resistance are discussed in Sections 1.4 and 1.5.

1.3 SUPPLEMENTARY CEMENTITIOUS MATERIALS

Supplementary Cementitious Materials (SCMs) or, Mineral Admixtures, such as slag cement, fly ash, or silica fume, are incorporated into concrete mixtures, primarily as partial replacements for portland cement as means of enhancing the concrete strength and durability and reducing the life cycle costs of concrete structures (Mindess et al. 2003, Russell 2004).

1.3.1 Slag Cement

Slag cement is a by-product of the production of pig iron. When molten slag from a blast furnace is cooled slowly in the air, it crystalizes and forms inert calcium magnesium silicates, and exhibits no cementitious properties. However, when it is cooled rapidly (quenched), it forms a hydraulically active calcium aluminosilicate glass. When this quenched glass ground is to a high fineness, it will form ground granulated blast furnace slag, also termed as slag cement (Mindess et al. 2003).

According to ASTM C989, slag cement is classified into three grades (80,100, and 120), based on the slag-activity index. The slag-activity index is taken as the ratio of the strength of a mortar composed of 50% slag cement and 50% portland cement with the strength of a mortar made entirely of portland cement at ages of 7 and 28 days.

The use of slag cement has beneficial effects on the workability of fresh concrete exhibiting higher slump and consolidating more easily than concrete containing no slag cement (Meusel and Rose 1983, Osborne 1989, Wimpenny et al. 1989). The setting time, the time it takes for concrete to harden, may increase when slag cement replaces more than 25% of portland cement (ACI Committee 233). Concrete containing slag cement has been shown to have greater long-term strength gain (over 20 years) than concrete made with 100% portland cement (Wood 1992). Concrete made with slag cement also has lower permeability than concrete containing only portland cement (Rose 1987). This decrease in permeability is due to changes in the pore structure of the cement paste matrix caused by the excess silica in slag cement reacting with the calcium hydroxide and alkalis released during cement hydration, leading to C-S-H filling the pores (Bakker 1980, Roy and Idorn 1983). The resulting reduction in pore size, observed within the first 28 days after mixing (Mehta 1980), enhances the resistance of the concrete to chloride penetration and corrosion of reinforcing steel (Fulton 1974, Bakker 1980, Mehta 1980).

The effects of using a partial replacement of slag cement in concrete mixtures on freeze-thaw durability and scaling resistance have been mixed. Mather (1957), Klieger and Isberner (1967), and Fulton (1974) reported that the freeze-thaw durability of mixtures with a slag-cement blend was similar to that of mixtures containing only portland cement. Malhotra (1987), however, observed that mixtures with slag cement did not perform as well as mixtures with only portland cement when tested for freeze-thaw durability.

1.3.2 Fly Ash

Fly ash is a widely used supplementary cementitious material because of its relatively low cost and its desirable effects on both plastic and hardened concrete properties (Mindess et al. 2003, ACI Committee 232-18). Fly ash is an inorganic, noncombustible residue of the combustion of pulverized coal in power plants. ASTM C618-22 classifies fly ash as Class C or Class F based on the percentages of acidic oxides (silicon dioxide [SiO_2], aluminum oxide [Al_2O_3], iron oxide [Fe_2O_3]), and calcium oxide (CaO). Class C fly ash has a minimum calcium oxide content of 18% while Class F fly ash has a maximum calcium oxide content of 18%. Concrete containing Class C fly ash may exhibit lower long-term strength gain than concrete containing Class F fly ash, but demonstrates higher early-age strength (ACI Committee 232-18).

Because fly ash particles have a spherical shape, concrete containing fly ash exhibits greater workability than mixtures with only portland cement (Mindess et al. 2003). The addition of a sufficient amount of fly ash can also lead to reduced permeability and can reduce the effects of the alkali-silica reaction (Mindess et al. 2003, Russell 2004).

1.3.3 Silica Fume

Silica fume is a highly pozzolanic material that is a byproduct of the production of silicon metal or ferrosilicon alloys. The spherical particles of silica fume are very fine, with diameters 100 times smaller than that of portland cement (Mindess et al. 2003). The addition of silica fume enhances the properties of concrete through various physical and chemical mechanisms, including reduced bleeding and improved packing of the solid particles (ACI Committee 234-06). Concrete with partial replacement of portland cement with silica fume results in a reduction in concrete permeability, providing better corrosion protection of reinforcing steel. Concrete containing silica fume also exhibits increased compressive strength than concrete without silica fume (Maage 1984, ACI Committee 234-06).

1.4 FREEZE-THAW DURABILITY

Porous materials that hold moisture, such as concrete, are prone to damage when subjected to cycles of freezing and thawing. In areas with cold climates, hardened concrete is at high risk for the effects of freezing and thawing and the damage can range from surface spalling to complete disintegration (Shang et al. 2009). The mechanisms of freeze-thaw damage in cement paste and aggregates are described in this section.

1.4.1 Freeze-Thaw Damage in Cement Paste

Cement paste contains different size pores, namely air voids, capillary pores, and gel pores in the hydration product of calcium silicate hydrate (C-S-H). The freeze-thaw behavior within cement paste can be explained by two primary processes–the generation of osmotic pressure and the desorption of water (Powers and Helmuth 1953, Mindess et al. 2003).

Powers and Helmuth (1953) described the generation of osmotic pressure due to an increase in solute concentration in the pore water near freezing sites. Different solutes, including alkalis, chlorides, and calcium hydroxide, are dissolved in the water present in capillary pores. As the water turns to ice, the solutes will increase their concentration in the pore solution near the ice due to the reduced volume of liquid. This, in turn, will draw more water from other surrounding pores in the cement paste (containing more dilute solution) through the process of osmosis. This movement of water will create an osmotic pressure, which will cause the paste to crack.

Freeze-thaw behavior due to spontaneous desorption of water was proposed by Litvan (1970). The freezing temperature of water depends on the diameter of the pores within the cement paste. Water freezes in the larger diameter air voids at temperatures of around 25°F (-4°C), but occurs in the smaller gel pores at lower temperatures, as -108 (-78°C) (Technology 2006). At temperatures below 32°F (0°C), water in the smaller diameter pores will remain in a supercooled state rather than freezing. The supercooled water has a higher chemical potential than ice. Thus, the supercooled water will migrate from smaller unfrozen pores to the freezing sites to maintain equilibrium. The result is an increase in the volume of ice at the locations containing ice in the paste, which results in stresses as the paste away from the frozen region shrinks.

1.4.2 Effect of Entrained Air

Entrained air will protect against the effects of freezing and thawing for concrete (Mindess et al. 2003). In non-air-entrained concrete, air voids are relatively large, widely spaced, and small in number, which results in capillary pores serving as the principal freezing sites. If entrained air is added to the concrete, the air bubbles provide relatively large empty spaces where water will freeze first, before it freezes within the capillary pores, drawing water from the surrounding cement paste, thus reducing the degree of saturation within the surrounding cement paste through the processes of osmosis and desorption.

The distribution of air voids within the cement paste also plays a role in improving the freeze-thaw durability of concrete. In concrete with air voids that are closely spaced and uniformly distributed, the osmotic and the vapor pressure from desorption will draw water into the air voids from most of the capillary pores. An air void spacing factor, which is the measure of the average distance from any point in the paste to the nearest air void, of less than 0.008 in. (0.20 mm) is suggested to provide sufficient freeze-thaw protection to the concrete (Powers 1954, Backstrom et al. 1954). In addition to the air void parameters, ACI Committee 201 (2016) recommends air content be a function of the nominal maximum aggregate size for protection from freezing and thawing. For example, to ensure adequate protection against freeze-thaw, it is recommended that mixtures containing aggregate with a nominal maximum size of ¾ or 1 inch (19 or 25 mm) and subjected to moderate exposure to freezing-thawing cycles should have an air content ranging from 5 to 8%. The current IC-LC-HPC specifications for bridge deck construction recommend air contents between 6.5 and 9.5% for concrete placement to provide adequate durability and strength (Schmitt and Darwin 1995, Miller and Darwin 2000, Lindquist et al. 2005, Kansas Department of Transportation 2015b).

1.4.3 Effect of Water-Cementitious Material Ratio

The water-cementitious material (*w/cm*) ratio is an especially important factor affecting concrete freeze-thaw durability. This is due to the effect of the *w/cm* ratio on total capillary porosity (Powers and Brownyard 1947) and pore size distribution (Parrott 1989). Powers and Brownyard (1947) observed that a reduction in the *w/cm* ratio from 0.6 to 0.4 resulted in a decrease in the pore volume (capillary and gel pores) in a fully hydrated portland cement paste from 50 to 30%. A lower *w/cm* ratio also results in fewer pores of larger diameter in the cement paste. Additionally, the permeability of the concrete decreases with a decrease in the *w/cm* ratio (Mindess et al. 2003).

The denser pore structure lowers the amount of absorbed water. IC-LC-HPC specifications require water-to-cementitious material ratios in the range of 0.43 to 0.45 (Kansas Department of Transportation 2015b).

1.4.4 Aggregate Freeze-Thaw Damage Mechanism

Freeze-thaw damage can occur in aggregate particles when they become saturated, even if the concrete contains a well-distributed air void system and an appropriate water-to-cementitious material ratio (Powers 1975). Some aggregates that are susceptible to freeze-thaw damage may damage concrete (Mindess et al. 2003). The reason is the pores in some aggregates are larger and can be saturated more easily than those in the smaller capillary pores of cement paste. Freeze-thaw damage in aggregates can be explained by the concept of hydraulic pressure due to the formation of ice within the pores (Transportation Research Board 1979). The water in the saturated capillary pores within aggregates must flow to the exterior surface of aggregate particles to relieve the hydraulic pressure to prevent possible fracture. The maximum distance from the pores to the exterior surface, termed critical size, will determine the likelihood of damage. In larger aggregate particles, the distance is greater than the critical size, making the aggregates more susceptible to fracture because water in the saturated capillary pores cannot flow to the exterior surface of the aggregate to relieve the hydraulic pressure. The effect of aggregate size also depends on the freezing rate, degree of saturation, permeability, and the tensile strength of the aggregate. Aggregates such as granite and high-quality limestones have very little porosity and, thus, low permeability, and do not saturate easily in concrete. Any hydraulic pressure is relieved by the available internal voids. On the other hand, aggregates with high porosity are hard to saturate and can be quickly dried because water can easily escape. A critical situation arises when aggregate with relatively high absorption (resulting due to high porosity) and low permeability is exposed to freezing and thawing conditions. The hydraulic pressure from the water expelled from the aggregate pores can also damage the surrounding cement paste, eventually damaging the concrete (Mindess et al. 2003).

Damage to concrete caused by freeze-thaw damage to aggregate is often described as D-cracking. D-cracking of concrete with non-durable limestone coarse aggregate has been a problem in the Midwest, and multiple studies have been conducted to investigate the causes (Scholer 1928, Gibson 1941, Bukovatz et al. 1973, Stark 1976, Myers and Stallard 1978, KDOT and FHWA 1990, Montney et al. 2008). D-cracking is typically identified in concrete pavements by the presence of crescent-shaped hairline cracks occurring adjacent to and following along joints, cracks, or free edges (KDOT 2007). With time, these cracks coalesce into larger distinct cracks. D-cracking causes serious damage to concrete, with the damage starting from the lower part of a pavement where the moisture accumulates, eventually progressing throughout the structure.

The study of the effect of freezing and thawing on concrete with internal curing (IC) through pre-wetted fine lightweight aggregate (LWA) is important because of the considerable amount of absorbed water that will be released and forced into the surrounding paste when frozen, contributing to concrete deterioration, especially when the concrete is exposed to freezing at early ages (Cusson and Margeson 2010, Jones et al. 2014). In research conducted by Cusson and Margeson (2010), concrete mixtures with IC and supplementary cementitious materials (slag and silica fume) with a water-to-cementitious ratio (*w/cm*) of 0.36 were subjected to 300 cycles of freezing and thawing in accordance with ASTM C666 Procedure A. They observed that the specimens exhibited good freeze-thaw resistance with the relative dynamic modulus of elasticity (E_{DYN}) of the specimens above 95.8%. Bentz and Weiss (2011) noted that freeze-thaw durability might only be of concern if significant amount of water remained in the aggregate before freezing takes place. In contrast to this conclusion, Feng and Darwin (2020) observed that the number of freeze-thaw cycles required to damage test specimens decreased when the IC water was increased from 5.3 to 9.7% (by the weight of cementitious materials). The mixtures contained slag and silica fume (30 and 3% of volume replacement of cement, respectively) as supplementary cementitious material and were tested in accordance with ASTM C666, Procedure B following the extended curing regime required by the Kansas Department of Transportation (KDOT) Test Method KTMR-22. Additionally, Lafikes et al. (2020), through a comprehensive study of the freeze-durability of concrete mixtures with different percentages of IC water by the weight of the cementitious material, suggested that the amount of IC water alone does not sufficiently characterize freeze-thaw durability; when the total internal water (consisting of the water in both the fine lightweight and normalweight aggregates) exceeded 12% by the weight of the cementitious materials, the freeze-thaw resistance of the mixtures decreased.

1.5 SALT SCALING

When concrete is repeatedly exposed to deicing salts and freeze-thaw cycles, scaling damage can occur even when the concrete has durable aggregates and is adequately air entrained. Scaling is characterized by spalling of small pieces of surface mortar, causing the surface to become roughened and pitted (Mindess et al. 2003, Pendergrass and Darwin 2014). Deicing salts such as sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$) are commonly used in regions with colder climates to melt ice on the surface of the concrete to provide safe driving conditions. Salt solutions have a lower vapor pressure than pure water, which lowers the evaporation rate and increases the degree of saturation near the concrete surface compared to surfaces with no exposure to deicing salts (Esmaeeli et al. 2017). The resulting additional free moisture present at the surface of the concrete may accelerate the localized growth of ice lenses, causing spalling on the concrete surface. Additionally, it has been suggested that a rapid change in temperature just below the surface of the concrete occurs due to the consumption of heat that is required to melt the ice in presence of deicing salts (Mindess et al. 2003). This causes differential thermal strains that can fracture concrete paste and mortar. Scaling damage is progressive in nature, inducing more severe damage, such as larger pop-outs of fine and coarse aggregate from the surface over time, although the process starts with the loss of small flakes of the surface mortar. Valenza and Scherer (2007a) observed improved scaling resistance with adequate air entrainment, which they explained as resulting from the decrease in bleed water at the surface and improved general freeze-thaw resistance.

Several mechanisms have been proposed that focus on the role of salts in concrete scaling. The "Glue Spall" mechanism proposed by Valenza and Scherer (2007b) has been supported by some authors (Çopuroğlu and Schlangen 2008, Bahafid et al. 2022). The mechanism is called after glue spalling, a process used in epoxy-coated glass production. When a salt solution freezes on a concrete surface, a bi-material composite of ice/concrete will form. When the temperature is lower than the melting point of the solution, the layer of ice contracts five times more than the concrete beneath it because the thermal expansion coefficient of ice is roughly five times greater than that of concrete. The concentration of the solution determines if the corresponding ice layer will induce tension on the concrete surface, leading to cracks.

When concrete is exposed to deicing salts, such as calcium chloride ($CaCl_2$), the calcium hydroxide ($Ca(OH)_2$) produced during hydration of portland cement reacts with the salt solution to produce the reaction product calcium oxychloride ($3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O$), as shown in Eq. (1.1) (Collepardi et al. 1994).

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow 3Ca(OH)_2 \cdot CaCl_2 \cdot 12H_2O \qquad (0.2)$$

Calcium oxychloride is expansive in nature and causes deterioration of concrete exposed to calcium chloride ($CaCl_2$) (Sutter et al. 2008, Ghazi and Bassuoni 2017). Qiao et al. (2017) constructed an isopleth of the phase diagram shown in Figure 1.1, for calcium oxychloride based on concentration and temperature. They found out that the expansive nature of calcium oxychloride leads to tensile stress in the paste deteriorating the concrete. Concrete in scaling tests that use calcium chloride, such as ASTM C672, is especially vulnerable to the formation of calcium oxychloride. Other tests, such as BNQ NQ 2621-900, use 3% sodium chloride. Thus, the effects of calcium oxychloride formation are not observed in concrete tested in accordance with BNQ NQ 2621-900.

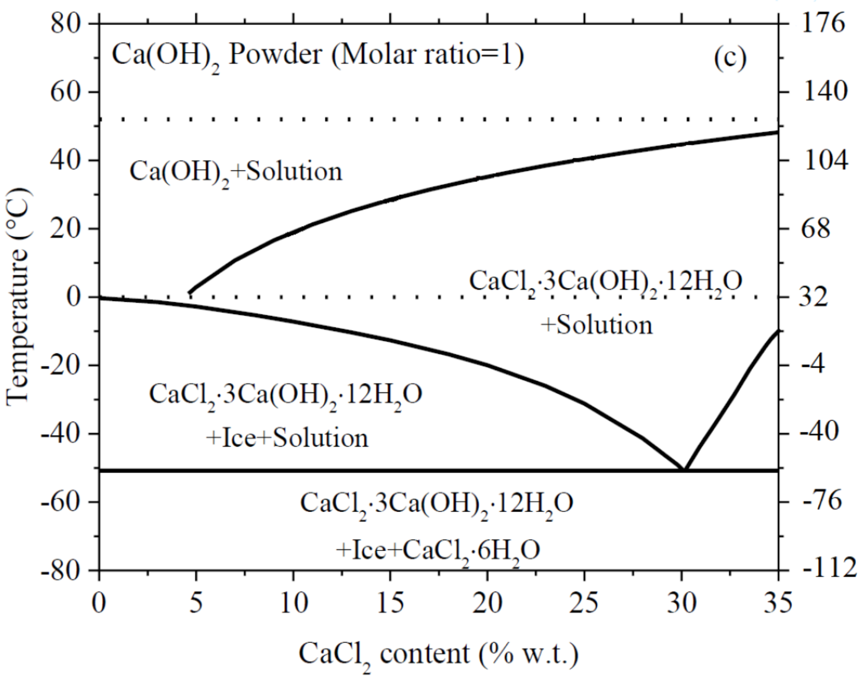

Fig 1.1: Isopleth of the phase diagram of calcium oxychloride (Qiao et al. 2017) – modified

The use of magnesium chloride ($MgCl_2$) as a deicer also has the potential to damage concrete. The magnesium and chloride ions interact with cement hydration products (C-S-H) resulting in the formation of non-cementitious materials such as magnesium silicate hydrate (M-

S-H) and $CaCl_2$ as shown in Eq. (1.2). Additionally, Santhanam et al. (2003) showed that $MgCl_2$ reacts with $Ca(OH)_2$ to form brucite (magnesium hydroxide) and additional $CaCl_2$ as shown in Eq. (1.3). The formation of brucite can cause debonding of fine aggregate by expanding into the interface between the paste and the fine aggregate (Newton and Skyes 1987), and the formation of $CaCl_2$ results in formation of calcium oxychloride, as shown in Eq. (1.1), causing further deterioration.

$$\text{C-S-H} + \text{MgCl}_2 \rightarrow \text{M-S-H} + \text{CaCl}_2 \tag{0.3}$$

$$\text{Ca(OH)}_2 + \text{MgCl}_2 \rightarrow \text{Mg(OH)}_2 + \text{CaCl}_2 \tag{0.4}$$

Improving durability through the use of supplementary cementitious materials (SCMs) such as slag cement, fly ash, and silica fume, as partial replacements of portland cement has had mixed results (Bilodeau et al. 1998, Sutter et al. 2008, Bouzoubaâ et al. 2008, Hooton and Vassilev 2012, Pendergrass and Darwin 2014, Abdul Baki et al. 2020). Bilodeau et al. (1998) evaluated concrete slab mixtures containing Class F fly ash tested in accordance with ASTM C672, but using 3% NaCl solution instead of 4% $CaCl_2$, and found that concrete with fly ash exhibited more scaling than control mixtures (those containing portland cement as the only cementitious material). In studies by Bouzoubaâ et al. (2008), specimens were cast using only portland cement (control mixtures) or using a partial replacement of cement with fly ash or slag, and tested in accordance with ASTM C672 and BNQ NQ 2621-900 for resistance to scaling. They observed that the concrete incorporating fly ash showed more scaling than the control mixtures when tested in accordance with ASTM C672, but had a similar performance to the control mixtures (concrete containing only portland cement) when tested in accordance with BNQ NQ 2621-900. The difference was attributed to the brushing of the surface that is mandated in ASTM C672, which forces the bleed water back into the surface of the concrete, whereas, in BNQ NQ 2621-900, the specimens were simply finished with a wooden trowel and then covered with a plastic sheet without any brushing. This observation is consistent with observations by Thomas (1997) that pointed out that not brushing the surface improves the scaling resistance of a concrete mixture when the bleed water on the surface is minimal. Additionally, mixtures containing a 25% replacement of portland cement with slag cement performed better than control mixtures in both tests. Concrete with a 35% replacement of cement with slag performed in a similar manner to control mixtures when tested in accordance with BNQ NQ 2621-900, but performed poorly when compared with control mixtures tested in accordance with ASTM C672.

Abdul Baki et al. (2020) studied the behavior of concretes with replacement levels of portland cement with 0, 20, 35, and 50% by weight of cement with slag cement or Class C fly ash on scaling resistance in accordance with Quebec Test BNQ NQ 2621-90, for NaCl or$CaCl_2$ salt solutions. For concrete mixtures containing up to a 20% replacement of cement with slag cement or Class C fly ash, $CaCl_2$ caused more scaling than NaCl, but when exposed to either deicing chemical, increasing replacement levels with slag cement or fly ash generally correlated with increased scaling. For concrete mixtures with a 50% replacement of cement with slag cement or Class C fly ash, NaCl caused more scaling than $CaCl_2$. Their recommendation was to use either slag cement or Class C fly ash to replace a maximum of 35% of portland cement to protect the concrete from scaling damage caused by freezing and thawing and exposure to both NaCl or $CaCl_2$. The effects of adding silica fume to concrete mixtures containing 30% slag cement by volume of cementitious materials on scaling resistance in accordance with BNQ NQ 2621-900 were studied by Pendergrass and Darwin (2014). They noted for concrete mixtures containing 30% slag cement, that mixtures with 6% volume replacement of cement by silica fume had a higher mass loss due to scaling damage than mixtures with 3% replacement.

The use of internal curing (IC) through pre-wetted fine lightweight aggregate (LWA) can impact the scaling resistance of concrete mixtures with or without supplementary cementitious materials. Pendergrass and Darwin (2014) observed that the scaling mass loss did not significantly increase in concrete mixtures with 8 and 10% volume replacements of total aggregate with LWA and 100% portland cement for tests conducted in accordance with BNQ NQ 2621-900. However, concrete mixtures containing LWA with a 30% volume replacement of portland cement with slag cement or 3 and 6% volume replacements of portland cement with silica fume exhibited higher mass loss than concrete mixtures with the same volume of LWA and 100% portland cement. Similar observations on scaling resistance in accordance with BNQ NQ 2621-900 were made by Feng and Darwin (2020), where concrete mixtures with IC (5.3 to 9.7% by weight of cementitious material) and without IC exhibited a low mass loss in the scaling test when only portland cement was used as the cementitious materials. However, when both IC and SCMs (volume replacements of portland cement by 30% and 3% slag cement and silica fume, respectively) were used, mass loss was above the acceptable mass loss limit (0.2 lb/ft^2 or 1 kg/m^2). Additionally, for concrete mixtures without IC and volume replacements of portland cement by 30% and 3% slag cement and silica fume, respectively, or 30% volume replacement of portland cement with slag cement, the scaling mass loss was less than for mixtures without IC and only portland cement.

In addition, the mass loss due to scaling is also affected by the salt concentration of the solution. Verbeck and Klieger (1957) found that salt solutions (sodium and calcium chlorides) with concentrations between 2 to 4% produce greater scaling damage than either higher or lower concentrations. Additionally, overfishing and over-consolidation in concrete tend to increase the paste content, air-void spacing factor, and *w/cm* ratio near the surface, which lowers resistance to scaling damage (Bouzoubaa et al. 2008, Bilodeau et al. 1994).

1.6 OBJECTIVE AND SCOPE

The current edition of Kansas Department of Transportation specifications for Internally Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) (2015), provided in Appendix C, specifies that coarse aggregate with absorption of up to 2%, high by normal standards, can be used. In a concrete mixture with normalweight coarse aggregate with a high absorption, the water absorbed by the normalweight coarse aggregate can provide a high amount of IC water in addition to being susceptible to freeze-thaw damage itself, a combination that could present durability issues. The current study aims to examine the effects of total internal (TI) water, provided by both normalweight coarse and fine aggregates and pre-wetted fine lightweight aggregate (LWA), on the durability of concrete mixtures.

Twelve concrete mixtures with different compositions of cementitious materials and TI water contents in the range of 6.8 to 17.3%, by weight of cementitious materials, were tested for scaling resistance and freeze-thaw durability. Three test specimens were cast for each mixture. Concrete mixtures with limestone with an absorption of 1.8%, providing 5.5 to 5.6% IC water by the weight of cementitious materials, are compared with mixtures with granite having an absorption of 0.6%, providing an additional 1.9% IC water. Paired mixtures with the two coarse aggregates were proportioned to provide similar TI water contents. The concrete mixtures contained either portland cement as the only cementitious material or a 30% weight replacement of portland cement with slag cement. The mixtures had a paste content of 24.2% and a water-to-cementitious material (*w/cm*) ratio of 0.43. The air contents ranged from 6.50 to 9.25%. The concrete mixtures were evaluated for freeze-thaw durability following the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22 using ASTM C666 Procedure B for up to 660 freeze-thaw cycles or until the dynamic modulus of elasticity dropped below 60% of its initial value. Scaling tests were performed in accordance with a modified version of BNQ NQ 2621-900 (with minor changes to temperature), where the mass loss was measured through 56 freeze-thaw cycles.

CHAPTER 2 - EXPERIMENTAL PROGRAM

2.1 GENERAL

This chapter describes the experimental program for this study. Twelve concrete mixtures were evaluated to investigate the effects of total internal (TI) water, consisting of absorbed water in both normalweight and pre-wetted fine lightweight aggregate (LWA), on the durability of concrete with different compositions of cementitious materials. Concrete mixtures with limestone (absorption of 1.8%), providing an additional 5.5 to 5.6% internal curing (IC) water by the weight of cementitious materials, is compared with mixtures with granite (absorption of 0.6%), providing an additional 1.9% IC water by the weight of cementitious materials. Six mixtures each with the two coarse aggregates were proportioned to provide similar TI water. The TI water of the mixtures ranged from 6.8 to 17.3%, by the weight of cementitious materials, a water-to-cementitious materials ratio (*w/cm*) of 0.43, and a paste content of 24.2%. The mixtures had different binder compositions (either with portland cement as the only cementitious material or with a 30% replacement of portland cement with slag cement).

The properties of the portland cement, slag cement, normalweight fine and coarse aggregates, LWA, and chemical admixtures used for the concrete mixtures are reported, along with the procedures used to proportion and prepare the concrete, the test methods used to evaluate the concrete mixtures for compressive strength test, scaling resistance, and freeze-thaw durability. Mixture proportions and plastic concrete properties are also described.

2.2 MATERIALS

This section describes the materials used in the concrete mixtures evaluated in the laboratory.

2.2.1 Cement

The cement used in the concrete mixtures in this study was a Type I/II portland cement and was obtained in two samples, C1 and C2, over the period of the study. The cement was both provided and analyzed by the Ash Grove Cement Company. The tests for fineness modulus and specific gravity were performed in accordance with ASTM C204 and ASTM C604, respectively. The chemical analyses for the composition were performed using X-Ray Fluorescence (XRF) elemental analysis using fused beads. The physical and chemical properties are listed in Table 2.1.

Table 2.1: Physical properties and chemical analysis of portland cement

	C1	**C2**
Producer	Ash Grove	Ash Grove
Specific Gravity	3.15	3.15
Blaine Fineness, cm^3/g	265	381
	Percentage by Weight	
XRF Analysis		
SiO_2	20.36	19.95
Al_2O_3	4.68	4.35
Fe_2O_3	3.06	2.92
CaO	62.38	63.30
MgO	2.01	1.96
SO_3	2.80	3.02
Na_2O	0.25	0.24
K_2O	0.57	0.58
TiO_2	0.29	0.26
P_2O_5	0.08	0.08
Mn_2O_3	0.10	0.10
SrO	0.25	0.28
ZnO	0.01	0.01
CuO	-	-
Cl^-	-	0.02
ZrO_2	-	-
LOI	3.14	3.29
Total	99.98	100.36
Eq. Alk.	0.63	0.62
C_3S	-	64
C_2S	-	9
C_3A	-	7
C_4AF	-	9

- Not Tested

2.2.2 Supplementary Cementitious Materials

For the concrete mixtures in the study, only Grade 100 slag cement was used as a supplementary cementitious material. The slag cement was provided by Skyway Cement Company LLC and analyzed by the Ash Grove Cement Company. The physical and chemical properties of the slag cement are listed in Table 2.2.

Table 2.2: Physical properties and chemical analysis of Grade 100 slag cement

Producer	Skyway Cement
Specific Gravity	2.90
Blaine Fineness, cm^3/g	514
	Percentage by Weight
XRF Analysis	
SiO_2	32.38
Al_2O_3	7.41
Fe_2O_3	1.36
CaO	43.04
MgO	8.74
SO_3	2.82
Na_2O	ǂ
K_2O	0.55
TiO_2	0.43
P_2O_5	0.05
Mn_2O_3	0.60
SrO	0.06
ZnO	1.15
CuO	0.49
Cl^-	0.08
ZrO_2	0.03
F^-	ǂ
LOI	0.73
Total	99.92
Eq. Alk.	0.36

ǂ Not Detected

2.2.3 Fine Aggregates

Kansas river sand, from Builder's Choice Aggregates, was used as the normalweight fine aggregate. The tests for specific gravity and absorption were performed in accordance with ASTM

C128. The particle size distribution (gradations) was determined in accordance with ASTM C136. The physical properties and gradation of the sand are listed in Table 2.3.

Table 2.3: Physical properties and gradation of normalweight fine aggregate

Supplier	Builder's Choice
Specific Gravity (SSD)	2.61
Absorption (%) (OD)	0.56
Fineness Modulus	3.04
Sieve Size	**Percent Retained on Each Sieve**
⅜-in. (9.5-mm)	0
No. 4 (4.75-mm)	3.2
No. 8 (2.38-mm)	12.4
No. 16 (1.18-mm)	19.8
No. 30 (0.60-mm)	28.1
No. 50 (0.30-mm)	24.0
No. 100 (0.15-mm)	11.5
No. 200 (0.075-mm)	0.9
Pan	0.1

2.2.4 Coarse Aggregates

Limestone and granite were used as the normalweight coarse aggregates. Limestone was obtained from Builder's Choice and referred to as "L." Granite was obtained from Sunflower Quarry in Kansas. Granite with maximum sizes of ¾ and ½ in. (19 and 13 mm) are referred to as "G-A" and "G-B," respectively. Two size fractions for granite were used to optimize the aggregate gradation and improve concrete workability. The tests for specific gravity and absorption are performed in accordance with ASTM C127. The absorption and the specific gravity provided represent the average of three tests. The particle size distribution (gradations) was determined in accordance with ASTM C136. The physical properties and the gradations of the normalweight coarse aggregates are listed in Table 2.4.

Table 2.4: Physical properties and gradations of normalweight coarse aggregates

	L	**G-A**	**G-B**
Supplier	Builder's Choice	Sunflower Quarry	Sunflower Quarry
Specific Gravity (SSD)	2.60	2.62	2.62
Absorption (%) (OD)	1.82	0.61	0.61
Fineness Modulus	6.40	7.00	6.35
Sieve Size	**Percent Retained on Each Sieve**		
1-½ in. (37.5-mm)	0	0	0
1-in. (25.4-mm)	0	0	0
¾-in. (19-mm)	0.4	0.8	0
½-in. (12.7-mm)	35.8	87.5	7.0
⅜-in. (9.5-mm)	15.5	11.7	37.0
No. 4 (4.75-mm)	39.4	0	50.0
No. 8 (2.38-mm)	5.8	0	3.0
Pan	3.1	0	3.0

2.2.5 Fine Lightweight Aggregates

The method of internal curing (IC) in this study involved partial replacement of normalweight fine aggregate with pre-wetted fine lightweight aggregate (LWA). The LWA used in the concrete mixtures was obtained from Builder's Choice. The tests for the specific gravity and absorption are performed in accordance with ASTM C1761, the specification for lightweight aggregate used for internal curing and ASTM C128 after the LWA was placed in a pre-saturated surface dry (PSD) state. To place the LWA in the PSD state, the aggregate was soaked in water for 72 hours prior to mixing, drained for at least 20 minutes to decant the excess water and placed in a centrifuge following a procedure outlined by Miller et al. (2014). This process has been found to give more consistent results than manually drying the sample with paper towels, the procedure described in ASTM C1761. The absorption and the specific gravity reported represent the average obtained based on four and two tests, respectively. The particle size distribution was determined in accordance with ASTM C136. The physical properties and the gradation of the LWA are listed in Table 2.5.

Table 2.5: Physical properties and gradations of LWA

Supplier	Builder's Choice
Specific Gravity (PSD)	1.58
Absorption (%) (OD)	14.62
Fineness Modulus	4.31
Sieve Size	**Percent Retained on Each Sieve**
⅜-in. (9.5-mm)	0
No. 4 (4.75-mm)	9.1
No. 8 (2.38-mm)	43.7
No. 16 (1.18-mm)	27.3
No. 30 (0.60-mm)	13.3
No. 50 (0.30-mm)	4.3
No. 100 (0.15-mm)	0.5
No. 200 (0.075-mm)	0.3
Pan	1.6

The centrifuge used for placing the LWA in the PSD state is shown in Figure 2.1. A representative sample of LWA with a mass 600 ± 10 g was weighed and designated as M_{WET}. The aggregate was then evenly spread out inside the centrifuge bowl. Four-μm filter paper was placed over the top of the bowl, and the bowl was placed in the centrifuge unit and fastened with the centrifuge bowl lid and nut. The centrifuge housing was used to cover the unit, and secured with clamps. The centrifuge was operated at 2000 revolutions per minute (rpm) for three minutes to place the LWA in the PSD state. The mass of the PSD sample was then weighed and designated as M_{PSD}. The PSD sample is carefully transferred into a bowl and put in an oven for 24 hours to measure the oven-dry mass M_{OD}.

The surface moisture is calculated using Eq. (2.1).

$$\text{Surface Moisture}\,(\%) = \frac{M_{WET} - M_{PSD}}{M_{PSD}} \times 100\% \qquad (2.5)$$

The absorption is calculated using Eq. (2.2).

$$\text{Absorption}\,(\%) = \frac{M_{PSD} - M_{OD}}{M_{OD}} \times 100\% \tag{2.6}$$

where M_{WET} = Mass of pre-wetted LWA (g)
M_{PSD} = Mass of pre-saturated surface dry LWA (g)
M_{OD} = Mass of oven dried LWA (g)

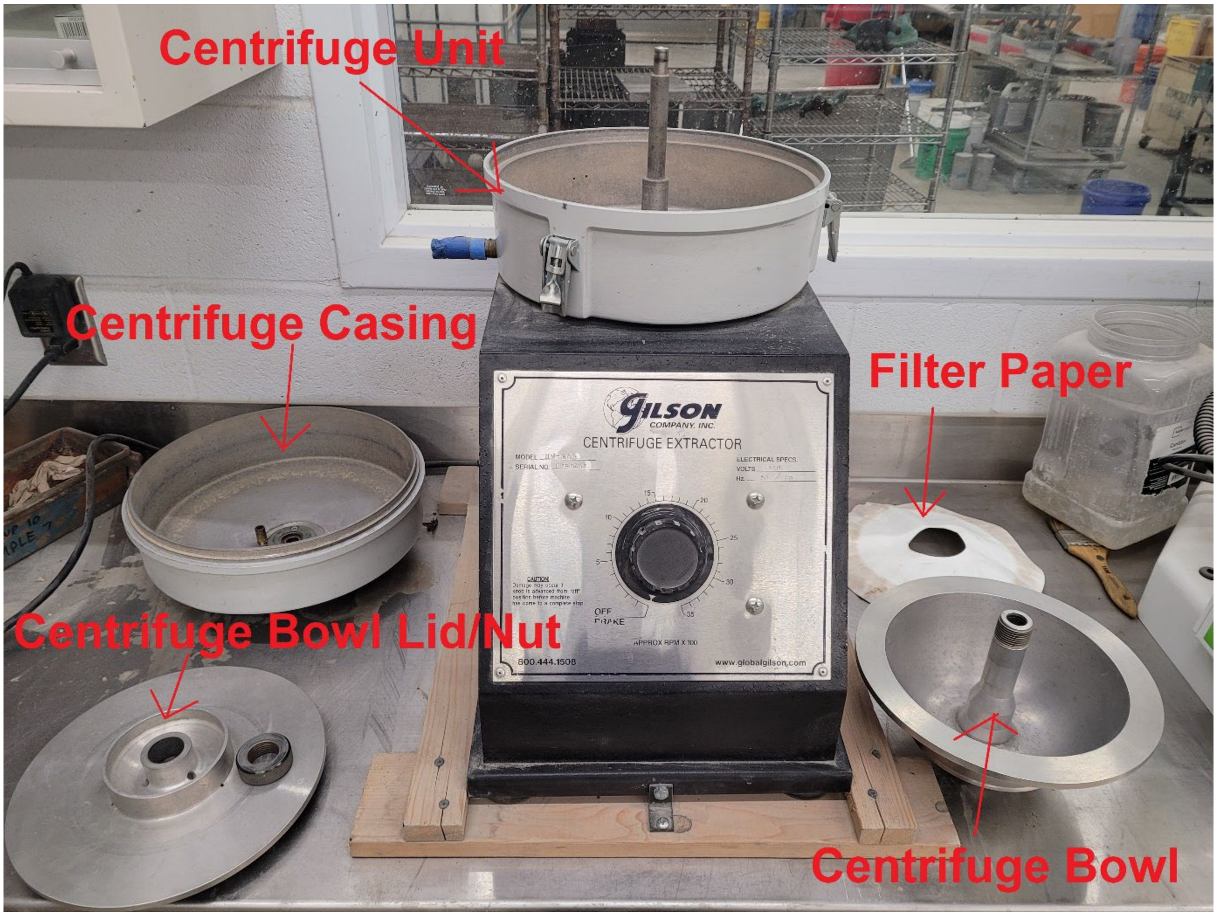

Figure 2.1: Centrifuge used for LWA testing

2.2.6 Chemical Admixtures

The air-entraining admixture (AEA) used in this study was Daravair 1400. Daravair 1400 is based on a high-grade saponified rosin formulation and produced by GCP Applied Technologies. The specific gravity of the admixture is 1.01. The amount of air-entraining admixture was determined using successive trials to produce air contents in the range of 8 ± 1.5%.

The dosages ranged from 0.52 to 1.67 fl oz per 100 lb of cementitious material (fl oz/cwt) (0.33 to 1.08 mL/kg) and the air contents in the mixtures ranged from 6.5 to 9.25%.

2.3 MIXTURE PREPARATION

This section describes the methods used to proportion and prepare the materials, and the mixing procedure used for the concrete used in this study.

2.3.1 Mixture Proportioning and Total Internal (TI) water.

For mixture proportioning, a mix design program developed at the University of Kansas, KU Mix, was used. KU Mix was developed by Lindquist et al. (2008). After specifying the material properties, paste content, and *w/cm* ratio, KU Mix optimizes aggregate gradations to produce workable concrete. The amount of internal curing (IC) water, provided by absorbed water from both normalweight and pre-wetted fine lightweight aggregate (LWA), is determined using Eq. (1.1), which is repeated here. Equation (1.1) was proposed by Bentz and Snyder (1999) to define the design quantity of LWA per yd^3 of concrete:

$$W_{LWA} = \frac{C_f \times IC}{\alpha \times \beta} \tag{0.7}$$

where C_f = Amount of Cementitious Materials (lb/yd^3)

IC = Desired percentage of internal curing water from LWA

α = LWA absorption (oven-dry basis, based on pre-wetting method and duration)

β = LWA desorption at specified RH

For both the normalweight aggregates and LWA, the desorption (as defined by β) is taken as 1.0 based on the work by Castro (2011) and Khayat (2018), who observed that desorption at relative humidity (RH) below 0.9 was above 0.9 and rapidly approached 1.0 once the RH was below 0.85.

The limestone coarse aggregate in this study was used in the construction of internally-cured low-cracking high-performance concrete (IC-LC-HPC) bridge deck located on Montana Rd over I-35 in Ottawa, Kansas. The construction and mixture proportions of this bridge deck are described by Bahadori et al. (2023). The volume percentage of the limestone in the laboratory concrete mixtures equaled to the volume in the concrete mixture used in that deck. The amount of IC water in the limestone was equal to 5.5 or 5.6% by the weight of the cementitious materials. Target IC water contents from the LWA of 0, 7, and 10% by the weight of the cementitious materials were used to determine the quantity of LWA. On the day of batching, due to natural variability in the absorption of LWA, the IC water from LWA varied by up to 1.5% from the target percentage by weight of cementitious materials. Thus, the amount of IC water from LWA ranged from 0 to 10.1% by the weight of cementitious materials and the corresponding amount of IC water from sand ranged from 1.3 to 0.6% by the weight of cementitious materials. The TI water contents (consisting of absorbed water in both normalweight coarse and fine aggregates and LWA) for mixtures with portland cement as the only cementitious material were 6.8, 13.5, and 15.6% by the weight of the cementitious materials, and for mixtures with a 30% weight replacement of portland cement with slag cement, were 6.9, 11.9, and 16.3% by the weight of the cementitious materials.

For the mixtures with granite as the normalweight coarse aggregate, the TI water content was targeted to be the same as the paired mixtures with limestone. The volume of the normalweight coarse aggregates were kept constant throughout the mixtures in the study. The amount of IC water in the granite was equal to 1.9% by the weight of the cementitious materials. The amount of IC water from LWA and sand was selected to provide a TI water content matching that of the paired mixture with limestone. The amount of IC water from LWA ranged from 4.2 to 15.1% by the weight of cementitious materials and the corresponding amount of IC water from sand ranged from

1.1 to 0.3% by the weight of cementitious materials. The TI water in the mixtures with granite differed from target TI water by up to 1.0% by the weight of the cementitious materials. The TI water contents for mixtures with portland cement as the only cementitious material were 7.1, 13.1, and 15.7% by the weight of the cementitious materials, and for mixtures with a 30% weight replacement of slag cement were 7.1, 12.5, and 17.3% by the weight of the cementitious materials.

2.3.2 Mixing Procedure

Prior to mixing, the coarse aggregate was soaked in water for at least 24 hours and then placed in a saturated surface-dry (SSD) state as described in ASTM C127. The free surface moisture of the normalweight fine aggregate (sand) was determined in accordance with ASTM C70. The weight of mixing water batched was adjusted to account for the free surface moisture in the sand.

A counter-current pan mixer was used for mixing. First, the SSD normalweight coarse aggregate and 80% of mixing water were added to the mixer as the blades started rotating. After mixing for 1½ minutes, the portland cement and, when used, slag cement were added and mixed for an additional 1½ minutes. The normalweight and pre-wetted fine lightweight aggregates were then added and mixed for two minutes. Next, 10% of the mixing water was added and the materials were mixed for an additional one minute. The air-entraining admixture along with the remaining 10% of the mixing water was then added over a period of one minute. The materials were now allowed to mix for three additional minutes. After three minutes has passed, the blades were stopped, and the mix was allowed to rest for five minutes. During the resting period, the concrete temperature was checked in accordance with ASTM C1064. After the rest period of five minutes, the concrete was mixed for final three minutes. The mixing time and procedures are summarized in Table 2.6.

Table 2.6: Summary of mixing procedure and time

Constituents added to the mix and procedure	Mixing Period (mins:sec – mins:sec)
Coarse Aggregate + 80% Water	Add all the ingredients before mixing. 00:00 – 01:30
Cement + Slag	01:30 – 03:00
Sand and LWA	03:00 – 05:00
10% Water	05:00 – 06:00
Air Entraining Admixture + 10% Water	06:00 – 07:00
Mixing	07:00 – 10:00
Resting Period	10:00 – 15:00
Mixing	15:00 – 18:00

The slump, air content, and unit weight were tested in accordance with ASTM C143, ASTM C173, and ASTM C138, respectively. Three 4 × 8 in. (100 × 205 mm) cylinders were cast in accordance with ASTM C31 and later tested for compressive strength in accordance with ASTM C39.

2.4 TEST PROCEDURES

The test procedures used in this study are described in this section. Test specimens were cured in lime-saturated water for the period described in the respective sections.

2.4.1 Compressive Strength

The compressive strength of the 4 × 8 in. (100 × 205 mm) was determined in accordance with ASTM C39 after 28 days of curing. The compressive strengths listed in this study are the average of three cylinders.

2.4.2 Scaling Resistance

The test for scaling resistance was performed in accordance with Quebec Test BNQ NQ 2621-900 Annex B, with minor changes to the freeze-thaw cycle temperature range. For the freezing period, BNQ NQ 2621-900 uses a temperature range of -0.4 ± 5.4 °F (-18 ± 3 °C). A temperature of 77 ± 5.4 °F (25 ± 3 °C) was used for the thawing period. There are no relative humidity restrictions in the Quebec Test. In this study, a temperature of 0 ± 5 °F (-18 ± 3 °C) was used during the freezing period and 73 ± 3 °F (23 ± 2 °C) during the thawing period. The relative humidity of the specimens during the thawing period was maintained at 50 ± 4%.

Three size 9 × 16 × 3 in. (230 × 405 × 75 mm) specimens were cast for each mixture using wooden molds. The molds were filled in two equal layers, each layer consolidated at a frequency of 60 Hz on a vibrating table. A 3 × ¾ in. (76 × 19 mm) wooden screed was used to strike off the top surface. Specimens were demolded after 24 hours, labeled, and then cured for 14 days. After curing, the specimens were allowed to dry in an environmentally controlled lab at a temperature of 73 ± 3 °F (23 ± 2 °C) and relative humidity of 50 ± 4% for 14 days. During the drying period, a polyurethane foam dike was placed at the edges of the top surface of the specimens and sealed with a polyurethane sealant, as shown in Figure 2.2. After 14 days of drying, a 3% sodium chloride (NaCl) solution was placed within the dike of each specimen providing a layer of salt solution with depth of at least ¼ in. (6 mm). Specimens were covered with plastic sheets to limit evaporation and kept in the environmentally controlled lab for another seven days. This period is termed the pre-saturation period. Following this period, the specimens were exposed to cycles of freezing and thawing. The freezing phase exposed the specimens to a temperature of 0 ± 5 °F (-18 ± 3 °C) for a period of 16 ± 1 hours. The freezing phase took place each night in a walk-in freezer. Specimens remained in the freezing phase during the weekends. The thawing phase exposed the specimens to a temperature of 73 ± 3 °F (23 ± 2 °C) for a period of 8 ± 1 hours in the environmentally controlled lab with a relative humidity of 50 ± 4%. The loose material generated by scaling of the top surface of the specimen was collected, wet-sieved through a No. 200 (75 µm) sieve, and dried in an oven for at least 24 hours to determine the mass loss after 7, 21, 35, and 56 cycles. The salt solution was changed after each of the mass loss measurements was performed. BNQ NQ 2621-900 considers scaling-resistant mixtures to be those with cumulative mass loss of less than 0.1 lb/ft^2 (0.49 kg/m^2) after 56 cycles.

Figure 2.2: Scaling resistance test specimen with foam dikes attached

2.4.3 Freeze-Thaw Durability

The freeze-thaw durability of the concrete was evaluated in accordance with Procedure B of ASTM C666. Three 16 × 3 × 4 in. (405 × 75 × 100 mm) freeze-thaw specimens were cast in steel molds for each mixture. The specimens were demolded 23½ ± ½ hours after casting and cured in lime-saturated water for 67 days, following the extended curing regime specified in KDOT Test Method KTMR-22. The specimens were then kept in an environmentally controlled room at a relative humidity of 50 ± 4% and a temperature of 73 ± 3 °F (23 ± 2 °C) for 21 days. This was followed by tempering in a water-filled, thermally insulated container maintained at a temperature of 70 °F (21 °C) for 24 hours, and an additional 24 hours in the same container at a temperature of 40 °F (4 °C). The initial fundamental frequency of the specimens was measured before placing the specimens in an automated freeze-thaw machine with continuous cycles of freezing and thawing.

Fundamental frequency was measured in accordance with ASTM C215. The automated freeze-thaw machine exposed the specimens to a freezing temperature of 0 ± 3 °F (-18 ± 2 °C) and a thawing temperature of 40 ± 3 °F (4 ± 2 °C) in a single freeze-thaw cycle.

The fundamental transverse frequency was measured without exceeding 54 freeze-thaw cycles between readings. The specimens were exposed for 660 freeze-thaw cycles or until the dynamic modulus of elasticity dropped below 60% of its initial value. The dynamic modulus of elasticity (E_{Dyn}) was determined for each specimen using Eq. (2.3).

$$E_{Dyn} = C \times M \times n^2 \tag{2.8}$$

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

KDOT Test Method KTMR-22 requires that specimens maintain at least 95% of the initial dynamic modulus of elasticity (E_{Dyn}) through 660 freeze-thaw cycles. In addition, specimens are also evaluated in terms of Durability Factor (DF), as defined in Eq. (2.4).

$$DF = \frac{P \times N}{M} \tag{2.9}$$

where DF = Durability Factor of specimens
P = Percentage of initial E_{Dyn} at N cycles
N = Number of cycles at which specimen has 60% of initial E_{Dyn}, or 660 cycles, whichever is less
M = 660 cycles

2.5 CONCRETE MIXTURES

Twelve concrete mixtures were cast to evaluate the effects of TI water content on the durability of concrete. The mixtures contain either limestone or granite as the normalweight coarse aggregate. The total internal (TI) water (provided by both normalweight and pre-wetted fine lightweight aggregate [LWA]), ranged from 6.8 to 17.3% by the weight of cementitious materials. The mixtures contained either portland cement as the only cementitious material or a 30% replacement of portland cement with slag cement, a paste content of 24.2%, and a water-to-cementitious material (*w/cm*) ratio of 0.43. The concrete mixture proportions are listed in Table 2.7.

Table 2.7: Concrete mixture proportions

Mixture ID[a]	**Material lb/yd^3 (SSD/PSD)**							**AEA**[b] **(fl oz/cwt)**	***w/cm* Ratio**
	Cement (Type I/II)	**G100 Slag**	**Coarse Agg.**		**Fine Agg.**	**Lightweight Agg.**	**Water**		
			L						
C-6.8%-L	546^{C1}	0	1683		1289	0	235	1.55	0.43
C-13.5%-L	546^{C2}	0	1683		775	311	235	1.14	0.43
C-15.6%-L	546^{C1}	0	1683		582	428	235	0.93	0.43
S-6.9%-L	378^{C1}	162	1683		1291	0	232	1.67	0.43
S-11.9%-L	378^{C1}	162	1683		796	308	232	1.25	0.43
S-16.3%-L	378^{C2}	162	1683		584	440	232	1.04	0.43
			G-A	**G-B**					
C-7.1%-G	546^{C2}	0	277	1407	1005	178	235	0.93	0.43
C-13.1%-G	546^{C2}	0	277	1407	506	489	235	0.52	0.43
C-15.7%-G	546^{C2}	0	277	1407	357	582	235	0.52	0.43
S-7.1%-G	378^{C2}	162	277	1407	1031	162	232	0.83	0.43
S-12.5%-G	378^{C2}	162	277	1407	659	395	232	0.73	0.43
S-17.3%-G	378^{C2}	162	277	1407	326	602	232	0.57	0.43

[a] Mixture IDs labeled as ‘D-E-F,’ where:

D: Cementitious material Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % of cementitious materials weight
F: Type of coarse aggregate (L=Limestone, G-A & G-B=Granite with max. size of ¾ and ½ in., respectively)

[b] See Section 2.2.6

C1, C2 – Cement Sources, see Table 2.1

Note: 1 lb/ft^3 = 0.59 kg/m^3; 1 oz/cwt = 0.652 mL/kg

The values of absorption, quantity of IC water from all aggregates, and concrete properties are listed in Table 2.8. As shown in the table, the measured absorption as a percentage of oven-dry (OD) weight of LWA just prior to mixing ranged from 10.8% to 16.1% for concrete mixtures with IC. The amount of IC water ranged from 5.5% to 5.6 % for the limestone and equaled 1.9% for the granite by the weight of the cementitious materials. The amount of IC water provided by LWA ranged from 0 to 15.1% by the weight of the cementitious materials, and the corresponding amount of IC water from the normalweight fine aggregate ranged from 1.3 to 0.3% IC water by the weight of the cementitious materials. The IC water from the normalweight coarse and fine aggregates and LWA summed up to total internal (TI) water, which ranged from 6.8 to 17.3% by the weight of cementitious materials. Slumps ranged from 1 to 3½ in. (25 to 90 mm), while the air contents ranged from 6.50 to 9.25%. The unit weights ranged from 131.5 to 143.5 lb/ft^3 (2106 to 2299 kg/m^3). The wide range in the unit weight resulted from the different quantities of LWA (ranging from 0 to 602 lb/yd^3 [0 to 357.1 kg/m^3]) used to provide the desired amount of IC water. The concrete mixtures with higher quantities of LWA has a lower unit weight. The unit weight of the mix labeled ‘S-11.9%-L’ was not measured while batching. The temperature of the plastic concrete ranged from 64 to 77 °F (17.8 to 25.0 °C). The 28-day compressive strengths ranged from 3730 to 5270 psi (25.7 to 36.3 MPa).

Table 2.8: Internal water and concrete properties

Mixture ID[a]	**LWA Absorption (OD basis) (%)**	**IC water from CA (% Binder Wt.)**	**IC water from FA (% Binder Wt.)**	**IC water from LWA (% Binder Wt.)**	**Total Internal Water (% Binder Wt.)**	**Concrete Properties**				
						Slump (in.)	**Air (%)**	**Unit wt. (lb/ft^3)**	**Temp. (°F)**	**28-day Comp. Strength (psi)**
C-6.8%-L	0.0	5.5	1.3	0.0	6.8	1.75	8.5	142.2	65	4230
C-13.5%-L	14.4	5.5	0.8	7.2	13.5	3	8.5	136.7	68	4240
C-15.6%-L	13.7	5.5	0.6	9.5	15.6	1.75	6.5	138.2	66	5070
S-6.9%-L	0.0	5.6	1.3	0.0	6.9	2	7.75	143.5	64	4550
S-11.9%-L	10.8	5.6	0.8	5.5	11.9	3	9.25	-	64	4290
S-16.3%-L	14.2	5.6	0.6	10.1	16.3	3	9	133.8	65	4530
C-7.1%-G	14.6	1.9	1.0	4.2	7.1	3.5	9.25	135.5	72	3730
C-13.1%-G	13.6	1.9	0.5	10.7	13.1	1.5	8	134.2	74	4750
C-15.7%-G	14.4	1.9	0.4	13.4	15.7	1.5	9	131.5	74	4280
S-7.1%-G	16.1	1.9	1.1	4.2	7.1	1	7.5	140.8	78	4910
S-12.5%-G	15.7	1.9	0.7	9.9	12.5	1.5	7.5	137.1	67	5270
S-17.3%-G	15.7	1.9	0.3	15.1	17.3	1	7	133.6	77	4980

[a] Mixture IDs labeled as ‘D-E-F,’ where:

D: Cementitious material Composition (C=100% portland cement, S=30% replacement of slag cement by weight)

E: Total internal water, % binder weight; F: Type of coarse aggregate (L=Limestone, G=Granite)

-: Not Measured

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

CHAPTER 3 – TEST RESULTS

3.1 GENERAL

This chapter presents the test results of the concrete mixtures described in Chapter 2. The concrete was tested for compressive strength, freeze-thaw durability, and scaling resistance with the latter two used to examine the effects of total internal (TI) water content, provided by both normalweight coarse and fine aggregates and pre-wetted fine lightweight aggregate (LWA), on the durability of concrete. Concrete mixtures with limestone (absorption of 1.8%), which provided 5.5 to 5.6% internal curing (IC) water by the weight of cementitious materials, are compared with mixtures with granite (absorption of 0.6%), which provided 1.9% IC water by the weight of cementitious materials. Overall, TI water contents ranged from 6.8 to 17.3% by the weight of cementitious materials.

The results represent the average of three specimens. Data for individual freeze-thaw test specimens are presented in Appendix A, and data for the individual scaling specimens are presented in Appendix B. The test procedures are described in Chapter 2.

3.1.1 Student's t-test

Student's t-test is used to evaluate differences in results in this study. Student's t-test is a parametric analysis that can be used to determine if the difference in the means between two samples (X_1 and X_2) is a result of the difference in the population means (μ_1 and μ_2). The test compares the sample means based on a probability value or *p*-value, which indicates the probability that the difference between the sample means occurred by chance at a specified level of significance, designated by α, when in fact, there is no difference between the population means. The sample means, sizes, and standard deviations are considered in determining the level of statistical significance. The most commonly used value for α is 0.05, indicating that there is only a 5% chance that the test will mistakenly identify a difference in the sample means when there is actually no difference, or a 95% chance that the test will correctly identify the difference; this was the value selected for this study. Thus, the value of $p \leq 0.05$ indicates that the difference between the two means is statistically significant.

3.1.2 Concrete Mixtures

The main variable used in this study is the quantity of total internal (TI) water, consisting of the water in both the fine lightweight and normalweight fine and coarse aggregates ranging from 6.8 to 17.3%, by the weight of the cementitious materials. The mixtures contained either limestone or granite as the coarse aggregate with different compositions of cementitious materials. Concrete mixtures with limestone with an absorption of 1.8%, providing 5.5 to 5.6% IC water by the weight of cementitious materials, are compared with mixtures with granite with an absorption of 0.6%, providing 1.9% IC water by the weight of cementitious materials. The concrete mixtures contained either portland cement as the only cementitious material or a 30% weight replacement of portland cement with slag cement.

The IC water content from LWA ranged from 0 to 15.1%, the IC water content from the normalweight coarse aggregates was 5.5 or 5.6% from limestone and 1.9% from granite, and the IC water content from the normalweight fine aggregate ranged from 1.3 to 0.3%, decreasing as the quantity of LWA increased, all by the weight of the cementitious materials. The water-to-cementitious material (*w/cm)* ratio was 0.43, and the paste content was 24.2%. The air contents and 28-day compressive strengths ranged from 6.50 to 9.25% and 3730 to 5270 psi (25.7 to 36.3 MPa), respectively.

The naming convention has the form 'D-E-F.' Indicator D represents the binder composition, with C representing concrete mixtures with portland cement as the only cementitious material and S representing mixtures with 30% weight replacement of portland cement with slag cement. The indicator E represents the total internal (TI) water as a percentage of the total weight of the cementitious materials; and the indicator F represents the type of coarse aggregate, with L representing limestone and G representing granite.

Mixtures were evaluated for freeze-thaw durability in accordance with ASTM C666-Procedure B cured under the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22, and for scaling resistance in accordance with Quebec Test BNQ NQ 2621-900 Annex B, with minor changes to the freeze-thaw cycle temperature range. Table 3.1 shows the LWA absorption, IC water from normalweight coarse and fine aggregates, and the total internal (TI) water, along with the 28-day compressive strength of the concrete mixtures.

Table 3.1: LWA absorption, internal water from normalweight coarse and fine aggregates, and LWA, TI water, and compressive strength of concrete mixtures

Mixture ID[a]	LWA Absorption (OD basis) (%)	IC water from CA (% Binder Wt.)	IC water from FA (% Binder Wt.)	IC water from LWA (% Binder Wt.)	Total Water (% Binder Wt.)	28-day Comp. Strength (psi)
C-6.8%-L	0.0	5.5	1.3	0.0	6.8	4230
C-13.5%-L	14.4	5.5	0.8	7.2	13.5	4240
C-15.6%-L	13.7	5.5	0.6	9.5	15.6	5070
S-6.9%-L	0.0	5.6	1.3	0.0	6.9	4550
S-11.9%-L	10.8	5.6	0.8	5.5	11.9	4290
S-16.3%-L	14.2	5.6	0.6	10.1	16.3	4530
C-7.1%-G	14.6	1.9	1.0	4.2	7.1	3730
C-13.1%-G	13.6	1.9	0.5	10.7	13.1	4750
C-15.7%-G	14.4	1.9	0.4	13.4	15.7	4280
S-7.1%-G	16.1	1.9	1.1	4.2	7.1	4910
S-12.5%-G	15.7	1.9	0.7	9.9	12.5	5270
S-17.3%-G	15.7	1.9	0.3	15.1	17.3	4980

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % binder weight
F: Type of coarse aggregate (L=Limestone, G=Granite)
Note: 1 psi = 6.89×10^{-3} MPa

3.2 Freeze-Thaw Durability

As outlined in Section 2.4.3, the freeze-thaw durability of the concrete mixtures was evaluated in accordance with ASTM C666 - Procedure B, following the extended curing regime under Kansas Department of Transportation (KDOT) Test Method KTMR-22, which specifies that the specimen must maintain at least 95% of the initial dynamic modulus of elasticity (E_{DYN}) through 660 freeze-thaw cycles. Freeze-thaw testing is continued through 660 freeze-thaw cycles or until the dynamic modulus drops below 60% of the initial dynamic modulus, whichever was earlier. A factor quantified as the Durability Factor (DF), as defined in Eq. (2.4), is also used to evaluate the freeze-thaw performance. Linear interpolation between the percent of initial dynamic moduli and the number of freeze-thaw cycles is used to determine the number of freeze-thaw cycles corresponding to 95% and 60% of the initial dynamic modulus values (if applicable) for the mixtures. The dynamic modulus of elasticity for each specimen is given in Tables A.1, and A.2 for mixtures with limestone, and granite, respectively.

The twelve mixtures evaluated for testing the freeze-thaw durability of concrete consisted of six with limestone coarse aggregate (absorption of 1.8% on an oven-dry basis) and six with granite coarse aggregate (absorption of 0.6% on an oven-dry basis). Tables 3.2 and 3.3 present the TI water contents, the number of freeze-thaw cycles corresponding to 95% of the initial dynamic modulus of elasticity, and durability factors (DF), along with the air content for the mixtures with limestone and granite, respectively.

Table 3.2: Internal water from all aggregates, air contents, and summary of freeze-thaw results of mixtures with limestone as the coarse aggregate

Mixture ID[a]	IC water from CA (% Binder Wt.)	IC water from FA (% Binder Wt.)	IC water from LWA (% Binder Wt.)	Total Internal Water (% Binder Wt.)	Air Content (%)	No. of Cycles to 95% of initial dynamic modulus of elasticity	Durability Factor[b]
C-6.8%-L	5.5	1.3	0.0	6.8	8.50	153	48
C-13.5%-L	5.5	0.8	7.2	13.5	8.50	260	48
C-15.6%-L	5.5	0.6	9.5	15.6	6.50	278	39
S-6.9%-L	5.6	1.3	0.0	6.9	7.75	150	33
S-11.9%-L	5.6	0.8	5.5	11.9	9.25	137	33
S-16.3%-L	5.6	0.6	10.1	16.3	9.00	208	28

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % binder weight
F: Type of coarse aggregate (L=Limestone, G=Granite)

[b] (DF) = (P × N)/660 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 660 cycles

Table 3.3: Internal water from all aggregates, air contents, and summary of freeze-thaw results of mixtures with granite as the coarse aggregate

Mixture ID[a]	IC water from CA (% Binder Wt.)	IC water from FA (% Binder Wt.)	IC water from LWA (% Binder Wt.)	Total Internal Water (% Binder Wt.)	Air Content (%)	No. of Cycles to 95% of initial dynamic modulus of elasticity	Durability Factor[b]
C-7.1%-G	1.9	1.0	4.2	7.1	9.25	-	100
C-13.1%-G	1.9	0.5	10.7	13.1	8.00	-	98
C-15.7%-G	1.9	0.4	13.4	15.7	9.00	-	96
S-7.1%-G	1.9	1.1	4.2	7.1	7.50	-	100
S-12.5%-G	1.9	0.7	9.9	12.5	7.50	-	98
S-17.3%-G	1.9	0.3	15.1	17.3	7.00	171	31

[a] Mixture IDs labeled as 'D-E-F,' where:
D: Binder Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % binder weight
F: Type of coarse aggregate (L=Limestone, G=Granite)

[b] (DF) = (P × N)/660 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 660 cycles

\- Not measured

Mixtures with limestone coarse aggregate: The average percentages of initial dynamic moduli of concrete mixtures as a function of the number of freezing and thawing cycles for the concrete mixtures with limestone are shown in Figure 3.1. As shown in the figure, all of the mixtures with limestone as the coarse aggregate failed the test (with the average relative E_{DYN} dropping below 95% of the initial value well before the specified 660 freeze-thaw cycles), regardless of the binder composition. The *p*-values obtained from Student's t-test for the difference in the number of cycles at which relative E_{DYN} drops below 95% for mixtures with limestone coarse aggregate are presented in Table A.2. For concrete mixtures with portland cement as the only cementitious material, the number of cycles for the average relative E_{DYN} to drop below 95% of the initial value were 153, 260, and 278 for mixtures with 6.8, 13.5, and 15.6% TI water by the weight of cementitious material (corresponding to 0.0, 7.2, and 9.5% IC water from LWA, respectively by the weight of cementitious material). The difference in the number of cycles is only statistically significant when the TI water content increased from 6.8 to 13.5% by the weight of the cementitious material ($p = 0.01$). This suggests that, for these mixtures with limestone, increasing TI water content above 6.8% by the weight of cementitious materials using more LWA resulted in an increase in the freeze-thaw durability, although all of the mixtures failed the test. For the mixtures with a 30% weight replacement of portland cement with slag cement, the number of cycles for the average relative E_{Dyn} to drop below 95% of the initial value were 150, 137, and 208 for mixtures with 6.9, 11.9, and 16.3% TI water by the weight of cementitious material (corresponding to 0.0, 5.5, and 10.1% IC water from LWA, respectively by the weight of cementitious material). The increase in durability for the mixture with a TI water content of 16.3% by the weight of cementitious materials compared with the other two mixtures was statistically significant ($p < 0.04$), suggesting that a higher TI water content obtained by using more LWA also could benefit the mixtures with a 30% weight replacement of portland cement with slag cement. Additionally, the value of the durability factor of the concrete mixtures with limestone, which depends on the number of cycles at which the average relative E_{DYN} to drop below 60% of the initial value, does not provide a measure of durability that is totally consistent with the observations and analysis based on the number of cycles at which the average relative E_{DYN} drops below 95% of the initial value.

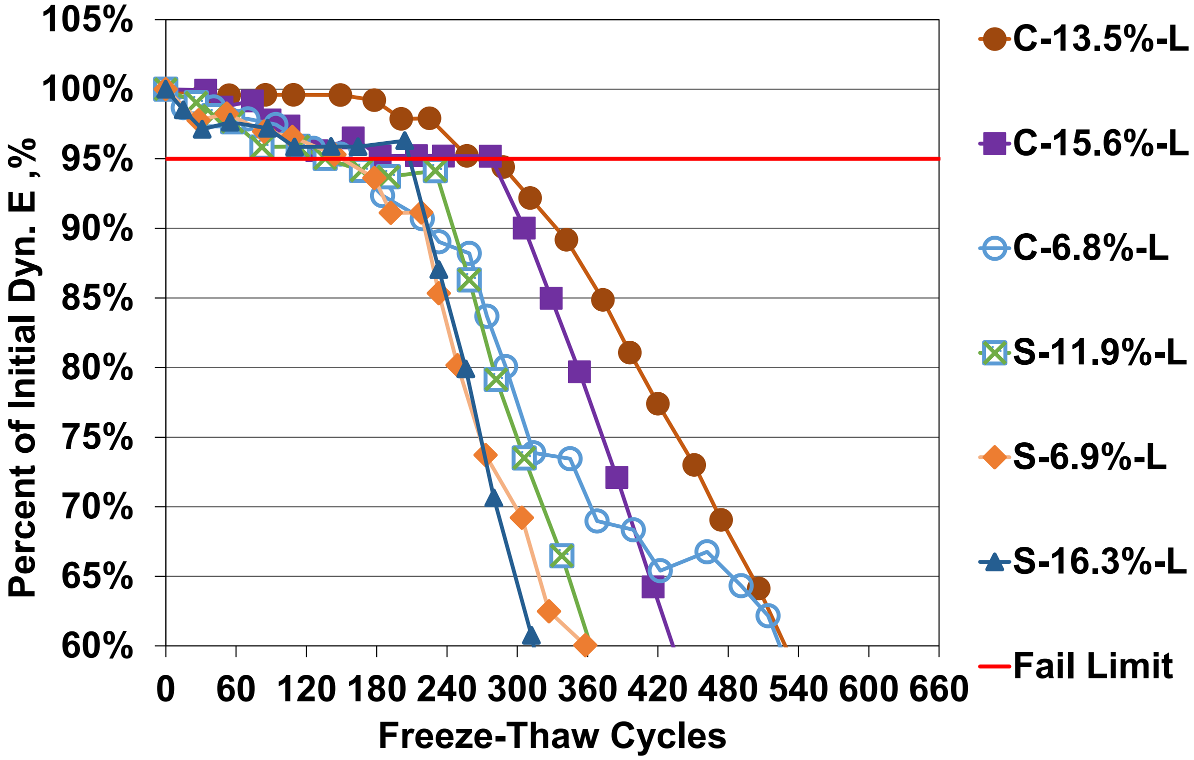

Figure 3.1: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for the mixtures with limestone as the coarse aggregate

Mixtures with granite coarse aggregate: Figure 3.2 shows the average percent of initial dynamic moduli of concrete mixtures as a function of the number of freezing and thawing cycles for concrete mixtures with granite coarse aggregate. All but one of the concrete mixtures had an average relative E_{DYN} above 95% of the initial value at 660 freeze-thaw cycles. That mixture had a TI water content of 17.3% by weight of the cementitious materials (corresponding to 15.1% IC water from LWA) and failed at 171 freeze-thaw cycles. The durability factors (DF) for the mixtures are shown in Table 3.3. The *p*-values obtained from Student's t-test for the differences in the durability factors are presented in Table A.4. The durability factors of the concrete mixtures with portland cement as the only cementitious material and 7.1, 13.1, and 15.7% TI water (corresponding to 4.2, 10.7, and 13.4% IC water from LWA, respectively) by the weight of cementitious material, were 100, 98, and 96%, respectively. For these mixtures, the difference in DF is statistically significant when the TI water content increases from 7.1 to 15.7% by the weight of the cementitious materials ($p = 0.01$). The durability factors of the concrete mixtures with 30% weight replacement of portland cement with slag cement and 7.1, 12.5, and 17.3% TI water (corresponding to 4.2, 9.9 and 15.1% IC water from LWA, respectively) by the weight of cementitious material, were 100, 98, and 31%, respectively. The differences in durability factor for these mixtures are only statistically significant for the increase in the TI water content is above 12.5% ($p < 1.3\times10^{-6}$). Based on these observations, an increase in TI water content by using more LWA lowers the freeze-thaw durability for concrete mixtures with granite, although at least 15.7% TI water (or 13.4% IC water from LWA) is needed to significantly reduce the freeze-thaw durability. These results contrast with to the behavior of mixtures with limestone as a coarse aggregate, in two ways: The overall freeze-thaw durability is measurably better for the mixtures with granite than for the mixtures with limestone coarse aggregate, but for the mixtures with more durable coarse aggregate (granite), increasing the quantity of TI water hurt performance, while the opposite effect of increased TI water was observed for the mixtures with the less durable coarse aggregate (limestone). The use of a 30% weight replacement of portland cement with slag cement in place of portland cement alone did not have a significant effect on the freeze-thaw durability of mixtures with granite when the TI water content was below 15.7%, by the weight of cementitious materials.

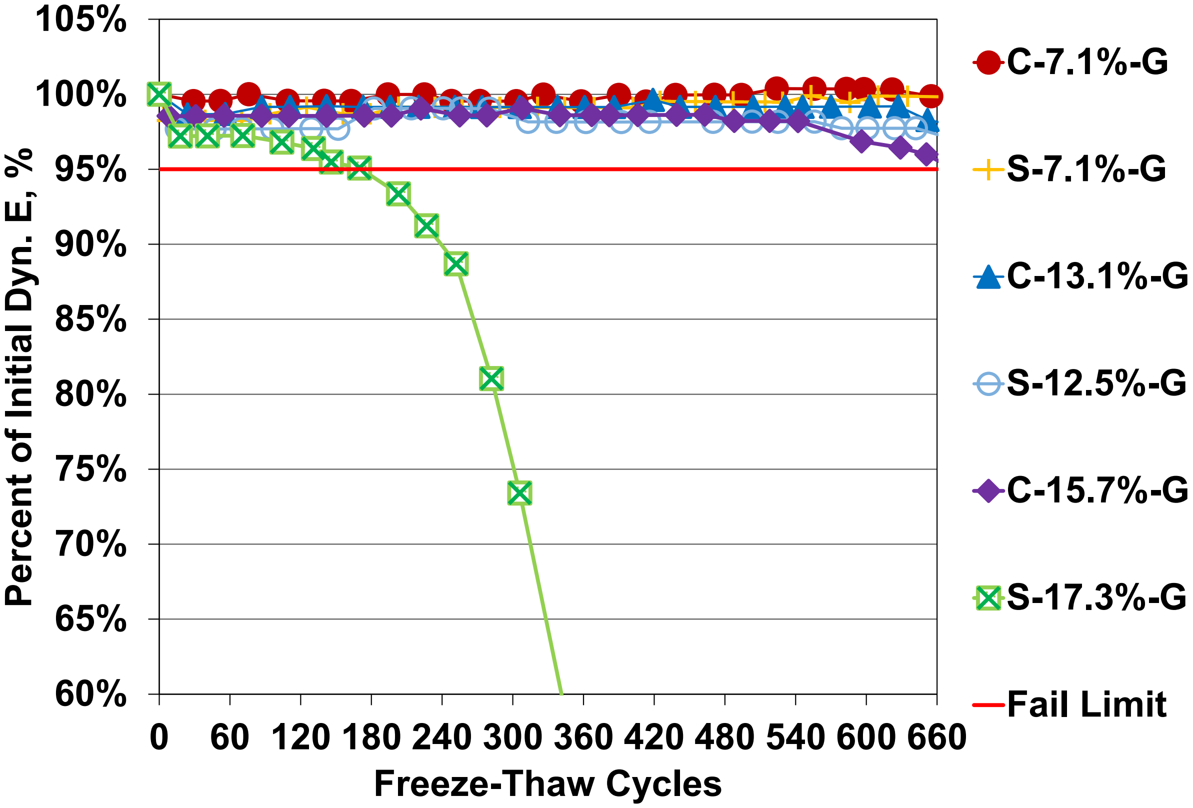

Figure 3.2: Average percent of initial dynamic modulus of elasticity vs. freeze-thaw cycles for the mixtures with granite as the coarse aggregate

Comparison of mixtures: Figure 3.3 shows the durability factors (DFs) of the concrete mixtures with limestone and granite as the coarse aggregate. Except for the highest values of total internal (TI) water for the two coarse aggregates, the limestone mixtures had significantly lower DFs, a difference that is statistically significant at all cases ($p < 1.2 \times 10^{-3}$). Based on these observations, it can be stated that concrete mixtures with limestone would not be considered acceptable under KDOT specifications, while the concrete mixtures with granite and TI water contents of 12.5% and less by the weight of cementitious materials would be considered acceptable.

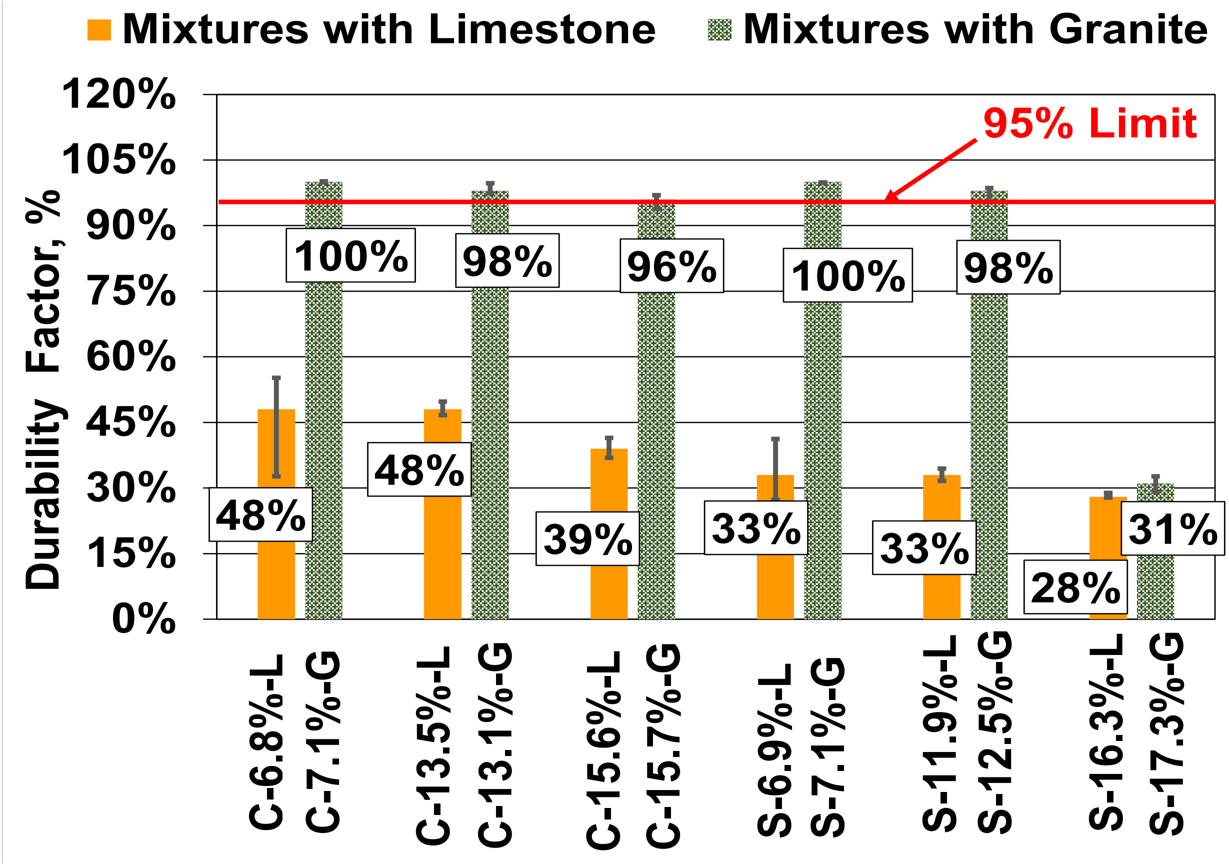

Figure 3.3: Durability factors for the mixtures with limestone and granite as the coarse aggregate

3.3 Scaling resistance

The test for the scaling resistance of the concrete mixtures was performed in accordance with Quebec Test BNQ NQ 2621-900 Annex B, with minor changes to the freeze-thaw cycle temperature range (Section 2.4.2). Mixtures are considered satisfactory if the cumulative mass loss is less than 0.1 lb/ft^2 (0.49 kg/m^2) after 56 freeze-thaw cycles. The cumulative mass losses at 7, 21, 35, and 56 days for each specimen are provided in Tables B.1 and B.2 for concrete mixtures with limestone and granite, respectively. The statistical significance of the differences in the cumulative 56-day mass loss between the mixtures was analyzed using Student's t-test, as described in Section 3.1.1. The *p*-values obtained from Student's t-test for the difference in the cumulative 56-day scaling mass loss are presented in Table B.3.

Mixtures with limestone coarse aggregate: Table 3.4 shows the average cumulative mass losses after 56 freeze-thaw cycles for the concrete mixtures with limestone coarse aggregate. For the mixtures with portland cement as the only cementitious material with 6.8, 13.5, and 15.6% TI water (corresponding to 0.0, 7.2, and 9.5% IC water from LWA, respectively) by the weight of the cementitious materials, the average 56-day cumulative mass loss was 0.012, 0.014, and 0.066 lb/ft^2, respectively. Thus, for these mixtures, increasing the TI water content by using more LWA above 13.5% by the weight of the cementitious material resulted in higher mass loss ($p < 0.01$), but at values that were acceptable. For the mixtures with a 30% weight replacement of portland cement with slag cement with 6.9, 11.9, and 16.3% TI water (corresponding to 0.0, 5.5, and 10.1% IC water from LWA, respectively) by the weight of the cementitious materials, the average 56-day cumulative mass loss was 0.160, 0.063, and 0.054 lb/ft^2, respectively. The mass loss for the mixture with 6.9% TI water was above the failure limit of BNQ NQ 2621-900 (0.1 lb/ft^2), and significantly higher than those with a TI water content of 11.9% or 16.3% by weight of cementitious material ($p < 1.9\times10^{-4}$). Unlike the scaling mass loss results for the mixtures with portland cement as the only cementitious material, where an increase in the TI water content resulted in a reduction in the level of performance, the mixtures with a 30% weight replacement of portland cement with slag cement performed better with an increase in the TI water content, but failed the test for the mixture without the use of LWA, suggesting that the IC water from the LWA may have aided the hydration of the blended cementitious materials, which is usually slower when slag cement is used.

Table 3.4: Internal water from all aggregates and the average cumulative mass loss for concrete mixtures with limestone as the coarse aggregate

Mixture ID[a]	IC water from CA (% Binder Wt.)	IC water from FA (% Binder Wt.)	IC water from LWA (% Binder Wt.)	Total Internal Water (% Binder Wt.)	Average Cumulative Mass Loss (lb/ft^2)
C-6.8%-L	5.5	1.3	0.0	6.8	0.012
C-13.5%-L	5.5	0.8	7.2	13.5	0.014
C-15.6%-L	5.5	0.6	9.5	15.6	0.066
S-6.9%-L	5.6	1.3	0.0	6.9	0.160
S-11.9%-L	5.6	0.8	5.5	11.9	0.063
S-16.3%-L	5.6	0.6	10.1	16.3	0.054

[a] Mixture IDs labeled as ‘D-E-F,’ where:
D: Binder Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % binder weight
F: Type of coarse aggregate (L=Limestone, G=Granite)
Note: 1 lb/ft^2 = 4.88 kg/m^2

Mixtures with granite coarse aggregate: Table 3.5 shows the average cumulative mass loss after 56 freeze-thaw cycles for the mixtures with granite coarse aggregate. For the mixtures with portland cement as the only cementitious material with 7.1, 13.1, and 15.7% TI water content (corresponding to 4.2, 10.7, and 13.4% IC water from LWA, respectively) by the weight of the cementitious materials, the average 56-day cumulative mass loss was 0.008, 0.015, and 0.021 lb/ft^2, respectively. For these mixtures, increasing the TI water content by using more LWA resulted in slightly higher mass losses ($p < 0.04$). For the mixtures with a 30% weight replacement of portland cement with slag cement with 7.1, 12.5, and 17.3% TI water (corresponding to 4.2, 9.9, and 15.1 % IC water from LWA, respectively), by the weight of the cementitious materials, the average 56-day cumulative mass loss was 0.049, 0.036, and 0.073 lb/ft^2, respectively. In contrast with the mixtures with limestone coarse aggregate and a partial replacement of portland cement with slag cement, which benefited from having higher TI water, increasing the TI water content up to 12.5% did not lower mass loss, and the mass loss increased significantly when TI water content was 17.3%, by the weight of cementitious material ($p = 4.9\times10^{-3}$).

Table 3.5: Internal water from all aggregates and the average cumulative mass loss for concrete mixtures with granite as the coarse aggregate

Mixture ID[a]	**IC water from CA (% Binder Wt.)**	**IC water from FA (% Binder Wt.)**	**IC water from LWA (% Binder Wt.)**	**Total Internal Water (% Binder Wt.)**	**Average Cumulative Mass Loss (lb/ft^2)**
C-7.1%-G	1.9	1.0	4.2	7.1	0.008
C-13.1%-G	1.9	0.5	10.7	13.1	0.015
C-15.7%-G	1.9	0.4	13.4	15.7	0.021
S-7.1%-G	1.9	1.1	4.2	7.1	0.049
S-12.5%-G	1.9	0.7	9.9	12.5	0.036
S-17.3%-G	1.9	0.3	15.1	17.3	0.073

[a] Mixture IDs labeled as ‘D-E-F,’ where:
D: Binder Composition (C=100% portland cement, S=30% replacement of slag cement by weight)
E: Total internal water, % binder weight
F: Type of coarse aggregate (L=Limestone, G=Granite)
Note: 1 lb/ft^2 = 4.88 kg/m^2

Comparison of mixtures: Figure 3.4 shows the 56-day cumulative mass losses of the concrete mixtures with limestone and granite as the coarse aggregate. The mixtures with portland cement as the only cementitious material have lower mass losses than the mixtures with a 30% weight replacement of portland cement with slag cement for the same coarse aggregate and a similar TI water content in all but one case. For that case, the mixture with limestone, portland cement as the only cementitious material, and 15.6% TI water by the weight of cementitious material has a mass loss of 0.066 lb/ft^2, which is higher than the mass loss of 0.054 lb/ft^2 for the mixture with limestone, a 30% weight replacement of portland cement with slag cement, and 16.3% TI water content, by the weight of cementitious material. This difference, however, is not statistically significant ($p = 0.42$), whereas the other differences are ($p < 1.4\times10^{-2}$). The higher scaling losses for the mixtures containing slag cement match those of Abdul Baki et al. (2020), as described in Chapter 1. Additionally, for mixtures with similar TI water contents but different coarse aggregates, the mixtures with granite have lower mass loss than mixtures with limestone in all but two cases: For the mixtures with portland cement as the only cementitious material, the mixture with limestone coarse aggregate and 13.5% TI water content by the weight of cementitious material has a slightly lower mass of 0.014 lb/ft^2 compared to mass loss of 0.015 lb/ft^2 in mixture with granite coarse aggregate and 13.1% TI water content. For the mixtures with 30% weight replacement of portland cement with slag cement, the mixture with limestone coarse aggregate and 16.3% TI water content has a lower mass of 0.054 lb/ft^2 compared to mass loss of 0.073 lb/ft^2 in mixture with granite coarse aggregate and 17.1% TI water content by the weight of cementitious material. In neither case, however, is the difference statistically significant ($p > 0.09$).

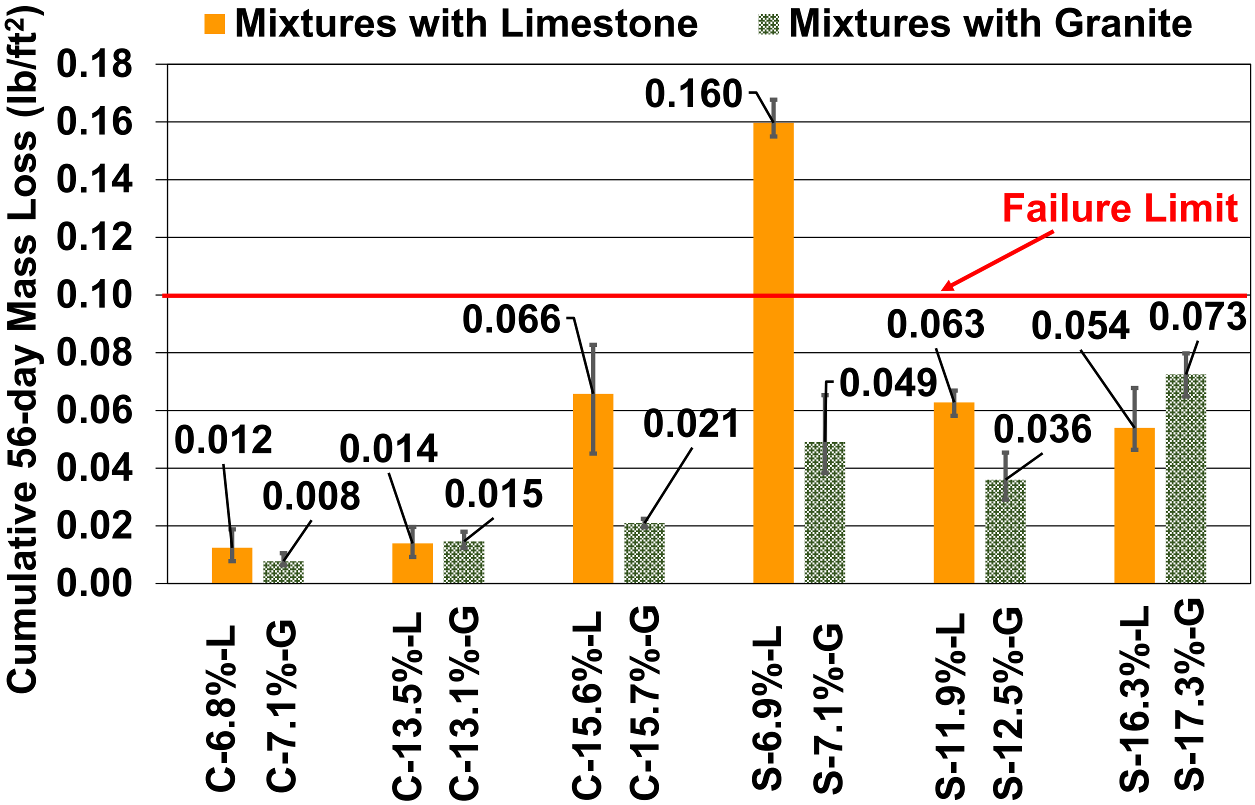

Figure 3.4: Cumulative 56-day scaling mass loss for the mixtures with limestone and granite as the coarse aggregate

3.4 SUMMARY OF FINDINGS

The Kansas Department of Transportation specifications for Internally Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) (2015), provided in Appendix C, specifies that coarse aggregate with absorption of up to 2%, high by normal standards, can be used for structural concrete. In a concrete mixture with coarse aggregate with a high absorption, the water absorbed by the coarse aggregate can provide a high amount of internal curing (IC) water in addition to being susceptible to freeze-thaw damage itself, a combination that could present durability issues. Lafikes et al. (2020) suggested that the total absorbed water or total internal (TI) water content (consisting of the water in both the fine lightweight and normalweight aggregates) is a better indicator of concrete durability than just the amount of IC water from pre-wetted fine lightweight aggregate (LWA) alone, a factor that becomes important when a high-absorption normalweight aggregates are used.

Based on the observations and analyses in Section 3.2 discussing the freeze-thaw durability of concrete mixtures with similar TI water contents tested in accordance with ASTM C666-Procedure B and KTMR-22, the mixtures with limestone coarse aggregate, with an absorption of 1.8%, would not be considered acceptable under KDOT specifications. Furthermore, the test results for mixtures containing limestone provide no useful information on the effect of TI water content obtained by changing the quantity of pre-wetted fine lightweight aggregate (LWA) because all of the mixtures failed the test. The tests do demonstrate that the limestone itself is susceptible to freeze-thaw damage, although it may be applicable in field applications where concrete is permitted to fully dry before exposure to freeze-thaw conditions. Thus, the KDOT specifications for Internally Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) (2015), which specifies that coarse aggregate with absorption of up to 2% can be used, does not ensure that aggregate will be acceptable when tested for freeze-thaw durability in accordance with ASTM C666-Procedure B and KTMR-22.

In contrast to the limestone mixtures, the mixtures containing granite coarse aggregate, with an absorption of 0.6%, performed well at TI water contents up to 15.7% (corresponding to an IC water content of 13.4% from the LWA) by the weight of cementitious materials. The only mixture that did not sustain a relative E_{DYN} above 95% of the initial value at 660 freeze-thaw cycles was the mixture with a 30% weight replacement of portland cement with slag cement and a TI water content of 17.3% by weight of the cementitious materials (corresponding to 15.1% IC water from LWA). This result indicates that it is possible to have too much internal curing water, and in this case, a value of TI water above 15.7% or an (IC water content above 13.4% from the LWA) is not recommended.

Based on observations and analysis in Section 3.3 discussing the scaling resistance of concrete in accordance with BNQ NQ 2621-900, the mixtures with granite coarse aggregate generally performed better in scaling test than mixtures with limestone coarse aggregate. Of the twelve mixtures, only the mixture with limestone coarse aggregate and a 30% weight replacement of portland cement with slag cement containing no IC water from LWA failed the test. The mixtures with limestone coarse aggregate and 30% weight replacement of portland cement with slag cement appear to have benefited from higher TI water content provided by the LWA. These results suggest that the IC water from the LWA may have aided the hydration of the blended cementitious materials, which is usually slower when slag cement is used. The increase in TI water content by using more LWA correlated with increased mass loss when portland cement was used as the only cementitious material for mixtures with limestone coarse aggregate, but these mixtures, nevertheless, passed the test. For concrete with granite coarse aggregate, the mass loss increased slightly with increased TI water content when portland cement was used as the only cementitious material. When a 30% weight replacement of portland cement with slag cement was used, the mass loss increased significantly for a TI water content above 12.5%, but remained below the failure limit, suggesting no benefits for higher TI water content. Additionally, the mixtures with portland cement as the only cementitious material had lower mass losses than the mixtures with a 30% weight replacement of portland cement with slag cement for the same coarse aggregate. This result matches the observations by Abdul Baki et al. (2020), who stated that increasing replacement levels with slag cement generally correlated with increased scaling. As described in Chapter 1, recommended IC water contents for internal curing are in the range of 7 to 8% by weight of cementitious materials (Bentz and Weiss 2011, Bitnoff 2014, Barrett et al. 2015, Kansas Department of Transportation 2015, Lafikes et al. 2018), corresponding to TI water contents of about 14% and about 10% for the limestone and granite mixtures evaluated in this study. The current study provides no evidence that it would be advantageous to stray much above these values.

CHAPTER 4 – SUMMARY AND CONCLUSIONS

4.1 SUMMARY

The study examines the effects of total internal (TI) water, provided by both normalweight coarse and fine aggregates and pre-wetted fine lightweight aggregate (LWA), on the durability of concrete mixtures. Twelve concrete mixtures with either limestone or granite as the coarse aggregate, different compositions of cementitious materials, and TI water contents in the range of 6.8 to 17.3% by weight of cementitious materials, corresponding to internal curing (IC) water in the LWA ranging from 0 to 15.1%, were tested for freeze-thaw durability and scaling resistance. Multiple studies have recommended an IC water content from LWA of 7 or 8%, by the weight of cementitious materials in a concrete mixture. Concrete mixtures with limestone with an absorption of 1.8%, that provides 5.5 to 5.6% IC water by the weight of cementitious materials, are compared with mixtures with granite with an absorption of 0.6%, that provides 1.9% IC water. Mixtures with the two coarse aggregates were proportioned to provide similar TI water contents. The mixtures contained either portland cement as the only cementitious material or a 30% weight replacement of portland cement with slag cement. The mixtures had a paste content of 24.2% and a water-to-cementitious material (*w/cm*) ratio of 0.43. The air contents ranged from 6.50 to 9.25%. The concrete mixtures were evaluated for freeze-thaw durability following the regime specified in Kansas Department of Transportation (KDOT) Test Method KTMR-22 using ASTM C666 Procedure B for up to 660 freeze-thaw cycles or until the dynamic modulus of elasticity dropped below 60% of its initial value. Scaling tests were performed in accordance with a modified version of BNQ NQ 2621-900, where the mass loss is measured through 56 freeze-thaw cycles.

4.2 CONCLUSIONS

The following conclusions are based on the results of this study.

1. All of the mixtures with limestone coarse aggregate failed the test, with the average dynamic modulus of elasticity (E_{DYN}) dropping below 95% of the initial value well before the specified 660 freeze-thaw cycles, demonstrating that the limestone itself is susceptible to freeze-thaw damage and, thus, would not be considered acceptable under KDOT specifications. Thus, the results for these mixtures provide no useful information on the effect of TI water content on freeze-thaw durability or the effect of changing the amount of IC water provided by the pre-wetted fine lightweight aggregate (LWA) on freeze-thaw durability.
2. The KDOT specifications for Internally Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) (2015), which specify that coarse aggregate with an absorption of up to 2% can be used, does not ensure that the aggregate will be acceptable when tested for freeze-thaw durability in accordance with ASTM C666-Procedure B and KTMR-22.
3. The mixtures containing granite coarse aggregate performed well and had an average relative E_{DYN} above 95% of the initial value at 660 freeze-thaw cycles in the test of freeze-thaw durability at TI water contents up to 15.7% (corresponding to an IC water content of 13.4% from the LWA) by the weight of cementitious materials. The only mixture with granite coarse aggregate that failed had a 30% weight replacement of portland cement with slag cement and a TI water content of 17.3% by weight of the cementitious materials (corresponding to 15.1% IC water from LWA). This result indicates that it is possible to have too much internal curing water, and for the materials used in this study, a value of TI water above 15.7% or an (IC water content above 13.4% from the LWA) is not recommended.

4. The mixtures with granite coarse aggregate generally performed better and had lower mass losses in the scaling test than mixtures with limestone coarse aggregate, although all but one of the twelve mixtures had a cumulative 56-day mass loss lower than 0.1 lb/ft^2, and thus passed the test. All of the mixtures with granite coarse aggregate contained pre-wetted fine lightweight aggregate (LWA).
5. The only mixture that failed the scaling test (cumulative 56-day mass loss greater than 0.1 lb/ft^2) had limestone as the coarse aggregate and a 30% weight replacement of portland cement with slag cement and contained no IC water from LWA. The limestone mixtures with IC water provided by the LWA passed the tests, as did the limestone mixture with portland cement as the only cementitious material, with or without IC water from LWA. This suggests that the scaling observed for the mixture with the 30% weight replacement of portland cement with slag cement and no IC water may have been due to limited pozzolanic activity.
6. For concrete with granite coarse aggregate, the mass loss increased slightly with increased TI water content when portland cement was used as the only cementitious material. When a 30% weight replacement of portland cement with slag cement was used, the mass loss increased for a TI water content above 12.5% (corresponding to 9.9% IC water from LWA), but remained below the failure limit, suggesting no benefits for higher TI water content above 12.5%, by the weight of cementitious materials.
7. The mixtures with portland cement as the only cementitious material had lower mass losses than the mixtures with a 30% weight replacement of portland cement with slag cement for the same coarse aggregate.

4.3 RECOMMENDATIONS

The following recommendation is based on the results of this study.

1. The recommended water contents from pre-wetted fine lightweight aggregate (LWA) for internal curing (IC) are in the range of 7 to 8% by weight of cementitious materials, which correspond to total internal (TI) water contents of about 14% and 10% for the limestone and granite mixtures evaluated in this study. The current study provides no evidence that it would be advantageous to stray much above these values and demonstrates that high values of TI/ IC water can be deleterious.

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APPENDIX A: FREEZE-THAW RESULTS

Table A.1: Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-6.8%-L									
Cycles	**0**			**15**			**41**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2167.97**	**2153.32**	**2167.97**	**2153.32**	**2138.67**	**2153.32**	**2153.32**	**2138.76**	**2153.32**
Mass [g]	**7406.6**	**7504**	**7315.4**	**7408.1**	**7505.8**	**7316.3**	**7410.7**	**7510**	**7320.2**
$E_{Dyn.}$ [Pa]	3.8E+10	3.8E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.76E+10			3.71E+10			3.71E+10		

Mixture: C-6.8%-L									
Cycles	**54**			**70**			**94**		
Specimen	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**C**
Frequency [Hz]	**2138.67**	**2124.02**	**2138.67**	**2124.02**	**2138.67**	**2124.02**	**2124.02**	**2124.02**	**2153.32**
Mass [g]	**7412.7**	**7511.9**	**7412.7**	**7511.9**	**7412.7**	**7511.9**	**7417.8**	**7515.8**	**7326.8**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.7E+10	3.6E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.68E+10			3.68E+10			3.66E+10		

Mixture: C-6.8%-L									
Cycles	**126**			**149**			**185**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2109.38**	**2138.67**	**2080.08**	**2109.38**	**2138.67**	**2036.13**	**2080.08**	**2109.39**
Mass [g]	**7423.4**	**7520.3**	**7331.2**	**7425.8**	**7522.4**	**7333**	**7432.2**	**7528.1**	**7337.7**
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.6E+10	3.5E+10	3.6E+10	3.6E+10	3.3E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.60E+10			3.58E+10			3.47E+10		

Mixture: C-6.8%-L									
Cycles	**219**			**233**			**259**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**2080.08**	**2094.73**	**1962.89**	**2065.43**	**2080.08**	**1948.24**	**2065.43**	**2065.43**
Mass [g]	**7437.2**	**7529**	**7343.3**	**7440.7**	**7532.9**	**7345.3**	**7439.8**	**7534.7**	**7347.7**
$E_{Dyn.}$ [Pa]	3.2E+10	3.5E+10	3.5E+10	3.1E+10	3.5E+10	3.4E+10	3.1E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.41E+10			3.34E+10			3.31E+10		

Mixture: C-6.8%-L									
Cycles	**274**			**290**			**314**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1860.35**	**2050.78**	**2006.84**	**1801.76**	**2006.84**	**1977.54**	**1699.22**	**1962.89**	**1889.65**
Mass [g]	**7440.3**	**7533.7**	**7348**	**7444**	**7537.1**	**7350.1**	**7446.91**	**7540.9**	**7353.2**
$E_{Dyn.}$ [Pa]	2.8E+10	3.4E+10	3.2E+10	2.6E+10	3.3E+10	3.1E+10	2.3E+10	3.1E+10	2.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.14E+10			3.01E+10			2.77E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-6.8%-L									
Cycles	**345**			**368**			**399**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1728.52**	**1962.89**	**1845.7**	**1640.63**	**1918.95**	**1801.76**	**1611.33**	**1933.59**	**1787.11**
Mass [g]	**7449.1**	**7543.2**	**7354.7**	**7449.9**	**7545.9**	**7358**	**7450.4**	**7546.1**	**7359.9**
$E_{Dyn.}$ [Pa]	2.4E+10	3.1E+10	2.7E+10	2.2E+10	3.0E+10	2.6E+10	2.1E+10	3.1E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.76E+10			2.59E+10			2.57E+10		

Mixture: C-6.8%-L									
Cycles	**422**			**462**			**491**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1567.38**	**1904.3**	**1743.16**	**1611.33**	**1904.3**	**1757.81**	**1567.38**	**1889.65**	**1713.87**
Mass [g]	**7449.3**	**7545.2**	**7357.5**	**7449.7**	**7543.2**	**7354.3**	**7454.2**	**7549.4**	**7362.2**
$E_{Dyn.}$ [Pa]	2.0E+10	3.0E+10	2.4E+10	2.1E+10	3.0E+10	2.5E+10	2.0E+10	2.9E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.46E+10			2.51E+10			2.42E+10		

Mixture: C-6.8%-L									
Cycles	**514**			**538**			**570**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1523.44**	**1845.7**	**1713.87**	**1450.2**	**1787.11**	**1625.98**	**1362.3**	**1728.52**	**1567.38**
Mass [g]	**7454.8**	**7551.5**	**7363.1**	**7458**	**7554.2**	**7366.2**	**7457.4**	**7555.4**	**7366.2**
$E_{Dyn.}$ [Pa]	1.9E+10	2.8E+10	2.3E+10	1.7E+10	2.6E+10	2.1E+10	1.5E+10	2.4E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.34E+10			2.14E+10			1.97E+10		

Mixture: C-6.8%-L									
Cycles	**601**			**624**			**655**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1303.71**	**1669.92**	**1479.49**	**1274.41**	**1640.63**	**1450.2**	**1215.82**	**1567.38**	**1420.9**
Mass [g]	**7459.7**	**7557**	**7367.2**	**7460.5**	**7558**	**7368.7**	**7467.4**	**7562.1**	**7343.3**
$E_{Dyn.}$ [Pa]	1.4E+10	2.3E+10	1.7E+10	1.3E+10	2.2E+10	1.7E+10	1.2E+10	2.0E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	1.80E+10			1.73E+10			1.61E+10		

Mixture: C-6.8%-L			
Cycles	**686**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1157.23**	**1508.79**	**1376.95**
Mass [g]	**7463.7**	**7560.8**	**7313.3**
$E_{Dyn.}$ [Pa]	1.1E+10	1.9E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	1.48E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-13.5%-L									
Cycles	**0**			**31**			**54**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2124.02**	**2080.08**	**2080.08**	**2109.38**	**2080.08**	**2080.08**	**2109.38**
Mass [g]	**7030.6**	**7062.5**	**7067.7**	**7030.1**	**7060.7**	**7069**	**7032.8**	**7063.7**	**7071.8**
E$_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.5E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10
Avg. E$_{Dyn.}$ [Pa]	3.35E+10			3.34E+10			3.34E+10		

Mixture: C-13.5%-L									
Cycles	**85**			**109**			**149**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2109.38**	**2080.08**	**2080.08**	**2109.38**	**2080.08**	**2080.08**	**2109.38**
Mass [g]	**7035.4**	**7066.1**	**7073.8**	**7035.1**	**7066**	**7073.7**	**7035**	**7063.9**	**7072**
E$_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10
Avg. E$_{Dyn.}$ [Pa]	3.34E+10			3.34E+10			3.34E+10		

Mixture: C-13.5%-L									
Cycles	**178**			**201**			**225**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2080.08**	**2109.38**	**2050.78**	**2065.43**	**2094.73**	**2050.78**	**2065.43**	**2094.73**
Mass [g]	**7041**	**7071.5**	**7079.2**	**7043.7**	**7074.2**	**7082.1**	**7048.1**	**7077.5**	**7085.1**
E$_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10	3.2E+10	3.3E+10	3.4E+10
Avg. E$_{Dyn.}$ [Pa]	3.33E+10			3.28E+10			3.28E+10		

Mixture: C-13.5%-L									
Cycles	**257**			**288**			**311**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2036.13**	**2065.43**	**2006.84**	**2021.48**	**2065.43**	**1977.54**	**1992.19**	**2050.78**
Mass [g]	**7051.1**	**7082.3**	**7089.4**	**7059.8**	**7089.4**	**7094.9**	**7059.4**	**7090.2**	**7098.2**
E$_{Dyn.}$ [Pa]	3.1E+10	3.2E+10	3.3E+10	3.1E+10	3.1E+10	3.3E+10	3.0E+10	3.0E+10	3.2E+10
Avg. E$_{Dyn.}$ [Pa]	3.19E+10			3.17E+10			3.09E+10		

Mixture: C-13.5%-L									
Cycles	**342**			**373**			**396**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1948.24**	**1962.89**	**2006.84**	**1904.3**	**1904.3**	**1962.89**	**1860.35**	**1860.35**	**1918.95**
Mass [g]	**7069.5**	**7100.8**	**7107.1**	**7071.4**	**7104.2**	**7111.9**	**7074**	**7108.3**	**7115.2**
E$_{Dyn.}$ [Pa]	2.9E+10	3.0E+10	3.1E+10	2.8E+10	2.8E+10	3.0E+10	2.7E+10	2.7E+10	2.8E+10
Avg. E$_{Dyn.}$ [Pa]	2.99E+10			2.85E+10			2.72E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-13.5%-L									
Cycles	**420**			**451**			**474**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1801.76**	**1889.65**	**1757.81**	**1743.16**	**1845.7**	**1713.87**	**1699.22**	**1787.11**
Mass [g]	**7078.7**	**7113.5**	**7121.2**	**7082.3**	**7118**	**7125.7**	**7083.6**	**7119.6**	**7127**
$E_{Dyn.}$ [Pa]	2.5E+10	2.5E+10	2.8E+10	2.4E+10	2.3E+10	2.6E+10	2.3E+10	2.2E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.60E+10			2.45E+10			2.32E+10		

Mixture: C-13.5%-L									
Cycles	**506**			**538**			**561**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1655.27**	**1625.98**	**1728.52**	**1596.68**	**1523.44**	**1655.27**	**1552.73**	**1494.14**	**1611.33**
Mass [g]	**7086.6**	**7123**	**7131.1**	**7089.9**	**7125.9**	**7132.6**	**7091.3**	**7126.5**	**7133.1**
$E_{Dyn.}$ [Pa]	2.1E+10	2.0E+10	2.3E+10	2.0E+10	1.8E+10	2.1E+10	1.9E+10	1.7E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	2.15E+10			1.96E+10			1.86E+10		

Mixture: C-13.5%-L									
Cycles	**586**			**619**			**642**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1523.44**	**1494.14**	**1611.33**	**1464.84**	**1420.9**	**1538.09**	**1420.9**	**1362.3**	**1494.14**
Mass [g]	**7094.6**	**7129**	**7135.6**	**7096.2**	**7131.6**	**7131.9**	**7096.2**	**7132.2**	**7132.5**
$E_{Dyn.}$ [Pa]	1.8E+10	1.7E+10	2.0E+10	1.7E+10	1.6E+10	1.8E+10	1.6E+10	1.4E+10	1.7E+10
Avg. $E_{Dyn.}$ [Pa]	1.84E+10			1.68E+10			1.57E+10		

Mixture: C-13.5%-L			
Cycles	**672**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**1362.3**	**1289.06**	**1450.2**
Mass [g]	**7096.4**	**7135.8**	**7130.3**
$E_{Dyn.}$ [Pa]	1.4E+10	1.3E+10	1.6E+10
Avg. $E_{Dyn.}$ [Pa]	1.45E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-15.6%-L									
Cycles	**0**			**34**			**48**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2094.73**	**2094.73**	**2109.38**	**2094.73**	**2094.73**
Mass [g]	**7206.9**	**7024.6**	**7169.4**	**7207**	**7204.8**	**7170.4**	**7214.4**	**7030.9**	**7176.2**
$E_{Dyn.}$ [Pa]	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.45E+10			3.41E+10		

Mixture: C-15.6%-L									
Cycles	**74**			**89**			**105**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2094.73**	**2094.73**	**2109.38**	**2080.08**	**2080.08**	**2094.73**	**2080.08**	**2080.08**
Mass [g]	**7212.1**	**7028.4**	**7177.2**	**7212.8**	**7028.6**	**7176.7**	**7215.3**	**7030.2**	**7178.2**
$E_{Dyn.}$ [Pa]	3.5E+10	3.3E+10	3.4E+10	3.5E+10	3.3E+10	3.4E+10	3.4E+10	3.3E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.43E+10			3.38E+10			3.36E+10		

Mixture: C-15.6%-L									
Cycles	**129**			**160**			**183**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2065.43**	**2050.78**	**2094.73**	**2080.08**	**2050.78**	**2080.08**	**2065.43**	**2036.13**
Mass [g]	**7217.6**	**7033.3**	**7181.1**	**7219.1**	**7034.7**	**7182**	**7221.8**	**7036.9**	**7186.1**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.30E+10			3.33E+10			3.29E+10		

Mixture: C-15.6%-L									
Cycles	**214**			**237**			**277**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2065.43**	**2036.13**	**2080.08**	**2065.43**	**2036.13**	**2080.08**	**2065.43**	**2036.13**
Mass [g]	**7224.5**	**7039.6**	**7189**	**7223.2**	**7037.6**	**7188.7**	**7220.9**	**7037.4**	**7187.6**
$E_{Dyn.}$ [Pa]	3.4E+10	3.3E+10	3.2E+10	3.4E+10	3.3E+10	3.2E+10	3.4E+10	3.3E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.29E+10			3.29E+10			3.29E+10		

Mixture: C-15.6%L									
Cycles	**306**			**329**			**353**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**2021.48**	**1948.24**	**1992.19**	**1962.89**	**1875**	**1948.24**	**1889.65**	**1801.76**
Mass [g]	**7234.1**	**7049.1**	**7201.2**	**7244.8**	**7057.4**	**7212**	**7257**	**7070.6**	**7223.8**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.0E+10	3.1E+10	2.9E+10	2.7E+10	3.0E+10	2.7E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.11E+10			2.94E+10			2.75E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-15.6%-L									
Cycles	**385**			**416**			**439**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1845.7**	**1801.76**	**1713.87**	**1772.46**	**1699.22**	**1582.03**	**1699.22**	**1625.98**	**1494.14**
Mass [g]	**7267.1**	**7080.1**	**7230.3**	**7275.9**	**7091.2**	**7239.6**	**7287.3**	**7092**	**7241.2**
$E_{Dyn.}$ [Pa]	2.7E+10	2.5E+10	2.3E+10	2.5E+10	2.2E+10	2.0E+10	2.3E+10	2.0E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.49E+10			2.22E+10			2.02E+10		

Mixture: C-15.6%-L									
Cycles	**470**			**501**			**524**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1582.03**	**1523.44**	**1391.6**	**1494.14**	**1406.25**	**1259.77**	**1406.25**	**1318.36**	**1171.88**
Mass [g]	**7285.1**	**7103.7**	**7250.1**	**7286.1**	**7101.4**	**7245.1**	**7294.7**	**7105.8**	**7248**
$E_{Dyn.}$ [Pa]	2.0E+10	1.8E+10	1.5E+10	1.8E+10	1.5E+10	1.2E+10	1.6E+10	1.3E+10	1.1E+10
Avg. $E_{Dyn.}$ [Pa]	1.76E+10			1.51E+10			1.33E+10		

Mixture: C-15.6%-L									
Cycles	**548**			**579**			**602**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1333.01**	**1259.77**	**1098.63**	**1215.82**	**1186.52**	**966.8**	**1142.58**	**1083.98**	**908.2**
Mass [g]	**7291.8**	**7107.7**	**7250.3**	**7295.6**	**7111**	**7248.2**	**7297.8**	**7113.3**	**7250.9**
$E_{Dyn.}$ [Pa]	1.4E+10	1.2E+10	9.5E+09	1.2E+10	1.1E+10	7.3E+09	1.0E+10	9.1E+09	6.5E+09
Avg. $E_{Dyn.}$ [Pa]	1.19E+10			9.96E+09			8.62E+09		

Mixture: C-15.6%-L									
Cycles	**634**			**666**			**689**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**996.09**	**981.45**	**791.02**	**849.61**	**864.26**	**629.88**	**820.31**	**805.66**	**585.94**
Mass [g]	**7301.1**	**7116.9**	**7254.1**	**7304.9**	**7120.6**	**7257.3**	**7306.7**	**7120**	**7258.9**
$E_{Dyn.}$ [Pa]	7.8E+09	7.4E+09	4.9E+09	5.7E+09	5.8E+09	3.1E+09	5.3E+09	5.0E+09	2.7E+09
Avg. $E_{Dyn.}$ [Pa]	6.73E+09			4.87E+09			4.35E+09		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-6.9%-L									
Cycles	**0**			**28**			**52**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2197.27**	**2167.97**	**2153.32**	**2167.97**	**2153.32**	**2153.32**	**2182.62**	**2153.32**
Mass [g]	**7533.6**	**7488.8**	**7389.8**	**7532.4**	**7488.4**	**7389.7**	**7535.6**	**7491.7**	**7392.7**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.8E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10	3.9E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.86E+10			3.77E+10			3.79E+10		

Mixture: S-6.9%-L									
Cycles	**84**			**108**			**144**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2138.67**	**2138.67**	**2167.97**	**2138.67**	**2167.97**	**2124.02**	**2124.02**	**2153.32**	**2109.38**
Mass [g]	**7540.6**	**7493.7**	**7396.3**	**7542.3**	**7496.5**	**7398.6**	**7544.6**	**7500.9**	**7403.2**
$E_{Dyn.}$ [Pa]	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10
Avg. $E_{Dyn.}$ [Pa]	3.74E+10			3.72E+10			3.68E+10		

Mixture: S-6.9%-L									
Cycles	**178**			**192**			**218**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2153.32**	**2080.08**	**2065.43**	**2138.67**	**2036.13**	**2065.43**	**2138.67**	**2036.13**
Mass [g]	**7547.7**	**7503.9**	**7407.4**	**7553.1**	**7507.4**	**7413.6**	**7552.1**	**7509.5**	**7416.5**
$E_{Dyn.}$ [Pa]	3.6E+10	3.8E+10	3.5E+10	3.5E+10	3.7E+10	3.3E+10	3.5E+10	3.7E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.61E+10			3.51E+10			3.52E+10		

Mixture: S-6.9%-L									
Cycles	**233**			**249**			**273**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2094.73**	**1933.59**	**1948.24**	**2050.78**	**1845.7**	**1875**	**2006.84**	**1713.87**
Mass [g]	**7555.5**	**7511.3**	**7419.2**	**7559.8**	**7515.8**	**7423.7**	**7565.7**	**7522.3**	**7427.1**
$E_{Dyn.}$ [Pa]	3.3E+10	3.6E+10	3.0E+10	3.1E+10	3.4E+10	2.7E+10	2.9E+10	3.3E+10	2.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.29E+10			3.09E+10			2.84E+10		

Mixture: S-6.9%-L									
Cycles	**304**			**327**			**358**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1787.11**	**1962.89**	**1669.92**	**1713.87**	**1889.65**	**1538.09**	**1699.29**	**1845.7**	**1494.14**
Mass [g]	**7569.8**	**7527**	**7430**	**7571.7**	**7530.8**	**7432.5**	**7573**	**7532.5**	**7433.3**
$E_{Dyn.}$ [Pa]	2.6E+10	3.1E+10	2.2E+10	2.4E+10	2.9E+10	1.9E+10	2.4E+10	2.8E+10	1.8E+10
Avg. $E_{Dyn.}$ [Pa]	2.67E+10			2.41E+10			2.32E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-6.9%-L									
Cycles	**381**			**421**			**450**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1655.27**	**1816.41**	**1435.55**	**1625.98**	**1831.05**	**1450.2**	**1508.79**	**1713.87**	**1347.66**
Mass [g]	**7572.1**	**7532.4**	**7433.1**	**7568.8**	**7528.8**	**7427.6**	**7580.2**	**7542.1**	**7439**
$E_{Dyn.}$ [Pa]	2.2E+10	2.7E+10	1.7E+10	2.2E+10	2.7E+10	1.7E+10	1.9E+10	2.4E+10	1.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.20E+10			2.20E+10			1.91E+10		

Mixture: S-6.9%-L									
Cycles	**473**			**497**			**529**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1450.2**	**1596.68**	**1274.41**	**1376.95**	**1508.79**	**1186.52**	**1245.12**	**1435.55**	**1083.98**
Mass [g]	**7582.7**	**7541.3**	**7439.7**	**7585.6**	**7544.9**	**7443.5**	**7588.1**	**7546.7**	**7445.2**
$E_{Dyn.}$ [Pa]	1.7E+10	2.1E+10	1.3E+10	1.6E+10	1.9E+10	1.1E+10	1.3E+10	1.7E+10	9.5E+09
Avg. $E_{Dyn.}$ [Pa]	1.71E+10			1.52E+10			1.30E+10		

Mixture: S-6.9%-L									
Cycles	**560**			**583**			**614**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1186.52**	**1289.06**	**996.09**	**1127.93**	**1245.12**	**908.2**	**1054.69**	**1171.88**	**878.91**
Mass [g]	**7589.4**	**7548**	**7446.6**	**7592.1**	**7551**	**7448.8**	**7595.7**	**7554.6**	**7453.1**
$E_{Dyn.}$ [Pa]	1.2E+10	1.4E+10	8.0E+09	1.0E+10	1.3E+10	6.7E+09	9.2E+09	1.1E+10	6.2E+09
Avg. $E_{Dyn.}$ [Pa]	1.11E+10			9.94E+09			8.88E+09		

Mixture: S-6.9%-L			
Cycles	**645**		
Specimen	**A**	**B**	**C**
Frequency [Hz]	**952.15**	**1025.39**	**747.01**
Mass [g]	**7597.9**	**7556.9**	**7455.2**
$E_{Dyn.}$ [Pa]	7.5E+09	8.6E+09	4.5E+09
Avg. $E_{Dyn.}$ [Pa]	6.86E+09		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-11.9%-L									
Cycles	**0**			**26**			**41**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2065.43**	**2065.43**	**2080.08**	**2050.78**	**2065.43**	**2065.43**	**2036.13**
Mass [g]	**7064.6**	**7085.1**	**7042.1**	**7062.2**	**7082.3**	**7038.4**	**7061.5**	**7082.3**	**7039.1**
$E_{Dyn.}$ [Pa]	3.3E+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]	3.30E+10			3.26E+10			3.23E+10		

Mixture: S-11.9%-L									
Cycles	**57**			**82**			**113**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2065.43**	**2036.13**	**2021.48**	**2050.78**	**2021.48**	**2021.48**	**2050.78**	**2021.48**
Mass [g]	**7064.1**	**7084.4**	**7041.4**	**7066.3**	**7087.8**	**7043.7**	**7069.6**	**7091.1**	**7047.3**
$E_{Dyn.}$ [Pa]	3.2E+10	3.3E+10	3.2E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.22E+10			3.16E+10			3.16E+10		

Mixture: S-11.9%-L									
Cycles	**136**			**167**			**190**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2036.13**	**2021.48**	**2006.84**	**2021.48**	**2021.48**	**1992.19**	**2021.48**	**2006.84**	**1992.19**
Mass [g]	**7074.4**	**7094.5**	**7051.3**	**7077.6**	**7097.9**	**7055.5**	**7078.3**	**7098.2**	**7056.5**
$E_{Dyn.}$ [Pa]	3.2E+10	3.1E+10	3.1E+10	3.1E+10	3.1E+10	3.0E+10	3.1E+10	3.1E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.13E+10			3.10E+10			3.09E+10		

Mixture: S-11.9%-L									
Cycles	**230**			**259**			**282**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2021.48**	**2021.48**	**1992.19**	**1948.24**	**1918.95**	**1904.3**	**1875**	**1831.05**	**1816.41**
Mass [g]	**7075.2**	**7097.1**	**7054.9**	**7091.8**	**7111.6**	**7072.9**	**7101.8**	**7124.4**	**7086.5**
$E_{Dyn.}$ [Pa]	3.1E+10	3.1E+10	3.0E+10	2.9E+10	2.8E+10	2.8E+10	2.7E+10	2.6E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.10E+10			2.84E+10			2.61E+10		

Mixture: S-11.9%-L									
Cycles	**306**			**338**			**369**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1743.16**	**1757.81**	**1728.52**	**1640.63**	**1684.57**	**1640.63**	**1523.44**	**1567.38**
Mass [g]	**7111.6**	**7136.1**	**7099.8**	**7122**	**7144.9**	**7103.4**	**7129.3**	**7151.7**	**7110.1**
$E_{Dyn.}$ [Pa]	2.5E+10	2.3E+10	2.4E+10	2.3E+10	2.1E+10	2.2E+10	2.1E+10	1.8E+10	1.9E+10
Avg. $E_{Dyn.}$ [Pa]	2.42E+10			2.19E+10			1.92E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-11.9%-L									
Cycles	**392**			**423**			**454**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1552.73**	**1435.55**	**1538.08**	**1508.79**	**1533.01**	**1406.25**	**1362.3**	**1171.88**	**1245.12**
Mass [g]	**7133.4**	**7157.2**	**7112.8**	**7142.6**	**7164.7**	**7120.8**	**7142.6**	**7166.7**	**7121.8**
$E_{Dyn.}$ [Pa]	1.9E+10	1.6E+10	1.8E+10	1.8E+10	1.8E+10	1.5E+10	1.4E+10	1.1E+10	1.2E+10
Avg. $E_{Dyn.}$ [Pa]	1.76E+10			1.70E+10			1.23E+10		

Mixture: S-11.9%-L									
Cycles	**477**			**501**			**532**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1303.71**	**1069.39**	**1215.82**	**1201.17**	**981.45**	**1098.63**	**1083.98**	**893.55**	**1010.74**
Mass [g]	**7145.3**	**7169.2**	**7123.8**	**7148.6**	**7172.1**	**7127**	**7156**	**7178.9**	**7133.1**
$E_{Dyn.}$ [Pa]	1.3E+10	8.9E+09	1.1E+10	1.1E+10	7.5E+09	9.3E+09	9.1E+09	6.2E+09	7.9E+09
Avg. $E_{Dyn.}$ [Pa]	1.12E+10			9.33E+09			7.74E+09		

Mixture: S-11.9%-L									
Cycles	**555**			**587**			**619**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1054.69**	**820.31**	**937.5**	**966.8**	**673.83**	**878.91**	**908.2**	**615.23**	**791.02**
Mass [g]	**7156.2**	**7178.9**	**7134**	**7161.6**	**7184.9**	**7139.3**	**7162.7**	**7189**	**7144.1**
$E_{Dyn.}$ [Pa]	8.6E+09	5.2E+09	6.8E+09	7.3E+09	3.5E+09	6.0E+09	6.4E+09	2.9E+09	4.8E+09
Avg. $E_{Dyn.}$ [Pa]	6.89E+09			5.59E+09			4.73E+09		

Mixture: S-11.9%-L						
Cycles	**642**			**667**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**864.26**	**527.34**	**761.72**	**820.31**	**424.8**	**703.13**
Mass [g]	**7164.2**	**7190.8**	**7143.8**	**7166.5**	**7196.3**	**7148.6**
$E_{Dyn.}$ [Pa]	5.8E+09	2.2E+09	4.5E+09	5.2E+09	1.4E+09	3.8E+09
Avg. $E_{Dyn.}$ [Pa]	4.15E+09			3.49E+09		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-16.3%-L									
Cycles	**0**			**15**			**31**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2065.43**	**2080.08**	**2036.13**	**2050.78**	**2065.43**	**2021.48**	**2036.13**	**2050.78**
Mass [g]	**6933.8**	**6932**	**6937.6**	**6932.5**	**6925.5**	**6931.2**	**6933.6**	**6926**	**6930.6**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.3E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10
Avg. $E_{Dyn.}$ [Pa]	3.21E+10			3.16E+10			3.11E+10		

Mixture: S-16.3%-L									
Cycles	**55**			**87**			**110**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2050.78**	**2065.43**	**2021.48**	**2036.13**	**2050.78**	**2006.84**	**2021.48**	**2036.13**
Mass [g]	**6935.9**	**6928.1**	**6932.7**	**6939.1**	**6931.6**	**6935.9**	**6941.2**	**6933.8**	**6938.3**
$E_{Dyn.}$ [Pa]	3.0E+10	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.0E+10	3.1E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.13E+10			3.12E+10			3.07E+10		

Mixture: S-16.3%-L									
Cycles	**141**			**164**			**204**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2006.84**	**2021.48**	**2036.13**	**2006.84**	**2021.48**	**2036.13**	**2006.84**	**2036.13**	**2036.13**
Mass [g]	**6944.8**	**6936.7**	**6940.9**	**6943.8**	**6936.2**	**6940.6**	**6941.7**	**6933.4**	**6937.8**
$E_{Dyn.}$ [Pa]	3.0E+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]	3.07E+10			3.07E+10			3.09E+10		

Mixture: S-16.3%-L									
Cycles	**233**			**256**			**280**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1889.65**	**1933.59**	**1948.24**	**1801.76**	**1860.35**	**1860.35**	**1699.22**	**1743.16**	**1743.16**
Mass [g]	**6960.7**	**6950.7**	**6957.1**	**6977**	**6970.1**	**6975.7**	**6994.7**	**6989.5**	**6994.3**
$E_{Dyn.}$ [Pa]	2.7E+10	2.8E+10	2.9E+10	2.5E+10	2.6E+10	2.6E+10	2.2E+10	2.3E+10	2.3E+10
Avg. $E_{Dyn.}$ [Pa]	2.79E+10			2.56E+10			2.26E+10		

Mixture: S-16.3%-L									
Cycles	**312**			**343**			**366**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1552.73**	**1611.33**	**1640.63**	**1391.6**	**1450.2**	**1433.55**	**1333.01**	**1362.3**	**1632.3**
Mass [g]	**7007.5**	**7000.1**	**7004.6**	**7017**	**7009.5**	**7013.5**	**7023**	**7012.1**	**7017.2**
$E_{Dyn.}$ [Pa]	1.8E+10	2.0E+10	2.0E+10	1.5E+10	1.6E+10	1.6E+10	1.4E+10	1.4E+10	2.0E+10
Avg. $E_{Dyn.}$ [Pa]	1.95E+10			1.54E+10			1.60E+10		

Table A.1 (con't): Freeze-Thaw results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-16.3%-L									
Cycles	**397**			**428**			**451**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1157.23**	**1215.82**	**1215.82**	**952.15**	**1025.39**	**1054.69**	**893.55**	**937.5**	**966.8**
Mass [g]	**7030.7**	**7022.8**	**7026.6**	**7034.7**	**7024.3**	**7026.7**	**7038.3**	**7027.9**	**7029.4**
$E_{Dyn.}$ [Pa]	1.0E+10	1.1E+10	1.1E+10	6.9E+09	8.0E+09	8.5E+09	6.1E+09	6.7E+09	7.1E+09
Avg. $E_{Dyn.}$ [Pa]	1.09E+10			7.79E+09			6.63E+09		

Mixture: S-16.3%-L									
Cycles	**475**			**506**			**529**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**776.37**	**834.96**	**834.96**	**688.48**	**717.77**	**747.07**	**527.34**	**629.88**	**615.23**
Mass [g]	**7043.2**	**7032**	**7033.7**	**7051.5**	**7039.8**	**7039.2**	**7054**	**7043**	**7043.9**
$E_{Dyn.}$ [Pa]	4.6E+09	5.3E+09	5.3E+09	3.6E+09	3.9E+09	4.3E+09	2.1E+09	3.0E+09	2.9E+09
Avg. $E_{Dyn.}$ [Pa]	5.08E+09			3.94E+09			2.68E+09		

Mixture: S-16.3%-L									
Cycles	**561**			**593**			**616**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**468.75**	**527.34**	**541.99**	**380.86**	**468.75**	**468.75**	**366.21**	**395.51**	**410.16**
Mass [g]	**7060**	**7049**	**7050**	**7067.8**	**7057.9**	**7058**	**7071.5**	**7061.9**	**7061.8**
$E_{Dyn.}$ [Pa]	1.7E+09	2.1E+09	2.2E+09	1.1E+09	1.7E+09	1.7E+09	1.0E+09	1.2E+09	1.3E+09
Avg. $E_{Dyn.}$ [Pa]	2.02E+09			1.49E+09			1.17E+09		

Mixture: S-16.3%-L						
Cycles	**641**			**674**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**322.27**	**366.21**	**380.86**	**234.38**	**234.38**	**292.97**
Mass [g]	**7083**	**7072.9**	**7073**	**7087.5**	**7079.4**	**7079.8**
$E_{Dyn.}$ [Pa]	8.0E+08	1.0E+09	1.1E+09	4.2E+08	4.2E+08	6.6E+08
Avg. $E_{Dyn.}$ [Pa]	9.79E+08			5.01E+08		

Table A.2: Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-7.1%-G									
Cycles	**0**			**29**			**52**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2153.32**	**2167.97**
Mass [g]	**7295.9**	**7223.6**	**7281.7**	**7295**	**7223.8**	**7282.1**	**7295**	**7223.7**	**7282.1**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.72E+10			3.70E+10			3.70E+10		

Mixture: C-7.1%-G									
Cycles	**76**			**109**			**140**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2153.32**	**2167.97**
Mass [g]	**7295.9**	**7223.6**	**7282.6**	**7295.4**	**7224.1**	**7282.7**	**7295.7**	**7224.3**	**7282.9**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.72E+10			3.70E+10			3.70E+10		

Mixture: C-7.1%-G									
Cycles	**163**			**194**			**225**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2167.97**
Mass [g]	**7294.2**	**7223.5**	**7282.4**	**7293.8**	**7223.5**	**7282.2**	**7293.9**	**7223.6**	**7282.1**
$E_{Dyn.}$ [Pa]	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.70E+10			3.72E+10			3.72E+10		

Mixture: C-7.1%-G									
Cycles	**248**			**272**			**303**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2153.32**	**2167.97**
Mass [g]	**7293.9**	**7223.6**	**7281.5**	**7293.5**	**7223.1**	**7282**	**7293.2**	**7223.1**	**7281.4**
$E_{Dyn.}$ [Pa]	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.70E+10			3.70E+10			3.70E+10		

Mixture: C-7.1%-G									
Cycles	**326**			**358**			**390**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2167.97**	**2167.97**
Mass [g]	**7293.1**	**7222.7**	**7281.1**	**7291.5**	**7222.6**	**7280.8**	**7290.3**	**7220.9**	**7280.6**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.70E+10			3.70E+10			3.72E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-7.1%-G									
Cycles	**413**			**438**			**471**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2153.32**	**2167.97**	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2167.97**
Mass [g]	**7290**	**7220.9**	**7279.9**	**7290**	**7220.5**	**7279.8**	**7290.7**	**7221.1**	**7280.3**
$E_{Dyn.}$ [Pa]	3.8E+10	3.6E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.7E+10
Avg. $E_{Dyn.}$ [Pa]	3.70E+10			3.72E+10			3.72E+10		

Mixture: C-7.1%-G									
Cycles	**494**			**524**			**556**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2182.62**	**2182.62**	**2167.97**	**2182.62**
Mass [g]	**7289.4**	**7220.9**	**7279.3**	**7288**	**7220.4**	**7278.3**	**7288.1**	**7219.2**	**7274.7**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.72E+10			3.73E+10			3.73E+10		

Mixture: C-7.1%-G									
Cycles	**583**			**598**			**622**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2182.62**	**2182.62**	**2167.97**	**2182.62**	**2182.62**	**2167.97**	**2182.62**
Mass [g]	**7287.7**	**7218.6**	**7273.2**	**7286.7**	**7217.5**	**7272.9**	**7286.7**	**7212.8**	**7272.8**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.73E+10			3.73E+10			3.73E+10		

Mixture: C-7.1%-G						
Cycles	**655**			**679**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2182.62**	**2167.97**	**2167.97**	**2182.62**	**2167.97**	**2182.62**
Mass [g]	**7287**	**7212.8**	**7271.6**	**7285.6**	**7211.7**	**7269.6**
$E_{Dyn.}$ [Pa]	3.8E+10	3.7E+10	3.7E+10	3.8E+10	3.7E+10	3.8E+10
Avg. $E_{Dyn.}$ [Pa]	3.71E+10			3.73E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-13.1%-G									
Cycles	**0**			**24**			**56**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2138.67**	**2124.02**	**2094.73**	**2124.02**	**2109.38**	**2094.73**	**2124.02**	**2109.38**
Mass [g]	**6973.5**	**7068**	**7027.8**	**6975.4**	**7070.7**	**7030**	**6978.2**	**7071.8**	**7032.1**
E$_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.3E+10	3.5E+10	3.4E+10	3.3E+10	3.5E+10	3.4E+10
Avg. E$_{Dyn.}$ [Pa]	3.43E+10			3.39E+10			3.39E+10		

Mixture: C-13.1%-G									
Cycles	**87**			**111**			**142**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6979.4**	**7073.5**	**7033.2**	**6980.4**	**7073.4**	**7031.8**	**6983.5**	**7080.2**	**7033.9**
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]	3.40E+10			3.40E+10			3.41E+10		

Mixture: C-13.1%-G									
Cycles	**173**			**196**			**220**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6979.8**	**7073.5**	**7031.8**	**6979.9**	**7074**	**7032.1**	**6980**	**7075.1**	**7032.2**
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]	3.40E+10			3.40E+10			3.40E+10		

Mixture: C-13.1%-G									
Cycles	**251**			**274**			**306**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6980.1**	**7073.5**	**7031.8**	**6979.8**	**7073.6**	**7031.9**	**6980.2**	**7072.7**	**7031.9**
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]	3.40E+10			3.40E+10			3.40E+10		

Mixture: C-13.1%-G									
Cycles	**338**			**361**			**386**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6978.6**	**7073.7**	**7033**	**6978.5**	**7072.6**	**7032.9**	**6979.2**	**7072.9**	**7032.2**
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]	3.40E+10			3.40E+10			3.40E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-13.1%-G									
Cycles	**419**			**442**			**472**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2138.67**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6979.7**	**7073.3**	**7033.8**	**6979.2**	**7072.4**	**7033.8**	**6979.9**	**7071.8**	**7034**
$E_{Dyn.}$ [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]	3.42E+10			3.40E+10			3.40E+10		

Mixture: C-13.1%-G									
Cycles	**504**			**531**			**546**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6980.2**	**7072**	**7034.9**	**6980.2**	**7071.7**	**7036.2**	**6979.4**	**7071.5**	**7036.5**
$E_{Dyn.}$ [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]	3.40E+10			3.41E+10			3.40E+10		

Mixture: C-13.1%-G									
Cycles	**570**			**603**			**627**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**	**2109.38**	**2124.02**	**2109.38**
Mass [g]	**6980.8**	**7071.9**	**7036.7**	**6980.8**	**7073.2**	**7038.2**	**6981.3**	**7073.8**	**7039.1**
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.41E+10			3.41E+10			3.41E+10		

Mixture: C-13.1%-G						
Cycles	**652**			**682**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2109.38**	**2109.38**	**2094.73**	**2094.73**	**2109.38**	**2094.73**
Mass [g]	**6979.2**	**7074.4**	**7040.5**	**6978.9**	**7076.5**	**7041.5**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.3E+10	3.3E+10	3.4E+10	3.3E+10
Avg. $E_{Dyn.}$ [Pa]	3.37E+10			3.36E+10		

Table A.2 (con’t): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-15.7%-G									
Cycles	**0**			**8**			**31**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2080.08**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**
Mass [g]	**6854.6**	**6911.6**	**6872.7**	**6851.3**	**6907.9**	**6867.5**	**6851.2**	**6908.4**	**6866.2**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+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]	3.26E+10			3.21E+10			3.21E+10		

Mixture: C-15.7%-G									
Cycles	**55**			**87**			**110**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**
Mass [g]	**6852.5**	**6910.7**	**6868.6**	**6851.9**	**6910.3**	**6867.5**	**6851**	**6909.8**	**6868**
$E_{Dyn.}$ [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]	3.21E+10			3.21E+10			3.21E+10		

Mixture: C-15.7%-G									
Cycles	**142**			**174**			**197**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**
Mass [g]	**6852**	**6910.8**	**6868.4**	**6853**	**6910.9**	**6869.2**	**6852.2**	**6911.4**	**6869.2**
$E_{Dyn.}$ [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]	3.21E+10			3.21E+10			3.21E+10		

Mixture: C-15.7%-G									
Cycles	**222**			**255**			**278**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**
Mass [g]	**6853**	**6911.8**	**6869.5**	**6853.5**	**6912.1**	**6870.2**	**6852.5**	**6912.5**	**6870.7**
$E_{Dyn.}$ [Pa]	3.3E+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]	3.22E+10			3.21E+10			3.21E+10		

Mixture: C-15.7%-G									
Cycles	**308**			**340**			**367**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**	**2080.08**	**2080.08**	**2065.43**
Mass [g]	**6853.5**	**6913.2**	**6871.6**	**6853.8**	**6913.6**	**6871**	**6853.8**	**6913.9**	**6872**
$E_{Dyn.}$ [Pa]	3.3E+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]	3.23E+10			3.21E+10			3.21E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: C-15.7%-G									
Cycles	382			406			439		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2080.08	2080.08	2065.43	2080.08	2080.08	2065.43	2080.08	2080.08	2065.43
Mass [g]	6854.1	6913.4	6870.8	6854.9	6914.3	6872.1	6855.1	6915.4	6873.4
$E_{Dyn.}$ [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]	3.21E+10			3.21E+10			3.21E+10		

Mixture: C-15.7%-G									
Cycles	463			488			518		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2080.08	2080.08	2065.43	2080.78	2080.08	2050.78	2080.78	2080.08	2050.78
Mass [g]	6855.9	6915.2	6873.5	6858.1	6916.4	6874.8	6856.7	6917.7	6875.3
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.21E+10			3.20E+10			3.20E+10		

Mixture: C-15.7%-G									
Cycles	542			596			629		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2080.08	2080.08	2050.78	2065.43	2065.43	2036.13	2065.43	2065.43	2021.48
Mass [g]	6858.7	6917.5	6877.1	6862	6919.2	6877.2	6862.6	6925.1	6879.5
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.20E+10			3.15E+10			3.14E+10		

Mixture: C-15.7%-G						
Cycles	651			682		
Specimen	A	B	C	A	B	C
Frequency [Hz]	2065.43	2050.78	2021.48	2050.78	2050.78	1992.19
Mass [g]	6865.6	6923.1	6881.3	6865.5	6926.2	6885.3
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.0E+10	3.1E+10	3.2E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.13E+10			3.08E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-7.1%-G									
Cycles	**0**			**7**			**39**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2226.56**	**2226.56**	**2241.21**	**2211.91**	**2211.91**	**2211.91**	**2211.91**	**2211.91**	**2211.91**
Mass [g]	**7369.3**	**7366.3**	**7404.6**	**7369.2**	**7365.4**	**7402.3**	**7370.1**	**7365.8**	**7403.7**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	4.0E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.98E+10			3.91E+10			3.91E+10		

Mixture: S-7.1%-G									
Cycles	**70**			**94**			**125**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2211.91**	**2211.91**	**2211.91**	**2211.91**	**2211.91**	**2226.56**	**2211.91**	**2226.56**	**2226.56**
Mass [g]	**7371.7**	**7365.7**	**7404.2**	**7371.8**	**7366.2**	**7404.2**	**7371.9**	**7366.5**	**7403.9**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	3.9E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.91E+10			3.93E+10			3.95E+10		

Mixture: S-7.1%-G									
Cycles	**156**			**179**			**203**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2211.91**	**2211.91**	**2226.56**	**2211.91**	**2211.91**	**2226.56**	**2211.91**	**2226.56**	**2226.56**
Mass [g]	**7371.2**	**7366**	**7404.3**	**7371.4**	**7366.1**	**7403**	**7372.2**	**7366.4**	**7404.5**
$E_{Dyn.}$ [Pa]	3.9E+10	3.9E+10	4.0E+10	3.9E+10	3.9E+10	4.0E+10	3.9E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.93E+10			3.93E+10			3.95E+10		

Mixture: S-7.1%-G									
Cycles	**234**			**257**			**289**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2211.91**	**2226.56**	**2226.56**	**2211.91**	**2226.56**	**2226.56**	**2211.91**	**2226.56**	**2226.56**
Mass [g]	**7370.9**	**7365.7**	**7403.5**	**7371.6**	**7366.6**	**7403.1**	**7371.1**	**7365.9**	**7403.7**
$E_{Dyn.}$ [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	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.95E+10			3.95E+10			3.95E+10		

Mixture: S-7.1%-G									
Cycles	**321**			**344**			**369**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2211.91**	**2226.56**	**2226.56**	**2211.91**	**2226.56**	**2226.56**	**2211.91**	**2226.56**	**2226.56**
Mass [g]	**7371.2**	**7365.9**	**7402.3**	**7370.4**	**7365.2**	**7401.1**	**7370.2**	**7364.9**	**7401.2**
$E_{Dyn.}$ [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	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.95E+10			3.95E+10			3.95E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-7.1%-G									
Cycles	**402**			**425**			**455**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2211.91**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**
Mass [g]	**7369.1**	**7365.3**	**7399.9**	**7368.3**	**7364.8**	**7398.1**	**7366.9**	**7364.7**	**7396.7**
$E_{Dyn.}$ [Pa]	3.9E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.95E+10			3.96E+10			3.96E+10		

Mixture: S-7.1%-G									
Cycles	**487**			**514**			**529**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**
Mass [g]	**7366.4**	**7363.9**	**7393.8**	**7365.6**	**7364.3**	**7394.4**	**7365.5**	**7362.5**	**7392**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.96E+10			3.96E+10			3.96E+10		

Mixture: S-7.1%-G									
Cycles	**553**			**586**			**610**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2226.56**	**2226.56**	**2241.21**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2226.56**	**2241.21**
Mass [g]	**7364.4**	**7361.9**	**7392.2**	**7363.3**	**7361.5**	**7391.8**	**7361.2**	**7361**	**7389.8**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.98E+10			3.96E+10			3.98E+10		

Mixture: S-7.1%-G						
Cycles	**635**			**665**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2226.56**	**2226.56**	**2241.21**	**2226.56**	**2226.56**	**2241.21**
Mass [g]	**7360.7**	**7359.8**	**7388.9**	**7357.3**	**7358.4**	**7387.7**
$E_{Dyn.}$ [Pa]	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10	4.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.98E+10			3.98E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-12.5%-G									
Cycles	0			15			47		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2138.67	2153.32	2153.32	2124.02	2124.02	2124.02	2124.02	2124.02	2124.02
Mass [g]	6997.6	7108.9	7031.4	6992.9	7104.3	7028.5	6994	7105.5	7027.9
$E_{Dyn.}$ [Pa]	3.5E+10	3.6E+10	3.5E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10	3.4E+10
Avg. $E_{Dyn.}$ [Pa]	3.52E+10			3.44E+10			3.44E+10		

Mixture: S-12.5%-G									
Cycles	70			96			129		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124.02	2124.02	2124.02	2124.02	2124.02	2124.02	2124.02	2124.02	2124.02
Mass [g]	6994.3	7105.8	7028.2	6995.4	7106.4	7028.4	6996	7106.1	7029.4
$E_{Dyn.}$ [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]	3.44E+10			3.44E+10			3.44E+10		

Mixture: S-12.5%-G									
Cycles	152			182			214		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124.02	2124.02	2124.02	2138.67	2138.67	2138.67	2138.67	2138.67	2138.67
Mass [g]	6994.9	7106.2	7028.9	6994.3	7107	7029.3	6995.2	7107.1	7029.8
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.44E+10			3.49E+10			3.49E+10		

Mixture: S-12.5%-G									
Cycles	241			256			280		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2138.67	2138.67	2138.67	2138.67	2138.67	2138.67	2138.67	2138.67	2138.67
Mass [g]	6995	7107.5	7029.4	6994.7	7106.3	7028.4	6994.3	7106.1	7027.8
$E_{Dyn.}$ [Pa]	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.49E+10			3.49E+10			3.49E+10		

Mixture: S-12.5%-G									
Cycles	313			337			362		
Specimen	A	B	C	A	B	C	A	B	C
Frequency [Hz]	2124.02	2124.02	2138.67	2124.02	2124.02	2138.67	2124.02	2124.02	2138.67
Mass [g]	6995	7107.5	7028.8	6995.1	7107.7	7029.5	6994.1	7106.9	7029.3
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.46E+10			3.46E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-12.5%-G									
Cycles	**392**			**416**			**470**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2124.02**	**2138.67**	**2124.02**	**2124.02**	**2138.67**	**2124.02**	**2124.02**	**2138.67**
Mass [g]	**6994.1**	**7107.7**	**7029**	**6995.4**	**7107.8**	**7027.9**	**6994.9**	**7108**	**7028.5**
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.46E+10			3.46E+10		

Mixture: S-12.5%-G									
Cycles	**503**			**525**			**556**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2124.02**	**2138.67**	**2124.02**	**2124.02**	**2138.67**	**2124.02**	**2124.02**	**2138.67**
Mass [g]	**6995.2**	**7111.9**	**7028.6**	**6995.1**	**7108.3**	**7027.9**	**6997.3**	**7109.1**	**7029.1**
$E_{Dyn.}$ [Pa]	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10	3.4E+10	3.5E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.46E+10			3.46E+10			3.46E+10		

Mixture: S-12.5%-G									
Cycles	**579**			**601**			**624**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2109.38**	**2138.67**	**2124.02**	**2109.38**	**2138.67**	**2124.02**	**2109.38**	**2138.67**
Mass [g]	**6996.9**	**7111**	**7029.3**	**6996.7**	**7111.3**	**7028.9**	**6996.9**	**7110.8**	**7029.1**
$E_{Dyn.}$ [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]	3.44E+10			3.44E+10			3.44E+10		

Mixture: S-12.5%-G						
Cycles	**642**			**680**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2124.02**	**2109.38**	**2138.67**	**2109.38**	**2094.73**	**2138.67**
Mass [g]	**6997.8**	**7112.2**	**7028.8**	**6998.9**	**7115.2**	**7029**
$E_{Dyn.}$ [Pa]	3.4E+10	3.4E+10	3.5E+10	3.4E+10	3.4E+10	3.5E+10
Avg. $E_{Dyn.}$ [Pa]	3.44E+10			3.41E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-17.3%-G									
Cycles	**0**			**18**			**41**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2094.73**	**2094.73**	**2065.43**	**2065.43**	**2065.43**	**2036.13**	**2065.43**	**2065.43**	**2036.13**
Mass [g]	**6857.7**	**6886.1**	**6860.1**	**6858.2**	**6886.3**	**6859.3**	**6858.8**	**6887.8**	**6859.3**
$E_{Dyn.}$ [Pa]	3.3E+10	3.3E+10	3.2E+10	3.2E+10	3.2E+10	3.1E+10	3.2E+10	3.2E+10	3.1E+10
Avg. $E_{Dyn.}$ [Pa]	3.24E+10			3.15E+10			3.15E+10		

Mixture: S-17.3%-G									
Cycles	**71**			**104**			**131**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2065.43**	**2065.43**	**2036.13**	**2050.78**	**2065.43**	**2036.13**	**2050.79**	**2065.43**	**2021.48**
Mass [g]	**6860.6**	**6889.1**	**6862**	**6862.6**	**6890.2**	**6863.3**	**6863.8**	**6892.1**	**6865.5**
$E_{Dyn.}$ [Pa]	3.2E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.1E+10	3.1E+10	3.2E+10	3.0E+10
Avg. $E_{Dyn.}$ [Pa]	3.15E+10			3.13E+10			3.12E+10		

Mixture: S-17.3%-G									
Cycles	**146**			**170**			**203**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**2050.78**	**2050.78**	**2006.84**	**2036.13**	**2050.78**	**2006.84**	**2021.48**	**2036.13**	**1977.54**
Mass [g]	**6865.1**	**6893.2**	**6866.9**	**6869.1**	**6897**	**6872.2**	**6876.3**	**6903.3**	**6880.4**
$E_{Dyn.}$ [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	2.9E+10
Avg. $E_{Dyn.}$ [Pa]	3.09E+10			3.08E+10			3.02E+10		

Mixture: S-17.3%-G									
Cycles	**227**			**252**			**282**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1992.19**	**2021.48**	**1948.24**	**1977.54**	**1992.19**	**1904.3**	**1889.65**	**1904.3**	**1816.41**
Mass [g]	**6883.8**	**6908.7**	**6892.3**	**6892.4**	**6918.1**	**6901.6**	**6902.6**	**6929.1**	**6914.9**
$E_{Dyn.}$ [Pa]	3.0E+10	3.1E+10	2.8E+10	2.9E+10	3.0E+10	2.7E+10	2.7E+10	2.7E+10	2.5E+10
Avg. $E_{Dyn.}$ [Pa]	2.95E+10			2.87E+10			2.62E+10		

Mixture: S-17.3%-G									
Cycles	**306**			**360**			**393**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1816.41**	**1845.7**	**1669.92**	**1538.09**	**1611.33**	**1362.3**	**1347.6**	**1420.9**	**1186.52**
Mass [g]	**6911.8**	**6938.5**	**6924.6**	**6935.4**	**6961**	**6946.6**	**6944.2**	**6971.2**	**6954.3**
$E_{Dyn.}$ [Pa]	2.5E+10	2.6E+10	2.1E+10	1.8E+10	2.0E+10	1.4E+10	1.4E+10	1.5E+10	1.1E+10
Avg. $E_{Dyn.}$ [Pa]	2.37E+10			1.71E+10			1.32E+10		

Table A.2 (con't): Freeze-Thaw results for concrete mixtures with granite as the coarse aggregate

Mixture: S-17.3%-G									
Cycles	**415**			**446**			**469**		
Specimen	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frequency [Hz]	**1171.88**	**1259.77**	**1040.04**	**1157.23**	**1245.12**	**952.15**	**849.61**	**834.96**	**703.13**
Mass [g]	**6952.4**	**6979.9**	**6961.3**	**6957.2**	**6987.5**	**6968.8**	**6965.1**	**6991.3**	**6972.5**
$E_{Dyn.}$ [Pa]	1.0E+10	1.2E+10	8.2E+09	1.0E+10	1.2E+10	6.8E+09	5.4E+09	5.3E+09	3.7E+09
Avg. $E_{Dyn.}$ [Pa]	1.02E+10			9.56E+09			4.82E+09		

Table A.3: *p* values obtained from Student's t-test for the difference in freeze-thaw cycles at which specimens dropped below 95% of the initial E_{DYN} for mixtures with limestone coarse aggregate

Mixture ID	**Avg. No. of Freeze-Thaw Cycles to Reach 90% of Initial Dyn. E**	**C-6.8%-L**	**C-13.5%-L**	**C-15.6%-L**	**S-6.9%-L**	**S-11.9%-L**	**S-16.3%-L**
		153	**260**	**278**	**150**	**137**	**208**
C-6.8%-L	**153**		**0.01**	0.24	0.89	0.24	0.07
C-13.5%-L	**260**			0.58	**0.01**	**1.7×10^{-3}**	**4.5×10^{-3}**
C-15.6%-L	**278**				0.25	0.10	0.67
S-6.9%-L	**150**					0.15	**0.04**
S-11.9%-L	**137**						**0.01**

Table A.4: *p* values obtained from Student's t-test for the difference in the durability factor for mixtures with granite coarse aggregate

Mixture ID	**Durability Factor**	**C-7.1%-G**	**C-13.1%-G**	**C-15.7%-G**	**S-7.1%-G**	**S-12.5%-G**	**S-17.3%-G**
		100	**98**	**96**	**100**	**98**	**31**
C-7.1%-G	**100**		0.08	**0.01**	0.11	0.05	**3.1×10^{-7}**
C-13.1%-G	**98**			0.10	0.10	0.54	**8.1×10^{-7}**
C-15.7%-G	**96**				**0.01**	0.27	**1.3×10^{-6}**
S-7.1%-G	**100**					0.06	**3.1×10^{-7}**
S-12.5%-G	**98**						**1.3×10^{-6}**

Table A.5: *p* values obtained from Student’s t-test for the difference in the durability factor for mixtures with limestone or granite

Mixture ID	Durability Factor	C-6.8%-L	C-7.1%-G	C-13.5%-L	C-13.1%-G	C-15.6%-L	C-15.7%-G	S-6.9%-L	S-7.1%-G	S-11.9%-L	S-12.5%-G	S-16.3%-L	S-17.3%-G
		48	100	48	98	39	96	33	100	33	98	28	31
C-6.8%-L	48		**1.2×10^{-3}**	0.67	**1.4×10^{-3}**	0.44	**1.7×10^{-3}**	0.22	**1.2×10^{-3}**	0.14	**1.5×10^{-3}**	0.07	0.10
C-7.1%-G	100			**5.8×10^{-7}**	0.08	**1.4×10^{-6}**	**0.01**	**8.1×10^{-5}**	0.11	**1.3×10^{-7}**	**0.05**	**3.0×10^{-9}**	**3.0×10^{-7}**
C-13.5%-L	48				**1.9×10^{-6}**	**0.01**	**3.5×10^{-6}**	0.03	**5.8×10^{-7}**	**2.3×10^{-4}**	**3.3×10^{-6}**	**3.3×10^{-5}**	**2.3×10^{-4}**
C-13.1%-G	98					**2.8×10^{-6}**	0.10	**9.7×10^{-5}**	0.10	**5.2×10^{-7}**	0.54	**1.2×10^{-7}**	**8.1×10^{-7}**
C-15.6%-L	39						**4.3×10^{-3}**	0.26	**1.4×10^{-6}**	**0.01**	**4.0×10^{-6}**	**1.4×10^{-3}**	**0.01**
C-15.7%-G	96							**1.2×10^{-4}**	**0.01**	**9.4×10^{-7}**	0.27	**3.0×10^{-7}**	**1.3×10^{-6}**
S-6.9%-L	33								**8.2×10^{-5}**	0.84	**1.1×10^{-4}**	0.25	0.54
S-7.1%-G	100									**1.3×10^{-7}**	0.06	**2.8×10^{-9}**	**3.1×10^{-7}**
S-11.9%-L	33										**9.3×10^{-7}**	**0.01**	0.22
S-12.5%-G	98											**3.1×10^{-7}**	**1.3×10^{-6}**
S-16.3%-L	28												0.07

APPENDIX B: SCALING RESULTS

Table B.1: Scaling results for concrete mixtures with limestone as the coarse aggregate

Mixture: C-6.8%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	70.83	0.1	3.24E-06	0.4	1.30E-05	0.7	2.27E-05	1.1	3.57E-05
B	76.86	0.4	1.19E-05	0.4	1.20E-05	0.4	1.20E-05	0.6	1.79E-05
C	73.89	0.4	1.24E-05	0.5	1.55E-05	0.5	1.55E-05	2.8	8.69E-05
Average	73.86		9.21E-06		1.35E-05		1.67E-05		4.69E-05
Cumulative mass loss (lb/ft^2)			**1.33E-03**		**3.27E-03**		**5.68E-03**		**1.24E-02**

Mixture: C-13.5%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	74.23	1.3	4.02E-05	0.5	1.55E-05	0.9	2.78E-05	1.7	5.26E-05
B	68.98	0.7	2.33E-05	0.3	9.98E-06	0.5	1.66E-05	1.2	3.99E-05
C	71.91	0.4	1.28E-05	0.2	6.38E-06	0.4	1.28E-05	1	3.19E-05
Average	71.71		2.54E-05		1.06E-05		1.91E-05		4.15E-05
Cumulative mass loss (lb/ft^2)			3.66E-03		5.19E-03		7.94E-03		1.39E-02

Mixture: C-15.6%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	68.20	0.7	2.36E-05	1.1	3.70E-05	2.6	8.75E-05	4.9	1.65E-04
B	66.64	0.6	2.07E-05	3.7	1.27E-04	4.2	1.45E-04	5.5	1.89E-04
C	68.29	1.4	4.71E-05	2.4	8.07E-05	5.6	1.88E-04	7.7	2.59E-04
Average	67.71		3.04E-05		8.17E-05		1.40E-04		2.04E-04
Cumulative mass loss (lb/ft^2)			4.38E-03		1.62E-02		3.63E-02		6.58E-02

Mixture: S-6.9%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.12	2.3	7.22E-05	10.5	3.30E-04	12	3.77E-04	12.3	3.86E-04
B	72.95	3	9.44E-05	7	2.20E-04	14.1	4.44E-04	10.1	3.18E-04
C	72.92	2.1	6.61E-05	6.5	2.05E-04	16.9	5.32E-04	9	2.83E-04
Average	72.99		7.76E-05		2.52E-04		4.51E-04		3.29E-04
Cumulative mass loss (lb/ft^2)			1.12E-02		4.74E-02		1.12E-01		1.60E-01

Table B.1 (con't): Scaling results for concrete mixtures with limestone as the coarse aggregate

Mixture: S-11.9%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	75.15	0.9	2.75E-05	4.1	1.25E-04	3.5	1.07E-04	6.7	2.05E-04
B	71.67	0.5	1.60E-05	4.8	1.54E-04	3	9.61E-05	4.3	1.38E-04
C	76.53	0.8	2.40E-05	6.1	1.83E-04	3.5	1.05E-04	4.3	1.29E-04
Average	74.45		2.25E-05		1.54E-04		1.03E-04		1.57E-04
Cumulative mass loss (lb/ft^2)			3.24E-03		2.54E-02		4.02E-02		6.28E-02

Mixture: S-16.3%-L									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.44	0.5	1.56E-05	1.4	4.38E-05	2.3	7.19E-05	6.1	1.91E-04
B	73.12	0.5	1.57E-05	1.9	5.97E-05	3.7	1.16E-04	8.9	2.79E-04
C	70.68	0.5	1.62E-05	1	3.25E-05	2.2	7.15E-05	6.5	2.11E-04
Average	72.41		1.59E-05		4.53E-05		8.65E-05		2.27E-04
Cumulative mass loss (lb/ft^2)			2.28E-03		8.81E-03		2.13E-02		5.40E-02

Table B.2: Scaling results for concrete mixtures with granite as the coarse aggregate

Mixture: C-7.1%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.40	0.3	9.51E-06	0.2	6.34E-06	0.5	1.59E-05	0.4	1.27E-05
B	73.16	0.4	1.26E-05	0.4	1.26E-05	0.4	1.26E-05	0.2	6.28E-06
C	72.11	0.5	1.59E-05	1	3.18E-05	0.5	1.59E-05	0.3	9.55E-06
Average	72.56		1.27E-05		1.69E-05		1.48E-05		9.50E-06
Cumulative mass loss (lb/ft^2)			1.82E-03		4.26E-03		6.39E-03		7.75E-03

Mixture: C-13.1%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	72.64	0.7	2.21E-05	0.7	2.21E-05	0.6	1.90E-05	0.7	2.21E-05
B	72.40	0.5	1.59E-05	0.9	2.85E-05	0.9	2.85E-05	0.7	2.22E-05
C	73.68	1	3.12E-05	1.1	3.43E-05	0.8	2.49E-05	1.1	3.43E-05
Average	72.91		2.30E-05		2.83E-05		2.41E-05		2.62E-05
Cumulative mass loss (lb/ft^2)			3.32E-03		7.40E-03		1.09E-02		1.46E-02

Mixture: C-15.7%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	76.62	2.2	6.59E-05	1.1	3.30E-05	1.1	3.30E-05	0.8	2.40E-05
B	71.19	1.7	5.48E-05	0.9	2.90E-05	0.9	2.90E-05	1	3.22E-05
C	72.88	1.2	3.78E-05	0.8	2.52E-05	1.2	3.78E-05	1.1	3.47E-05
Average	73.56		5.28E-05		2.91E-05		3.33E-05		3.03E-05
Cumulative mass loss (lb/ft^2)			7.61E-03		1.18E-02		1.66E-02		2.09E-02

Mixture: S-7.1%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	73.40	1.5	4.69E-05	2.4	7.51E-05	1.7	5.32E-05	2.9	9.07E-05
B	74.13	1.8	5.57E-05	3.2	9.91E-05	1.4	4.34E-05	3.4	1.05E-04
C	73.40	2.3	7.19E-05	4.9	1.53E-04	3.4	1.06E-04	3.9	1.22E-04
Average	73.65		5.82E-05		1.09E-04		6.76E-05		1.06E-04
Cumulative mass loss (lb/ft^2)			8.38E-03		2.41E-02		3.38E-02		4.91E-02

Table B.2 (con't): Scaling results for concrete mixtures with granite as the coarse aggregate

Mixture: S-12.5%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	in^2	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**	**g**	**lb/in^2**
A	71.64	1.2	3.85E-05	1.9	6.09E-05	1.2	3.85E-05	2	6.41E-05
B	69.89	1	3.28E-05	3.6	1.18E-04	2.8	9.20E-05	2.2	7.23E-05
C	69.89	0.7	2.30E-05	2.3	7.56E-05	2.1	6.90E-05	2	6.57E-05
Average	70.47		3.14E-05		8.49E-05		6.65E-05		6.74E-05
Cumulative mass loss (lb/ft^2)			4.53E-03		1.68E-02		2.63E-02		3.60E-02

Mixture: S-17.3%-G									
Specimen	**Effective Area**	**Mass loss at 7 days**		**Mass loss at 21 days**		**Mass loss at 35 days**		**Mass loss at 56 days**	
	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	6	2.05E-04	1.5	5.13E-05	4.6	1.57E-04
B	70.83	3.3	1.07E-04	5.8	1.88E-04	3.3	1.07E-04	4.7	1.52E-04
C	72.40	3	9.51E-05	3.4	1.08E-04	2.9	9.20E-05	4.9	1.55E-04
Average	70.13		9.81E-05		1.67E-04		8.34E-05		1.55E-04
Cumulative mass loss (lb/ft^2)			1.41E-02		3.82E-02		5.02E-02		7.25E-02

Table B.3: *p* values obtained from Student's t-test for the difference in cumulative 56-day scaling mass loss of mixtures with limestone and granite as the coarse aggregate

Mixture ID	**56-day average mass loss (lb/ft^2)**	**C-6.8%-L**	**C-7.1%-G**	**C-13.5%-L**	**C-13.1%-G**	**C-15.6%-L**	**C-15.7%-G**	**S-6.9%-L**	**S-7.1%-G**	**S-11.9%-L**	**S-12.5%-G**	**S-16.3%-L**	**S-17.3%-G**
		0.012	**0.008**	**0.014**	**0.015**	**0.066**	**0.021**	**0.160**	**0.049**	**0.063**	**0.036**	**0.054**	**0.073**
C-6.8%-L	**0.012**		0.26	0.76	0.58	**0.01**	0.07	**9.3×10^{-6}**	**0.01**	**2.7×10^{-4}**	**0.02**	**5.7×10^{-3}**	**3.8×10^{-4}**
C-7.1%-G	**0.008**			0.14	**0.04**	**6.5×10^{-3}**	**1.3×10^{-3}**	**3.7×10^{-6}**	**7.8×10^{-3}**	**4.6×10^{-5}**	**5.1×10^{-3}**	**2.8×10^{-3}**	**1.4×10^{-4}**
C-13.5%-L	**0.014**				0.84	**0.01**	0.09	**8.6×10^{-6}**	**0.02**	**9.5×10^{-5}**	**0.01**	**5.3×10^{-3}**	**2.4×10^{-4}**
C-13.1%-G	**0.015**					**0.01**	**0.03**	**4.9×10^{-6}**	**0.01**	**9.5×10^{-5}**	**0.01**	**5.3×10^{-3}**	**2.4×10^{-4}**
C-15.6%-L	**0.066**						**0.02**	**1.3×10^{-2}**	0.29	0.81	0.07	0.42	0.60
C-15.7%-G	**0.021**							**4.6×10^{-6}**	**0.03**	**9.9×10^{-5}**	**0.04**	**9.1×10^{-3}**	**3.0×10^{-4}**
S-6.9%-L	**0.160**								**2.7×10^{-4}**	**3.5×10^{-5}**	**4.0×10^{-5}**	**1.9×10^{-4}**	**1.2×10^{-4}**
S-7.1%-G	**0.049**									0.19	0.24	0.68	0.07
S-11.9%-L	**0.066**										**8.2×10^{-3}**	0.30	0.13
S-12.5%-G	**0.036**											0.10	**5.0×10^{-3}**
S-16.3%-L	**0.054**												0.09

APPENDIX C: 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, 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 **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**.

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**.											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.

$$CF = \frac{\text{+3/8'' Material \% Retained}}{\text{+ \# 8 Material \% Retained}} \text{x}100$$

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 **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)