Cracking and Durability in Sustainable Concretes

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Internal Curing and Supplementary Cementitious Materials in Bridge Decks

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Synopsis: Supplementary cementitious materials (SCMs) in conjunction with pre-wetted fine lightweight aggregate to provide internal curing are being increasingly used to produce high-performance, low-shrinking concrete to mitigate bridge deck cracking, providing more sustainable projects with a longer service life. Additionally, the SCMs aid in concrete sustainability by reducing the amount of cement needed in these projects. This study examines the density of cracks in bridge decks in Indiana and Utah that incorporated internal curing with various combinations of portland cement and SCMs, specifically, slag cement, Class C and Class F fly ash, and silica fume, in concrete mixtures with water-cementitious material ratios ranging from 0.39 to 0.44. When compared with crack densities in low-cracking high-performance concrete (LC-HPC) and control bridge decks in Kansas, concrete mixtures with a paste content higher than 27% exhibited more cracking, regardless of the use of internal curing or SCMs. Bridge decks with paste contents below 26% that incorporate internal curing and SCMs exhibited low cracking at early ages, although additional surveys will be needed before conclusions on long-term behavior can be made.

Keywords: bridge decks, cracking, high-performance concrete, internal curing, sustainability

INTRODUCTION

Cracking in bridge decks is a serious concern because cracks provide corrosive agents a direct path to reinforcing steel and reduce the freeze-thaw resistance of the concrete, ultimately reducing the service life of the structure. Regardless of the type of concrete being used in bridge deck construction, sustainability is significantly improved through the reduction of cracking. One initiative in recent concrete construction includes the addition of shrinkage reducing technologies as a measure to reduce cracking. Concrete mixture proportioning and construction practices have also been examined as measures to result in longer-lasting bridge decks. Over the past two decades, the Kansas Department of Transportation (KDOT) has been working with the University of Kansas (KU) to minimize cracking in bridge decks. Through a pooled-fund study supported by KDOT, other state and federal transportation organizations, and concrete material suppliers and organizations, the University of Kansas has developed specifications for Low-Cracking High-Performance Concrete (LC-HPC) bridge decks.

These specifications address cement and water content, plastic concrete properties, construction methods, and curing requirements. The constituent that undergoes shrinkage in concrete is cement paste (cementitious materials plus water in a concrete mixture). As a measure to reduce shrinkage compared to conventional bridge deck concrete, LC-HPC specifications limit cement content and dictate a tight range of water-cementitious material (*w/cm*) ratios. Cement contents are limited to 500 to 540 lb/yd^3 (296 to 320 kg/m^3). Because of a lack of consensus on the effect of supplementary cementitious materials (SCMs) on drying shrinkage at the time LC-HPC specifications were first written, only portland cement is permitted in LC-HPC decks. A *w/cm* ratio (0.43 to 0.45) is specified to help limit strength because of the relationship between high strength and increased cracking due to reduced creep, which can result in increased cracking if drying shrinkage is restrained. For portland cement mixtures following LC-HPC specifications for *w/cm* ratio and cement content, the paste content is inherently limited to 24.6% by volume. The 28-day strength of concrete is limited to values between 3500 and 5500 psi (24.1 and 37.9 MPa), and the air content of fresh concrete must be 8.0 ± 1.5% to improve durability and reduce cracking. An optimized aggregate gradation is used in LC-HPC mixtures. This can be achieved with tools such as described by Shilstone (1990) or provided by the KU Mix Method (Lindquist et al. 2008, 2015). These criteria provide concrete with better workability at a lower slump. LC-HPC specifications limit slump between 1½ and 3 in. (40 and 75 mm) at the point of placement and 3½ in. (90 mm) at the truck because high slump increases settlement cracking above reinforcing bars. To limit thermal and plastic shrinkage cracking, the temperature of fresh concrete must be between 55 and 70 ºF (13 and 21 ºC). The temperature range may be extended to 50 to 75 ºF with approval by the Engineer.

To reduce the amount of water lost during construction and to avoid plastic shrinkage limits, the evaporation rate during bridge deck placement is limited to 0.2 lb/ft^2/hr (1.0 kg/m^2/hr). If the evaporation rate exceeds this limit, special actions, such as cooling the concrete or installing wind breaks, are required. Procedures for ensuring proper consolidation of concrete (through the use of vertically mounted internal gang vibrators) are also specified along with strike-off and finishing. The surface must be finished using a burlap drag, a metal pan, or both, followed by bullfloating (only if needed). Finishing aids, including water, are prohibited. To minimize plastic shrinkage cracking caused by loss of surface water after placement, early initiation of curing is required using a layer of pre-saturated burlap placed on the deck within 10 minutes after final strikeoff. A second layer of burlap must be placed within the next 5 minutes. The burlap must be soaked for at least 12 hours prior to placement.

In Kansas, 16 bridge decks have been constructed following the LC-HPC specifications (Kansas Department of Transportation 2011, 2014a, 2014b), with 11 bridge decks constructed following normal KDOT specifications to provide a basis of comparison. To provide a consistent method to compare bridge decks, a specific crack survey procedure has been developed to minimize variations from year to year (Lindquist et al. 2008, Yuan et al. 2011, Pendergrass et al. 2014). Results from the pooled-fund study show that the LC-HPC bridge decks are performing better than the decks constructed in accordance with normal KDOT specifications across the state (Lindquist et al. 2008, McLeod et al. 2009, Darwin et al. 2010, 2012, Yuan et al. 2011, Pendergrass et al. 2014, Alhmood et al. 2015, Darwin et al. 2016).

There are other approaches available in addition to LC-HPC to reduce cracking in bridge decks. These include the use of internal curing (IC) through a partial replacement of aggregate with pre-wetted fine lightweight aggregate (LWA). For concrete with water cementitious material (*w/cm*) ratios below about 0.42, the cement paste can experience self-desiccation during early hydration, resulting in autogenous shrinkage of the concrete. In cases where the concrete is restrained from shrinking, tensile stresses develop and crack the concrete. Proper distribution of IC water has been shown to improve performance of concrete due to the reduction of autogenous shrinkage by providing additional water for hydration throughout the entire cement paste matrix (Bentz and Weiss 2011). IC water is also available to reduce drying shrinkage for concrete made with *w/cm* ratios both above and below 0.42. Applicability of this technology for bridge deck cracking and durability is discussed in this report.

The initial survey results of six bridge decks in Indiana are the primary focus of this report. The first deck (IN-IC) was placed with IC concrete that contained 100% portland cement with IC, obtained by replacing a portion of aggregate with pre-wetted fine LWA. The control deck for IN-IC, designated IN-Control, incorporated mixture proportions similar to the IN-IC deck but with no IC water provided (no LWA replacement). The other four bridges were constructed with internally cured high-performance concrete (IN-IC-HPC) containing SCMs, either Class C fly ash or slag cement along with silica fume. The IN-IC-HPC decks contained higher quantities of IC water than IN-IC.

In addition to the six bridges in Indiana, the results of crack surveys conducted by Brigham Young University (BYU) on two internally cured decks in Utah (UT-IC-1 and UT-IC-2) are also included in this paper for comparison. UT-IC-1 and UT-IC-2 were constructed in spring 2012 and are similar in structure type (including precast panels to support an internally cured deck topping) and mixture proportions. The concrete used in both UT-IC decks incorporated a partial replacement of cement with Class F fly ash. The age of both Utah bridges was 24 months at the time of most recent surveys and followed a procedure similar to that used by KU for visually inspecting bridge decks for cracks. This report analyzes the cracking performance of the eight bridge decks and compares them with that of the LC-HPC and conventional KDOT bridge decks being analyzed in the pooled-fund study.

RESEARCH SIGNIFICANCE

Cracking of concrete bridge decks can lead to rapid deterioration and shortened service life. It follows that the sustainability of concrete bridge decks is significantly increased with improved cracking performance. Based on research findings at the University of Kansas (KU), specifications for Low-Cracking High-Performance Concrete (LC-HPC) bridge deck construction were developed and include requirements for cementitious material and cement paste contents, curing, maximum concrete compressive strength, slump, and finishing operations. LC-HPC specifications do not currently specify the use of SCMs or IC. The bridge decks included in this paper serve as a basis for evaluating cracking and durability performance of concrete with IC or SCMs and IC at early ages.

CRACK SURVEY PROCEDURE

Crack surveys for both LC-HPC and control bridge decks are performed on an annual basis during late spring, summer, and early fall. The survey procedures are summarized next.

Procedure

To provide accurate and comparable results, a standard procedure is followed for crack surveys as outlined by Lindquist et al. 2005. Crack surveys should be performed only on a day that is at least mostly sunny with an air temperature not less than 60°F (16°C) at the time of surveying. Moreover, the bridge deck should be completely dry. The crack survey is invalid if it rains during the time of the survey or if the sky becomes overcast.

A scaled plan (map) for the bridge deck is developed and printed before the survey and serves as the template to indicate the location and length of the cracks on the actual bridge deck. A grid on a separate sheet of paper is included underneath the deck plan. The grid helps the surveyor keep track of crack location and length. Some variations are expected when drawing the cracks.

Traffic control is provided to ensure the safety of the surveyors during the bridge survey. After closing at least one lane of the bridge to traffic, two surveyors draw a 5 ft × 5 ft (1.52 m × 1.52 m) grid on the bridge deck using sidewalk chalk or lumber crayons. This is called the bridge grid and should match the grid prepared for use with the plans. Surveyors mark cracks on the deck they can see while bending at waist height (cracks that cannot be seen from waist height should not be marked). At least two surveyors should inspect each section of the bridge. This method results in consistent crack survey results between surveys (Lindquist et al. 2005, 2008). After cracks are marked on the bridge, another surveyor draws the marked cracks on the scaled bridge plan.

To determine crack density, the bridge plans with the marked cracks are scanned into a computer and converted to digital drawing files. Any lines on the bridge plan not representing cracks (such as bridge abutments or barriers) are erased in post-processing. The total length of the cracks can then be measured using drawing software. Crack density is calculated by dividing the total length of the cracks by the area of the bridge deck. Crack densities are reported in m/m^2 for the whole bridge, each placement, and each span (1 m/m^2 = 0.305 ft/ft^2). For most bridge decks, the majority of cracks present are transverse, although longitudinal cracks form, especially adjacent to abutments (Schmitt and Darwin 1995; Krauss and Rogalla 1996). As will be shown later in this paper, the cracks in the Indiana decks tended to be longitudinal. For the two Utah decks discussed in this paper, crack surveys were conducted by BYU researchers using a similar procedure for identifying, measuring, and recording crack lengths and widths (Guthrie et al. 2014).

BRIDGES

The Indiana bridges are located in two Indiana Department of Transportation (INDOT) districts, Seymour and Vincennes. The four IN-IC-HPC decks are supported by steel girders and have steel stay-in-place forms; the other two are supported by prestressed box beams. Two Utah IC deck toppings, surveyed by Brigham Young University researchers (included as an additional reference for comparison) are supported by precast half-deck concrete panels supported by precast prestressed concrete girders. Information on the decks is summarized in Table 1. In this report, the IC and control decks in Indiana are designated IN-IC and IN-Control, respectively, and the internally cured high-performance concrete decks are designated IN-IC-HPC-1 through IN-IC-HPC-4. The internally cured Utah deck toppings are designated UT-IC-1 and UT-IC-2.

Table 1—Bridge properties

Bridge ID	District	Type of Support	Spans	Skew (deg.)	Length		Width	
					(ft)	(m)	(ft)	(m)
IN-IC	Seymour	Prestressed box beam	1	10.6	40.3	12.3	29	8.8
IN-Control	Seymour	Prestressed box beam	1	0	50	15.2	29	8.8
IN-IC-HPC-1	Vincennes	Steel beam	3	0	224	68.3	34.5	10.5
IN-IC-HPC-2	Seymour	Steel beam	1	0	55	16.8	43.5	13.3
IN-IC-HPC-3	Seymour	Steel beam	4	34.8	256	78.0	33	10.1
IN-IC-HPC-4	Vincennes	Steel beam	2	6.7	230	70.1	43.8	13.4
UT-IC-1	-	Prestressed girder	1	34	127.5	38.9	50.8	15.5
UT-IC-2	-	Prestressed girder	1	4	119.8	36.5	50.8	15.5

IN-IC

IN-IC is a single-span bridge located in the INDOT Seymour district near the city of Bloomington and spans over Stephens Creek on North Gettys Creek Rd. The deck was placed in September 2010 in a single placement. It is supported by prestressed concrete box beams. IN-IC is 29 ft (8.4 m) wide, and the deck varies in depth from 4½ in. (114 mm) at edge gutters to 8 in. (205 mm) at the roadway centerline. A single layer of reinforcing steel was placed at the mid-depth of the decks. The IN-IC bridge deck spans approximately 40.3 ft (12.3 m). The concrete contained 657 lb/yd^3 (390 kg/m^3) of Type I/II portland cement, compared to a maximum of 540 lb/yd^3 (320 kg/m^3) used for LC-HPC bridge decks. IN-IC contained pre-wetted fine LWA for providing IC water. The *w/cm* ratio was 0.39, well below the range of 0.43 to 0.45 used for LC-HPC bridge decks. The paste content was 27.6%, by volume, which is higher than the 22.8 to 24.6% used in LC-HPC bridge decks and threshold of 27% based on the work by Schmitt and Darwin (1995, 1999). Without internal curing, these parameters typically lead to concrete with high crack densities. The lightweight aggregate used in this bridge provided an average IC water content of 7.2% by weight of cement. The average 28-day strength of the lab-cured cylinders was 4900 psi (33.8 MPa), which is within the suggested range of 3500 to 5500 psi (24.1-37.9 MPa) for LC-HPC. The strength, however, was low considering the *w/cm* ratio of 0.39.

Fresh concrete properties including slump, temperature, and air content are not available for this deck.

IN-Control

IN-Control is a single-span bridge located in close proximity to IN-IC and also spans over Stephens Creek on North Gettys Creek Rd. It serves as the control deck for IN-IC and did not utilize internal curing. Like IN-IC, IN-Control is supported by prestressed concrete box girders. The deck was, like IN-IC, constructed in September 2010 in a single placement. Deck geometry and reinforcement layout are similar to IN-IC. IN-Control spans approximately 50 ft (15.2 m). This bridge deck used the same type and amount of cement and *w/cm* ratio as the IN-IC deck. The average 28-day strength of the cylinders was 4380 psi (30.2 MPa), which is again low, considering the low *w/cm* ratio. Fresh concrete properties including slump, temperature, and air content are not available for this deck.

IN-IC-HPC-1

IN-IC-HPC-1 is located north of West Baden Springs on US 150 crossing the Lost River. It is a three-span bridge with a length and width of 224 ft (68.3 m) and 34.5 ft (10.5 m), respectively. The deck is supported by steel girders and was constructed in two placements, in July and October 2013. The deck has a depth of 8 in. (205 mm), with 2.5 in. (64 mm) of top cover over reinforcing bars. The concrete contained 568 and 567 lb/yd^3 (324 kg/m^3) of cementitious material for placements 1 and 2, respectively, 18% of which was slag cement and 4% of which was silica fume (by weight). For IC, the concrete also contained pre-wetted fine LWA, accounting for approximately 15% of total aggregate volume. The actual absorption of the LWA, determined prior to casting, was 18.7% for both placements (versus 14.9% used in design). This resulted in average IC water contents of 9.1 and 8.5% by weight of binder for placements 1 and 2, respectively. The *w/cm* ratios for placements 1 and 2 were 0.401 and 0.426, respectively, which are below the range for LC-HPC decks. The paste contents for placements 1 and 2 were 24.6 and 25.2% of total volume, respectively. The paste content for placement 2 was slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slumps for placements 1 and 2 were 4¾ in. (120 mm) and 5¾ in. (145 mm) as measured at the point of placement, respectively, which exceed the maximum slump of 3½ in. (90 mm) for LC-HPC decks. The average air contents for placements 1 and 2 were 5.1 and 5.5%, respectively, which are below the range (8.0 ± 1.5%) in the LC-HPC specifications. The average 28-day strengths for placements 1 and 2 were 7680 and 6640 psi (53.0 and 45.8 MPa), respectively, which exceed the upper limit for compressive strength under LC-HPC specifications.

IN-IC-HPC-2

IN-IC-HPC-2 is located in the town of Austin on US 31 over Hutto Creek. It is a single-span bridge with a length and width of 55 ft (16.8 m) and 43.5 ft (13.3 m), respectively, and is supported by steel girders. The deck was placed in October 2013. The deck is 8 in. (205 mm) thick. The concrete contained 575 lb/yd^3 (340 kg/m^3) of cementitious material, 25% of which was Class C fly ash, and 4% of which was silica fume. For internal curing, the concrete also contained pre-wetted fine LWA, accounting for 15% of total aggregate volume. The actual absorption of LWA determined prior to casting for this deck was 20% (versus a design absorption of 13.75%). This resulted in an average IC water content of 9.2% by weight of binder. The *w/cm* ratio for this deck was 0.418, which is lower than the 0.43 to 0.45 range used in LC-HPC specifications. The paste content was 25.3% which is slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slump was 5 in. (125 mm), and the average air content was 6.4%. The average 28-day strength was 6720 psi (46.3 MPa). The concrete slump, air content, and compressive strength were outside of the ranges specified by LC-HPC specifications.

IN-IC-HPC-3

IN-IC-HPC-3 is located on SR 46 over interstate highway I-74 in the town of West Harrison. This four-span bridge has a length and width of 256 ft (78 m) and 33 ft (10.1 m), respectively, and is supported by steel girders. The deck was constructed in a single placement in November 2014. The concrete contained 600 lb/yd^3 (355 kg/m^3) of cementitious material, 24% of which was Class C fly ash and 4% of which was silica fume. The concrete also contained 21% pre-wetted fine LWA of total aggregate volume to provide an IC water content of 11.6% by weight of binder. The average *w/cm* ratio was 0.417 for this deck, outside the range suggested in the LC-HPC specifications (0.43 to 0.45). The paste content was 25.9%, which is outside of the range used in LC-HPC decks (22.8 to 24.6%). The average slump was 5½ in. (140 mm), and the average air content was 7.0%. The average 28-day strength was 5500 psi (37.9 MPa). Air content and strength met the LC-HPC requirements, but slump was higher than the limit specified within LC-HPC specifications.

IN-IC-HPC-4

IN-IC-HPC-4 is located on SR 61 crossing over I-64. The two-span bridge has a length and width of 230 ft

(70.1 m) and 43.8 ft (13.4 m), respectively and is supported by steel girders. The deck was constructed in two placements, in July and October of 2015. The concrete contained 582 and 585 lb/yd^3 (345 and 347 kg/m^3) of cementitious material for placements 1 and 2, respectively, 20% of which was slag and 4% of which was silica fume (by weight). The concrete also contained 21% pre-wetted fine LWA of total aggregate by volume for internal curing. The actual absorption of the LWA determined prior to casting was 20.1% (versus a design absorption of 13%). This resulted in average IC water contents of 12.0 and 11.2% by weight of binder for placements 1 and 2, respectively. The average *w/cm* ratios for placements 1 and 2 were 0.414 and 0.420, respectively, lower than those used in the LC-HPC decks. The actual paste contents for placements 1 and 2 were 25.7% and 26%, respectively, slightly outside of the range used in LC-HPC decks (22.8-24.6%). The average slumps for placements 1 and 2 were 4¾ in. (120 mm) and 5¼ in. (130 mm), respectively. The average air content was 6.2% for the first placement and 5.5% for the second placement. Strength data were not provided for separate placements. The average 28-day compressive strength was given as 6120 psi (42.2 MPa). Slump, air content, and strength are outside the ranges given in the LC-HPC specifications.

UT-IC-1 and UT-IC-2

UT-IC-1 and 2 are located in the city of West Jordan. UT-IC-1 is along Dannon Way Road, and UT-IC-2 is on 8200 South Road. Both are single span bridges supported by prestressed concrete girders and were placed in the spring of 2012. The length and width of UT-IC-1 are 127.5 ft (38.9 m) and 50.8 ft (15.5 m), respectively. The length and width of UT-IC-2 are 119.8 ft (36.5 m) and 50.8 ft (15.5 m), respectively. Precast half-deck concrete panels support the IC deck topping for both bridges. The deck topping was specified to have 2½ in. (75 mm) of cover over top reinforcing bars and varies in thickness. The IC deck toppings had identical mix designs and contained 605 lb/yd^3 (347 kg/m^3) of cementitious material, 21% of which was Class F fly ash. The concrete also contained 16% pre-wetted fine LWA of total aggregate volume to provide an IC water content of 7% by weight of binder. The *w/cm* ratio was 0.44, which is within the range suggested in LC-HPC specifications. The paste content was 28%, above of the range used in LC-HPC decks (22.8-24.6%).

The average slumps for UT-IC-1 and UT-IC-2 were 3½ in. (90 mm) and 3¼ in. (85 mm), respectively. The average air contents for UT-IC-1 and UT-IC-2 were 6.4% and 6%, respectively. The average 28-day strengths of the concrete for UT-IC-1 and UT-IC-2 were 5710 psi (39.4 MPa) and 5370 psi (37.0 MPa), respectively. Air content for both decks and strength for UT-IC-1 did not meet LC-HPC specifications.

Concrete Properties and Construction Procedures

The mixture proportions used for the bridge decks are shown in Table 2. Plastic concrete properties along with 28-day compressive strengths are listed in Table 3. Two concrete mix designs were used for internally cured bridge decks in Indiana, IN-IC and IN-IC-HPC. The IN-IC concrete contained 657 lb/yd^3 (390 kg/m^3) of portland cement, the only binder, and a *w/cm* ratio of 0.39, which resulted in a paste volume of 27.6%, exceeding the paste content range in Kansas LC-HPC specifications. For IC concrete mixtures, current literature typically reports the amount of IC water in lb per 100 lb (kg per 100 kg) of cementitious material. For this paper, the amount of IC water is reported as a percentage by weight of cementitious material. IC water for the IN-IC deck was provided through replacement of 24% of total aggregate (by volume) with pre-wetted fine LWA that provided 7.2% of IC water by weight of cement in the mixture (Di Bella et al. 2012). Determination of absorption in laboratory was based on soaking the material for 24 hours before placing it in a pre-wetted surface dry (PSD) condition. For fine LWA, absorption tends to increase with longer soak times, so properties are described in terms of the PSD condition rather than the SSD condition since the material is not fully saturated. A commercially available fine LWA with a 24-hour absorption of 10.4% and a PSD specific gravity of 1.56 was used. All LWA referenced in this paper is expanded shale. The mixture proportions conformed to INDOT specifications and determination of LWA properties followed procedures outlined by the New York State DOT (NYSDOT) for construction of a series of internally cured bridge decks (Wolfe 2012). A modified paper towel test method (NY 703-19E Test Method) that includes instructions for determining LWA properties in the field as well as in the lab was used in lieu of ASTM C128.

IN-IC-HPC mixtures that were used for construction of the remaining four internally cured bridge decks in Indiana were designed to improve cracking and ionic transport properties of concrete (Barrett et al. 2015). First, to reduce ion transport and have a denser microstructure, a ternary binder system with cement, silica fume (3 to 7% by mass), and slag cement (15 to 20% by mass) or Class C fly ash (20 to 25% by mass), was used to produce a refined pore system and greater calcium hydroxide consumption. For all the IN-IC-HPC bridges in this study, absorption of the pre-wetted LWA obtained before batching exceeded the values determined in laboratory testing. IN-IC-HPC mixtures, as batched, had between 8.8 and 12% of IC water by weight of binder. The fine LWA used for the IN-IC-HPC decks had a 24-hour absorption capacity (based on dry weight) and PSD specific gravity of approximately 13% and 1.70, respectively. Second, the IN-IC-HPC specifications placed a 25% (±1.0%) limit on the paste content of the mixtures to improve the shrinkage and cracking performance of the concrete. The actual paste contents of the four IN-IC-HPC decks ranged from 24.6% to 26.0% by volume. As explained by Barret et al. (2015), this limitation was applied based on the recommendations by Schmitt and Darwin (1995) as a result of their study of 33 bridge deck placements in Kansas that showed a clear relationship between paste content and bridge deck cracking. Schmitt and Darwin (1995) concluded that when volume of the paste exceeded 27%, cracking significantly increases. A 7-day wet burlap curing regime was used for all Indiana bridges. INDOT removed the requirement for bridge decks to be covered by a commercial sealant for the internally cured decks.

Table 2—Mixture proportions (SSD/PSD basis)

Bridge ID	**Date Placed**	**Cementitious Material Percentages**[b]	**Coarse Aggregate lb/yd^3 (kg/m^3)**	**Fine Aggregate lb/yd^3 (kg/m^3)**	**Fine LWA (PSD) lb/yd^3 (kg/m^3)**
IN-IC	9/24/2010	100% C	1764 (1046)	528 (313)	455 (270)
IN-Control	9/23/2010	100% C	1764 (1046)	1224 (726)	-
IN-IC-HPC-1[a]	7/19/2013	78% C, 18% S, 4% SF	1805 (1071)	795 (472)	375 (222)
	10/18/2013		1800 (1068)	801 (475)	348 (206)
IN-IC-HPC-2	10/1/2013	71% C, 25% C-FA, 4% SF	1726 (1024)	819 (486)	334 (198)
IN-IC-HPC-3	11/1/2014	72% C, 24% C-FA, 4% SF	1758 (1043)	644 (382)	446 (265)
IN-IC-HPC-4[a]	7/14/2015	76% C, 20% S, 4% SF	1763 (1046)	665 (395)	447 (265)
	10/3/2015		1768 (1049)	663 (393)	448 (266)
UT-IC-1	Spring 2012	79% C, 21% F-FA	1721 (1021)	706 (419)	324 (192)
UT-IC-2	Spring 2012	79% C, 21% F-FA	1721 (1021)	706 (419)	324 (192)

[a] – First row is for placement 1 and the second row is for placement 2.

[b] – C = portland cement; S = slag cement; SF = silica fume; C-FA = Class C fly ash; F-FA = Class F fly ash

Table 2—Mixture proportions (continued)

Bridge ID	Cementitious Material Content	Water Content	Design IC Water	Actual IC Water	*w/cm* Ratio	Paste Content
	lb/yd³ (kg/m³)	lb/yd³ (kg/m³)	Percent of Binder by Weight	Percent of Binder by Weight		Percent
IN-IC	657 (390)	256 (152)	7	7.2	0.39	27.6
IN-Control	657 (390)	256 (152)	-	-	0.39	27.6
IN-IC-HPC-1*	568 (337)	228 (135)	8	9.1	0.401	24.6
	567 (336)	238 (141)	8	8.5	0.426	25.2
IN-IC-HPC-2	567 (336)	237 (141)	8	9.2	0.418	25.3
IN-IC-HPC-3	600 (356)	250 (148)	8	11.6	0.417	25.9
IN-IC-HPC-4*	582 (345)	241 (143)	8	12	0.414	25.7
	585 (348)	246 (146)	8	11.2	0.42	26
UT-IC-1	605 (359)	266 (158)	7	7	0.44	28
UT-IC-2	605 (359)	266 (158)	7	7	0.44	28

[*] = First row is for placement 1 and the second row is for placement 2.

Table 3—Average plastic properties and compressive strengths

Bridge ID	Slump	Air Content	28-day Strength
	in. (mm)	(%)	psi (MPa)
IN-IC	-	-	4900 (33.8)
IN-Control	-	-	4380 (30.2)
IN- IC-HPC-1*	4¾ (120)	5.1	7680 (53.0)
	5¾ (145)	5.5	6640 (45.8)
IN-IC-HPC-2	5 (125)	6.4	6720 (46.3)
IN-IC-HPC-3	5½ (140)	7.0	5500 (37.9)
IN-IC-HPC-4*	4¾ (120)	6.2	6120 (42.2)[a]
	5¼ (135)	5.5	
UT-IC-1	3½ (90)	6.4	5710 (39.4)
UT-IC-2	3¼ (85)	6.0	5370 (37.0)

[*] = First row is for placement 1 and the second row is for placement 2

[a] = Data on separate placements not available

For the IC bridge decks in Indiana, the *w/cm* ratio was permitted to be between 0.39 and 0.42 to achieve high compressive strength and maintain durability, notably lower than the *w/cm* ratios used in the LC-HPC bridge decks in Kansas (0.44 to 0.45). IC water for these bridges was used to eliminate chemical shrinkage, defined as the change in volume due to the chemical reaction between cement and water (Barret et al. 2015), and autogenous shrinkage, defined as the change in volume due to self-desiccation, particularly in mixtures with low *w/cm* ratios (Di Bella et al. 2012, Barret et al. 2015). For mixtures without SCMs, the amount of IC water was specified to be 7% of the cement weight, based on work by Bentz and Weiss (2011), which indicated that chemical and autogenous shrinkage of portland cement can be mitigated by providing 7% internal curing water by weight of cement. For the IN-IC-HPC mixtures, which had a ternary binder system, the amount of IC water was specified to be 8% of the binder weight. The shrinkage behavior and rate of hydration for SCMs requires a higher amount of internal curing water to counteract the effects of chemical and autogenous shrinkage (Bentz and Weiss 2011). For the Indiana bridges, the 24-hour absorption (based on dry weight) and the PSD specific gravity of pre-wetted fine LWA, determined before construction, were used to design and batch the internally cured concrete mixtures. At the batching plant, the LWA stockpile was sprinkled for at least 48 hours and drained for 12 hours prior to batching. Prior to batching, the absorption, surface moisture, and specific gravity of the LWA were determined using the centrifuge method developed by Miller et al. (2014). Surface moisture and specific gravity values obtained before batching were used to adjust the mixture proportions to achieve a proper yield and *w/cm* ratio. The amount of fine LWA and subsequent amount of IC water in the mixtures, however, were adjusted only if the absorption was lower than that of the 24-hour absorption obtained in laboratory testing (Barrett et al. 2015). The four IN-IC-HPC decks had a total of six placements. The placements were 10.5 to 37.2 months old when the first crack surveys were performed. The IN-IC deck concrete was placed using buckets, but the IN-Control concrete was pumped. Concrete in the four IN-IC-HPC decks was also pumped. All Indiana decks were tined shortly after concrete placement.

The internally cured deck toppings in Utah were placed on precast half-deck concrete panels supported by five precast prestressed single span concrete girders. The topping concrete had a *w/cm* of 0.44 and a paste content of 28% by volume. This paste content exceeds Kansas LC-HPC concrete. The deck topping concrete incorporated Class F fly ash (21% by mass) as a partial replacement for portland cement; 16.7% of the total aggregate (by volume) was replaced with pre-wetted fine LWA with an absorption capacity of 15% and PSD specific gravity of 1.56 to provide IC water equal to 7% of the weight of binder (Guthrie et al. 2014). The 24-hour absorption of the pre-wetted fine LWA was used to proportion the aggregates. The LWA stockpile was sprinkled for a minimum of two days prior to mixing. The absorption was measured periodically, and when an absorption of 15% was achieved, the stockpile was drained. A curing compound was sprayed on the deck after finishing, followed by a 14-day period of curing under plastic. The two Utah IC deck toppings were constructed by the same contactor and utilized conventional wooden formwork. The deck surfaces were tined shortly after placement.

RESULTS

The crack surveys for the Indiana decks were completed between August 8 and 11, 2016. Placement ages range between 10.5 and 71.6 months. Additional surveys are planned for summer 2018. The two-year survey results presented for the Utah decks were completed in by 2012 Brigham Young University researchers (Guthrie et al. 2014). Crack densities for the Indiana and Utah decks ranged from 0 to 0.784 m/m^2 and are listed in Table 4. Based on previous work at KU, surveys should be conducted one and three years after placement and the survey at three years has proven to be a good predictor of long-term performance (Shrestha et al. 2013 and Pendergrass and Darwin 2014). Thus, ideally, the surveys conducted on the IC-HPC and Utah decks should be repeated but do serve as a baseline for future surveys and lend to the conclusions presented in this report.

Table 4—Summary of LWA information and crack densities

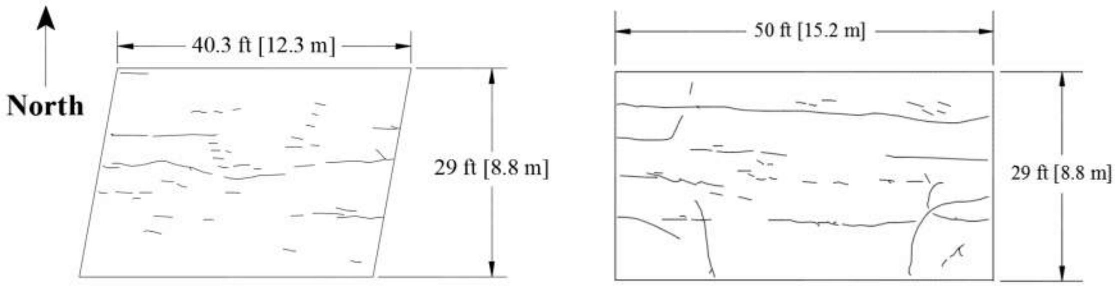
Bridge ID	**LWA Used**	**IC Water (percent of binder)**	**Age at Survey (months)**	**Crack Density (m/m^2)**
IN-IC	Expanded Shale	7.2	71.6	0.347
IN-Control	-	-	71.6	0.507
IN-IC-HPC-1*	Expanded Shale	9.1	34.7	0
		8.5	37.2	0.020
IN-IC-HPC-2	Expanded Shale	9.2	34.8	0.003
IN-IC-HPC-3	Expanded Shale	11.6	21.6	0.016
IN-IC-HPC-4*	Expanded Shale	12	10.5	0.021
		11.2	15.6	0.005
UT-IC-1	Expanded Shale	7	24	0.784
UT-IC-2	Expanded Shale	7	24	0.427

* = First row is for placement 1 and the second row is for placement 2.

IN-IC and Control

IN-IC was surveyed at an age of 71.6 months with a resultant crack density of 0.347 m/m^2. Figure 1(a) shows the crack survey results for IN-IC. The majority of the cracks in this deck are oriented in the longitudinal direction, with the longest cracks appearing to occur at the prestressed box girder boundaries. The average crack width for this bridge was 0.006 in. (0.15 mm).

IN-Control was surveyed at an age of 71.6 months. The crack survey results are shown in Fig. 1(b). The crack density was 0.507 m/m^2. Like IN-IC, most of the cracks are oriented in the longitudinal direction, with the longest cracks occurring at or near the prestressed box girder boundaries. There are more transverse cracks in IN-Control than IN-IC. The average crack width in this bridge was 0.010 in. (0.25 mm). In some cases, the box girders experienced differential settlement with respect to each other of as much as 3/8 in. (10 mm). This uneven settlement of adjacent girders may have contributed to the high number of longitudinal cracks on the deck.



(a) (b)

Fig. 1—Crack survey results for: (a) IN-IC and (b) IN-Control

IN-IC-HPC

The two placements of IN-IC-HPC-1 were surveyed at ages of 34.7 and 37.2 months and have crack densities of 0 and 0.02 m/m^2, respectively. Both placements showed noticeable coarse aggregate pop-outs throughout the deck, more so on placement 2 than placement 1. Placement 2 showed a few short longitudinal cracks on an end span, close to the abutment, and a few longer transverse cracks over the pier between the other two spans. The average crack width was 0.006 in. (0.15 mm). The deck surface showed moderate scaling damage near the north end. Minor freeze-thaw damage was observed on both placements. Figure 2, although showing IN-IC-HPC-2, is representative of this damage.

IN-IC-HPC-2 was surveyed at an age of 34.8 months. The crack density was 0.003 m/m^2. There was only one short longitudinal crack on the deck, with a width of 0.006 in. (0.15 mm). As shown in Fig. 2, there were some coarse aggregate pop-outs and deterioration on the walls of tined surface grooves that may have been caused by a combination of freeze-thaw damage and poor tining.

Fig. 2—Freeze-thaw damage and aggregate pop-outs on IN-IC-HPC-2

IN-IC-HPC-3 was surveyed at 21.6 months. The overall crack density was found to be 0.016 m/m^2. The highest concentration of cracking on this deck was observed on one of the end spans. Most of the cracks were short, longitudinal, and narrow, located at the two abutments. The average crack width of all cracks recorded was 0.006 in. (0.15 mm). There were no transverse cracks, even over the piers. The surface of the deck did not show any indication of freeze-thaw damage or aggregate pop-outs. With the deck being relatively young, little cracking was expected.

The two placements of IN-IC-HPC-4 were surveyed at ages of 10.5 and 15.6 months, respectively, and have the lowest ages of the decks in this study. The crack densities for placements 1 and 2 were 0.021 and 0.005 m/m^2, respectively, as shown in Fig. 3. Span 1 of placement 1 had some plastic shrinkage cracking close to the abutment and there were some short longitudinal cracks on span 2 for both placements; the cracks in placement 2 were closer to the abutment. No transverse cracks were observed, even over the piers. The average crack width was 0.006 in. (0.15 mm) for this bridge. The cracks located in span 1 were significantly wider (average width of 0.014 in. [0.36 mm]) than those located in span 2 (average width of 0.004 in. [0.10 mm]). Similar to the defects shown in Fig. 2, freeze-thaw damage and poor surface finishing (poor tining/grooving) were observed on the surface of the deck; more so on placement 1 than placement 2. No aggregate pop-outs were observed.

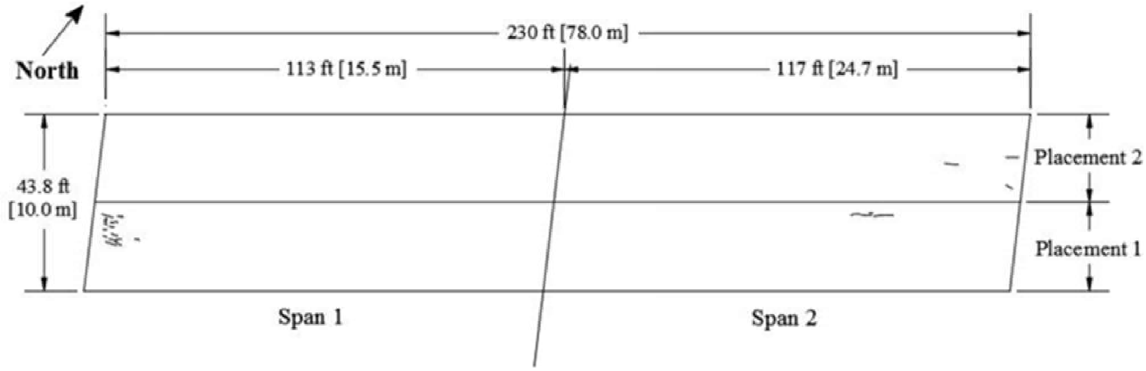


Fig. 3—IN-IC-HPC-4 crack survey result

UT-IC

UT-IC-1 and UT-IC-2 were surveyed by a Brigham Young University research team at the ages of 2, 5, 8, 12, and 24 months (Guthrie et al. 2014). According to the most recent surveys, the crack densities for UT-IC-1 and UT-IC-2 were found to be 0.784 and 0.427 m/m^2, respectively at 24 months. For UT-IC-1, longitudinal, transverse, and map cracks were spread along the driving lanes of the deck with less cracking observed along the shoulders. Short longitudinal cracks formed adjacent to the left abutment across the entire width of the deck. For UT-IC-2, most of the cracks were transverse, with longitudinal cracks adjacent to the abutments. UT-IC-2 had less map cracking compared to UT-IC-1. The majority of transverse and longitudinal cracks were at the pre-cast half deck panel joints in both decks. For both decks, the crack width ranged from 0.008 to 0.050 in. (0.20 to 1.27 mm); the majority of cracks had widths ranging from 0.01 to 0.02 in. (0.25 to 0.51 mm).

Internal Curing with Pre-Wetted Fine LWA

To study the effectiveness of internal curing in reducing cracking in bridge decks, the crack densities of the five Indiana IC bridge decks and two Utah IC deck toppings are compared with Kansas control and LC-HPC decks and the control deck in Indiana. Information on the seven IC decks is summarized in Table 4. Data is plotted for individual placements when more than one placement was used, which is the case for IN-IC-HPC-1 and IN-IC-HPC-4. As shown in Fig. 4, the IN-IC-HPC decks exhibited significantly less cracking than the IN-IC and UT-IC deck toppings. Because these bridges have different ages, different mixture types, varying amounts of IC water, and different superstructure (steel girders, prestressed box beams, and prestressed girders) and deck (monolithic or topping over precast panels) types, it is difficult to make a fair comparison and explain why there are differences, significant in some cases, in crack densities between these decks. However, it appears that having a low paste content is a dominant factor in reducing the occurrence of cracking. The reduction in shrinkage when using SCMs combined with internal curing has been shown previously (De la Varga et al. 2012, Pendergrass and Darwin 2014). A greater amount of IC water and inclusion of a ternary binder system in IN-IC-HPC decks may have also contributed to low crack densities, but these decks were all placed at close to or less than three years at the time of the most recent survey. Although the UT-IC deck toppings are fundamentally different in terms of structure type from the Indiana decks, previous work at KU that included deck toppings with an SCM and low paste content (below 25%) placed on top of precast deck panels exhibited low crack densities (at or below 0.10 m/m^2) through more than 40 months after construction (Shrestha et al. 2013). Additional surveys at later dates are needed to monitor cracking and durability issues and establish a better estimate of long-term behavior.

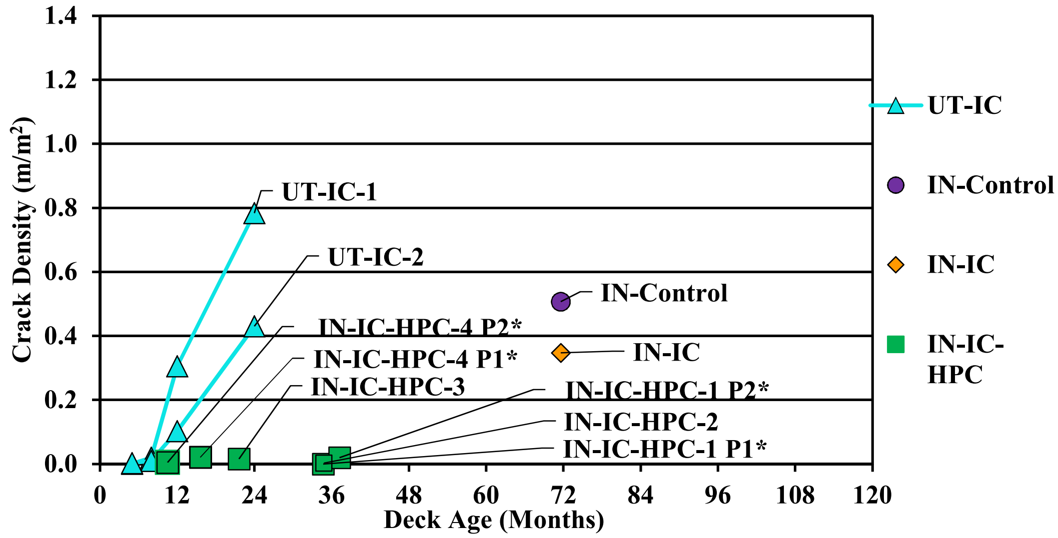


Fig. 4— Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. deck age. *P1 and P2 denotes the first and second placement of the bridge, respectively.

Figure 5 compares the crack densities of the IC decks in Indiana and IC deck toppings in Utah with the crack densities of the control decks in Kansas (denoted as KS-Control) as a function of age. As shown in Fig. 5, the six IN-IC-HPC placements (IN-IC-HPC-1 through IN-IC-HPC-4) exhibited lower crack densities than Kansas control decks at similar ages. The IN-IC deck, performing better than the IN-Control deck at the same age, falls within the spread of Kansas control deck data. The internally cured Utah deck toppings (UT-IC-1 and UT-IC-2), despite their relatively young ages, exhibited the highest cracking density among all IC decks in this study. The crack density of UT-IC-1 was higher at 24 months than all but one of the Kansas control decks. The crack density for UT-IC-2 s also greater than most Kansas control decks surveyed at a similar age.

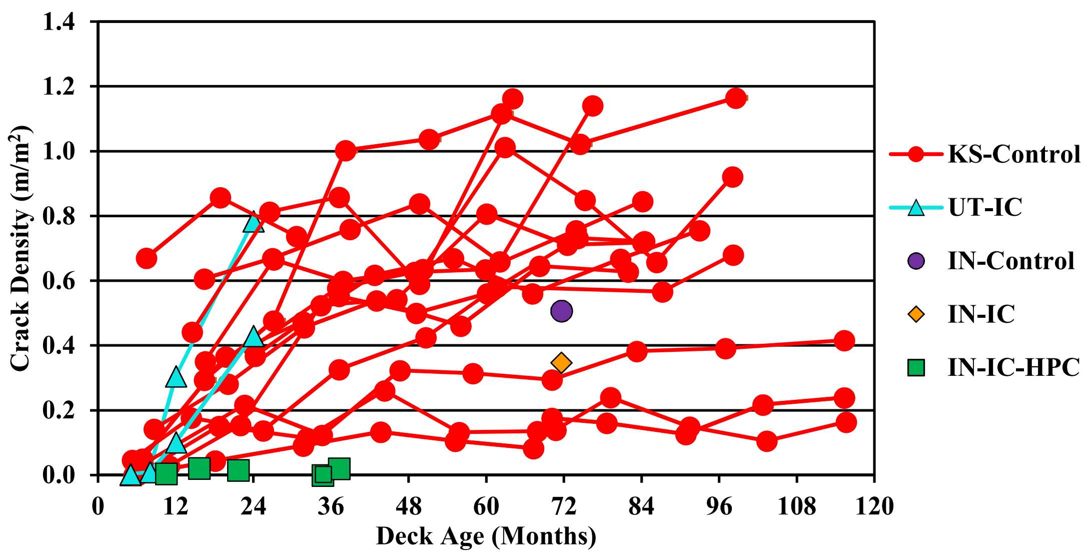


Fig. 5—Crack densities of Kansas control decks and IC decks vs. deck age

Figure 6 compares the crack densities as a function of age for the IC decks in Indiana and IC deck toppings in Utah against LC-HPC decks in Kansas. As shown in the figure, the IN-IC-HPC decks had lower crack densities than most of the LC-HPC decks at similar ages. IN-IC and IN-Control exhibited greater crack densities than most LC-HPC decks; at 24 months, the Utah IC deck toppings had higher crack densities than all LC-HPC decks at similar ages. It appears that internal curing and SCMs contributed greatly to reducing the cracking of IN-IC-HPC bridges.

Internal curing and SCMs or internal curing alone, however, provided no advantage for the Utah IC deck toppings (UT-IC-1 and UT-IC-2) or the Indiana IC deck (IN-IC), which had paste contents above 27% by volume and, thus, greater than both the IN-IC-HPC and LC-HPC decks.

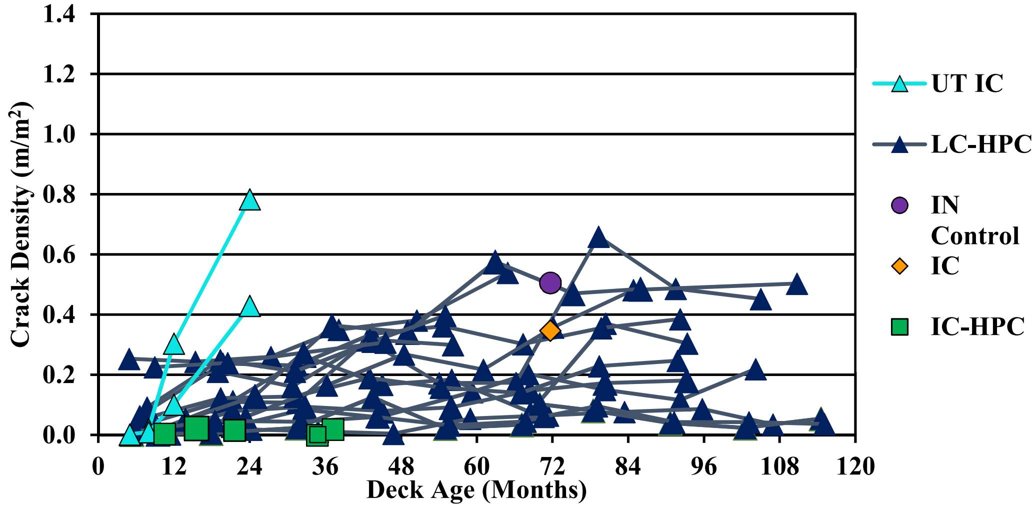


Fig. 6—Crack densities of LC-HPC decks and IC decks vs. deck age

Figure 7 shows the crack density on bridge decks in this study as a function of paste content. Aggregate has a high stiffness, making it dimensionally stable, regardless of moisture loss. Paste in the constituent of concrete that undergoes shrinkage. Studies conducted by University of Kansas dating back to over twenty years ago (Schmitt and Darwin 1995; Miller and Darwin 2000; Lindquist et al. 2008) have shown that increased paste content, independent of other factors, leads to increased cracking in bridge decks. Paste contents less than 27% by volume consistently result in reduced cracking. Figure 7 clearly supports this finding. The Utah deck toppings, with paste contents of 28%, and the IN-Control and IN-IC decks, with paste contents of 27.6%, exhibited significantly greater cracking than the IN-IC-HPC decks, with paste contents lower than 26%. Both Utah deck toppings and the IN-Control and IN-IC decks also had higher crack densities than almost all Kansas LC-HPC decks, and most Kansas control decks at similar survey ages. The internally cured Utah deck toppings had the highest cracking densities in spite of having the required amount of IC water and being supported by prestressed concrete girders, which are also believed to be more helpful in improving cracking performance of the deck than steel girders (*Durability* 1970). These findings demonstrate that a high paste volume can significantly increase bridge deck cracking, even when a crack reduction technology is used.

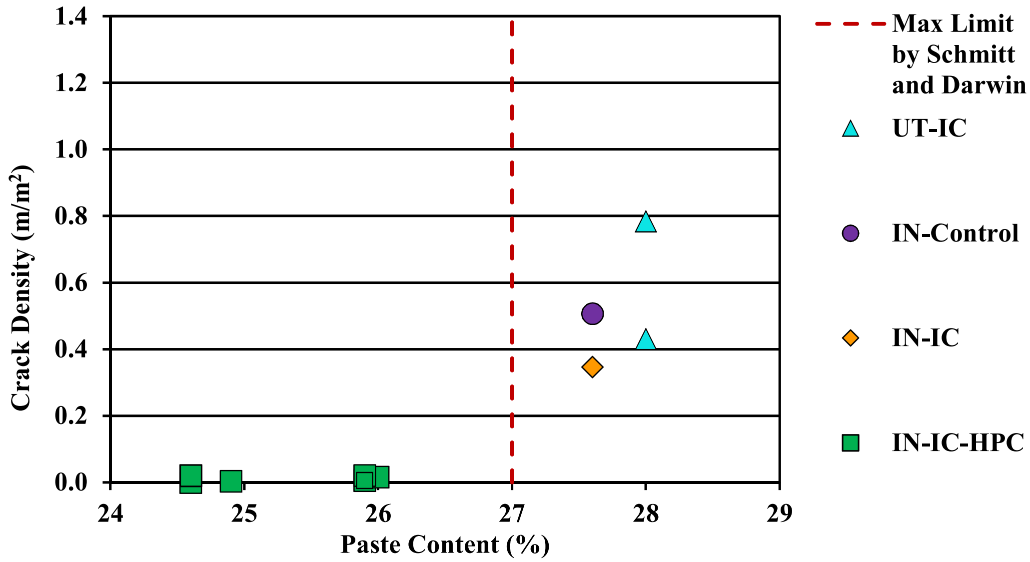


Fig. 7—Crack densities of Indiana and Utah IC bridge decks and Indiana control deck vs. paste content

Figure 8 shows the crack density of bridge decks in this study as a function of 28-day compressive strength. Schmitt and Darwin (1995), Miller and Darwin (2008), and Lindquist et al. (2008), in addition to showing the benefits of decreased paste content, also showed the benefits of having decks constructed with lower-strength concrete. As concrete compressive strength increases, creep decreases. Creep reduces stresses caused by restrained shrinkage and, thus, reduces the potential for cracking. As shown in Fig. 8, the IN-IC and IN-Control decks have 28-day compressive strengths of 4900 and 4380 psi (33.8 and 30.2 MPa), respectively, which are within the recommended range in the LC-HPC specifications, exhibited crack density values of 0.347 and 0.507 m/m^2, respectively – greater than all IN-IC-HPC decks and also greater than most of LC-HPC decks at a similar age. It appears that the higher paste contents of IN-IC, IN-Control and UT-IC deck toppings were more influential in increasing cracking than their lower compressive strengths in reducing cracking. However, it must be mentioned that two oldest IN-IC-HPC decks (37.2 month old IN-IC-HPC-1 and 34.8 month old IN-IC-HPC-2) exhibited the lowest crack densities among all IC decks and better than almost all LC-HPC decks despite having the highest 28-day compressive strength (6640 and 6720 psi [45.8 and 46.3 MPa], respectively) among the decks investigated in this study. Recent studies have suggested that the use of internal curing and one SCM, fly ash, reduce the modulus of elasticity and increase creep (De la Varga et al. 2012). Menkulasi et al. (2010) showed that IC mixtures exhibited lower shrinkage and higher creep coefficients than mixtures that did not contain any lightweight aggregate.

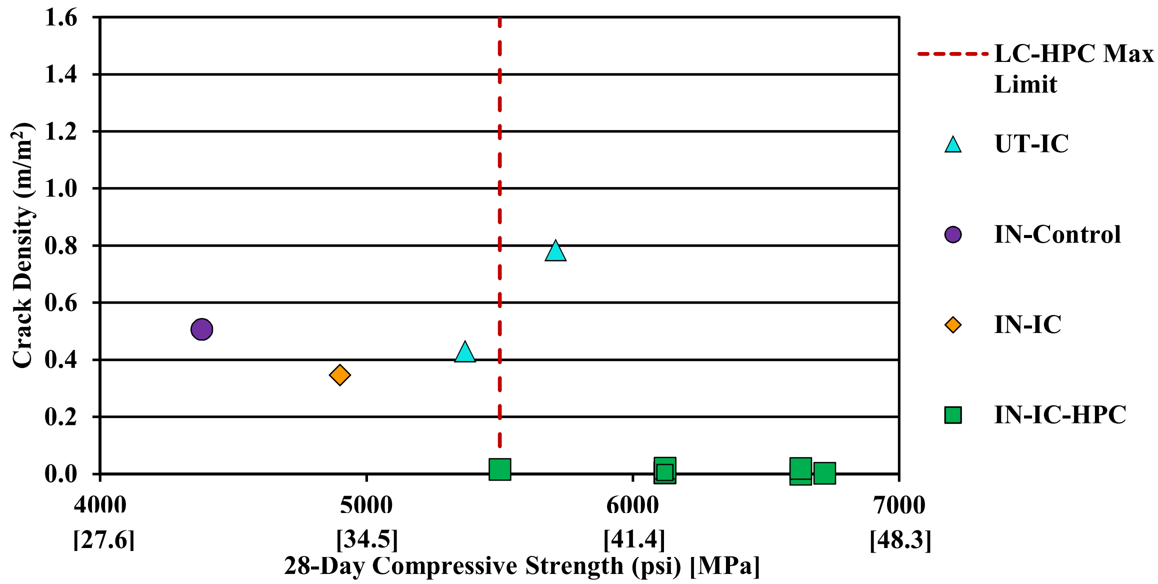


Fig. 8—Crack density vs. 28-day compressive strength of concrete for Indiana and Utah IC and Indiana control bridge decks

Figure 9 compares the crack density for Utah and Indiana IC bridge decks with the actual amount of IC water. The amount of IC water is also listed in Tables 2 and 4. The results indicate that decks that had more than 8% IC water by weight of binder exhibited lower cracking. Pendergrass and Darwin (2014) showed that mixtures containing pre-wetted LWA, slag, and silica fume exhibit a reduction in both early-age (0 to 90 days) and long-term (90 to 360 days) drying shrinkage. They concluded that drying shrinkage was reduced as slag was added in conjunction with lightweight aggregate. An additional reduction in shrinkage was observed as silica fume was added in conjunction with the lightweight aggregate and slag. A possible explanation for the lower crack densities in the IN-IC-HPC decks is that in addition to including SCMs, providing more IC water than required for eliminating chemical and autogenous shrinkage can also help reduce drying shrinkage.

The effectiveness of internal curing in reducing drying and autogenous shrinkage of concrete has been shown by many researchers (for example Henkensiefken et al. 2009; Browning et al. 2011). When used in bridge decks, pre-wetted LWA can potentially reduce cracking caused by restrained shrinkage. One area of concern for internally cured bridge decks is with freeze-thaw durability. For concrete with excess IC water, trapped water can remain in the pores of the LWA (Jones et al. 2014). Depending on the degree of saturation, on freezing, this water can cause local failures, such as scaling damage and pop-outs, or general freeze-thaw damage (Powers 1975). For concrete placed later in the construction season and prone to freezing prior to the system drying out, excess IC water would tend to compromise durability. The freeze-thaw performance of IC concrete has also been shown to depend on the type and proportions of the fine LWA used (Jones et al. 2014). Scaling resistance of concrete, including internally cured mixtures, depends heavily on finishing procedures. For the noted freeze-thaw and scaling damage on the affected IN-IC-HPC decks, it is possible that specifying a longer curing time would have helped mitigate these issues. Providing additional curing time for concrete mixtures with SCMs has also been shown to be beneficial in increasing strength and reducing shrinkage (Tazawa et al. 1989). Based on results described by Jones et al. (2014), scaling resistance does not appear to be negatively affected by providing internal curing to concrete mixtures. Future surveys of the IN-IC-HPC decks are needed to evaluate long-term durability of concrete with excess IC water. Ongoing research at KU will examine the effects of varying the amount of IC water on shrinkage and durability for a series of concrete mixtures.

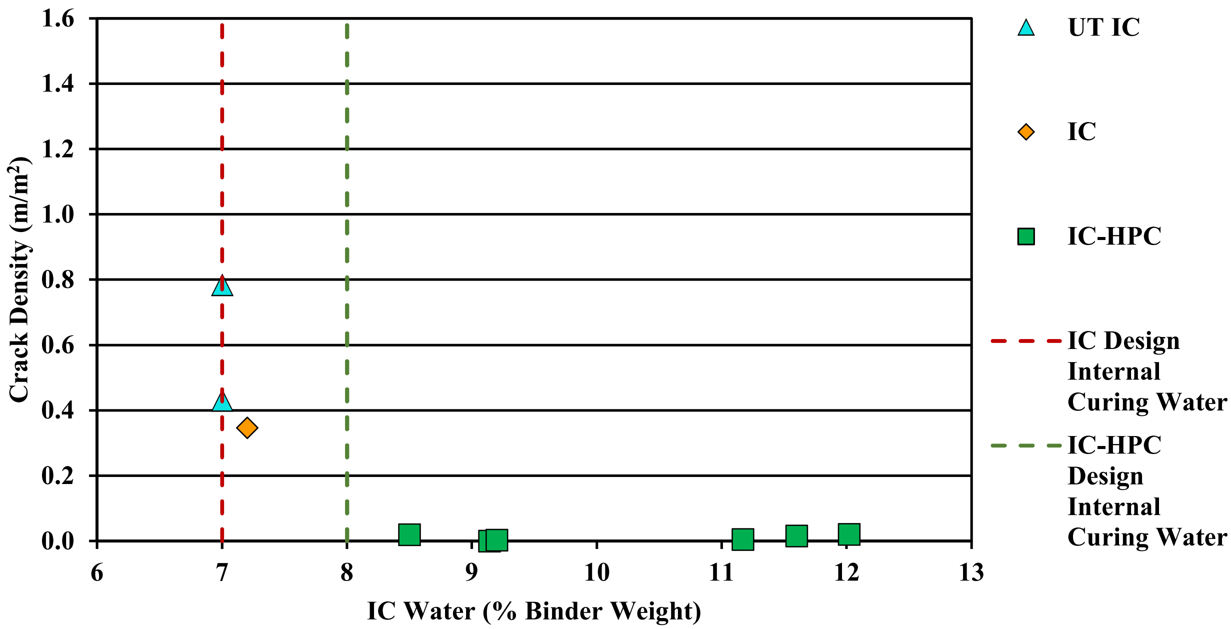


Fig. 9—Crack density vs. actual IC water for Indiana and Utah IC bridge decks

SUMMARY AND CONCLUSIONS

To determine the effect of IC and SCMs on bridge deck cracking, crack surveys were performed on six decks in Indiana; crack surveys by BYU researchers of two Utah bridges with deck toppings (UT-IC) were also used for comparison. Five of the decks in Indiana had internally cured concrete obtained by replacing a portion of aggregate with pre-wetted fine LWA. One deck, IN-Control, was constructed with plain concrete (no LWA) and is used as a control. Four of the decks surveyed in Indiana are supported by steel girders and two are supported by prestressed concrete box beams. The four decks supported by steel girders had a ternary concrete mixture containing SCMs, slag or Class C fly ash, with silica fume and internal curing (IN-IC-HPC). The two decks supported by prestressed box beams contained 100% portland cement mixtures, including IN-Control and one with internally cured concrete (IN-IC). The two internally cured deck toppings in Utah that were surveyed by BYU are both supported by prestressed concrete girders and precast deck panels. The internally cured decks are compared for cracking performance with low-cracking high-performance (LC-HPC) and control bridge decks in Kansas.

These surveys will serve as a baseline for future surveys and provide the data for some conclusions concerning the early performance of the decks. Future surveys will aid in making additional conclusions on the long-term performance of bridge decks that utilize SCMs and/or IC.

The following conclusions can be drawn from the surveys as well as previous studies:

1. The IN-IC-HPC bridge decks are exhibiting less cracking than the IN-IC and IN-Control decks, the UT-IC toppings, and the Kansas LC-HPC and control decks within the first three years after placement.
2. The Kansas LC-HPC decks exhibit less cracking than the IN-IC and IN-Control decks and the UT-IC deck toppings.
3. Paste content appears to be the dominant factor affecting cracking, with the IN-IC-HPC and LC-HPC decks, with paste contents of 26% or less performing significantly better than the IC decks with paste contents greater than 27% by volume. Even when including IC and an SCM in the UT-IC deck toppings, the high paste content led to more cracking than most of the Kansas control decks.
4. Further research is needed to establish the long-term cracking and durability performance of concrete bridge decks that incorporate internal curing or internal curing and SCMs.

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