Report No. FHWA-KS-20-04 ▪ FINAL REPORT ▪ September 2020

Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology

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The University of Kansas

A Transportation Pooled Fund Study — TPF-5(336)

Kansas Department of Transportation

1 Report No. FHWA-KS-20-04	**2 Government Accession No.**	**3 Recipient Catalog No.**
4 Title and Subtitle Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology		**5 Report Date** September 2020 **6 Performing Organization Code**
7 Author(s) James Lafikes, P.E.; David Darwin, Ph.D., P.E.; Matthew O'Reilly, Ph.D., P.E.; Muzai Feng, Ph.D., P.E.; Alireza Bahadori; Rouzbeh Khajehdehi, Ph.D., P.E.		**8 Performing Organization Report No.** SM 132
9 Performing Organization Name and Address The University of Kansas Department of Civil, Environmental & Architectural Engineering 1530 West 15th St Lawrence, Kansas 66045-7609		**10 Work Unit No. (TRAIS)** **11 Contract or Grant No.** C2078
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195		**13 Type of Report and Period Covered** Final Report January 2016–June 2019 **14 Sponsoring Agency Code** RE-7000-01 TPF-5(336)
15 Supplementary Notes For more information write to address in block 9.		

16 Abstract

Construction and early-age crack evaluations of four bridge decks in Minnesota placed from 2016 to 2018 that incorporate specifications for Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) are documented in this study. Two additional decks followed specifications for high-performance concrete and served as controls paired with IC-LC-HPC decks. Pre-wetted fine lightweight aggregate (FLWA) was used to provide a targeted internal curing water content of 8% by total weight of binder. The IC-LC-HPC mixtures included 27 to 30% slag cement by total binder weight while the control mixtures included 25 or 35% Class F fly ash by total weight of binder. For one IC-LC-HPC deck, mixture proportions were modified based on a higher FLWA absorption than originally used to design the mixture. One IC-LC-HPC placement failed due to errors in FLWA moisture corrections and concrete batching that led to rejections of batches, leaving an inadequate supply of material to complete the deck. Crack surveys were completed for the IC-LC-HPC and control decks placed in 2016 and 2017. Crack densities at these ages were low compared to most Low-Cracking High-Performance Concrete decks in Kansas and Internally-Cured High-Performance Concrete decks in Indiana. The only exception was one IC-LC-HPC deck that exhibited extensive cracking within one year after placement, which had an overlay with a high cement paste content and no internal curing. This project serves as a foundation for implementing IC-LC-HPC in upcoming bridge decks in Kansas and Minnesota.

17 Key Words Bridge Decks, Concrete Construction, Cracking, Internally-Cured Low-Cracking High-Performance Concrete, Lightweight Aggregate, Paste Content, Supplementary Cementitious Materials		**18 Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.	
19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages** 101	**22 Price**

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A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

THE UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

September 2020

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Construction and early-age crack evaluations of four bridge decks in Minnesota placed from 2016 to 2018 that incorporate specifications for Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) are documented in this study. Two additional decks followed specifications for high-performance concrete and served as controls paired with IC-LC-HPC decks. Pre-wetted fine lightweight aggregate (FLWA) was used to provide a targeted internal curing water content of 8% by total weight of binder. The IC-LC-HPC mixtures included 27 to 30% slag cement by total binder weight while the control mixtures included 25 or 35% Class F fly ash by total weight of binder. For one IC-LC-HPC deck, mixture proportions were modified based on a higher FLWA absorption than originally used to design the mixture. One IC-LC-HPC placement failed due to errors in FLWA moisture corrections and concrete batching that led to rejections of batches, leaving an inadequate supply of material to complete the deck. Crack surveys were completed for the IC-LC-HPC and control decks placed in 2016 and 2017. Crack densities at these ages were low compared to most Low-Cracking High-Performance Concrete decks in Kansas and Internally-Cured High-Performance Concrete decks in Indiana. The only exception was one IC-LC-HPC deck that exhibited extensive cracking within one year after placement, which had an overlay with a high cement paste content and no internal curing. This project serves as a foundation for implementing IC-LC-HPC in upcoming bridge decks in Kansas and Minnesota.

Acknowledgements

Funding for this research was provided by the Kansas Department of Transportation (KDOT) and the Minnesota Department of Transportation (MnDOT) for the "Construction of Low-Cracking High-Performance Bridge Decks Incorporating New Technology" Transportation Pooled Fund Study, Project No. TPF-5(336).

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Chapter 1: Introduction

1.1 Background

Although strides have been made over the past decade to address the need for repair or replacement of bridges in the U.S., 8.9% of bridges (more than 54,000) are still classified as structurally deficient (FHWA, 2017). The backlog of repair and rehabilitation costs is estimated at $123 billion. Furthermore, the number of bridges that have been in service for more than 50 years is also increasing each year, resulting in an increasing number of bridges that are considered structurally deficient (ASCE, 2017). Cracking in concrete bridge decks is a primary factor that leads to a structurally deficient rating. Cracks provide a direct path for chlorides and moisture to reach steel reinforcement, which can initiate corrosion and subsequent spalling and lead to significant reductions in service life (Lindquist, Darwin, & Browning, 2005, 2006; Darwin et al., 2016). Durability may also be compromised by an increased potential of freeze-thaw damage due to cracking (Darwin et al., 2016).

1.2 Previous Work

To investigate methods of reducing crack-related problems in bridge decks, a two-phase Pooled Fund research program at the University of Kansas (KU) entitled *Construction of Crack-Free Bridge Decks* was completed by Darwin et al. (2016). The approaches taken to minimize cracking in a series of 17 bridge decks (in 22 placements) in Kansas used specifications for Low-Cracking High-Performance Concrete (LC-HPC). These include using concrete mixtures with low cement paste (cementitious material and water) contents (below 25% by volume of concrete) to limit shrinkage, low slump (1½ to 3 in. [40 to 75 mm]) to mitigate settlement cracking, and limitations on compressive strength (3,500 to 5,500 psi [27.6 to 37.9 MPa]) to allow for concrete to creep more over time and help relieve tensile stresses. Construction procedures were also outlined in the LC-HPC specifications and include concrete temperature control to limit thermal stresses, thorough consolidation, minimal finishing, early application of curing to limit plastic shrinkage cracking, and extended curing to limit drying shrinkage (Darwin et al., 2016). Results from this study have shown a reduction in cracking compared to a series of 13 control bridge decks constructed using conventional procedures (Yuan, Darwin, & Browning, 2011; Pendergrass & Darwin, 2014; Darwin et al., 2016; Khajehdehi & Darwin, 2018).

The conclusions reached at the end of the Kansas LC-HPC bridge deck study identified limiting cement paste content and slump, concrete temperature control, consolidation, finishing, and curing as the major contributors to minimizing bridge deck cracking (Darwin et al., 2016). In a wider-ranging study that also included Kansas LC-HPC data, Khajehdehi and Darwin (2018) identified low cement paste content, minimum ambient temperature change on the day of placement, and good construction procedures as the principal contributors to minimum bridge deck cracking. In both studies, good construction practices were highlighted as being significant in minimizing bridge deck cracking. Regardless of the use of low-shrinkage/low-cracking concrete mixtures and technologies, bridge decks that were not consolidated properly, had workers walk through previously consolidated concrete, were over finished, or had delayed curing exhibited higher amounts of cracking.

The LC-HPC decks in the Pooled-Fund project were constructed using 100% portland cement concrete mixtures. Over the past decade, new crack-reduction technologies have been used by other state Departments of Transportation (DOTs) in an attempt to further minimize cracking. The combination of internal curing (IC) with selected supplementary cementitious materials (SCMs) is one of the technologies being used in newer initiatives to reduce bridge deck cracking (Barrett, Miller, & Weiss, 2015a; Guthrie, Yaede, & Bitnoff, 2014). Prior to the current study, concrete with IC and SCMs had yet to be applied in conjunction with the LC-HPC approach to bridge-deck construction. Laboratory research and limited field applications have demonstrated that the use of IC provided through pre-wetted fine lightweight aggregate (FLWA) combined with slag cement (with or without small quantities of silica fume) can have a greater impact on shrinkage and subsequent cracking than concrete made using current LC-HPC specifications alone (Pendergrass & Darwin, 2014).

The use of pre-wetted FLWA is one means of providing IC to concrete. Lightweight aggregates typically have a significantly higher absorption capacity than normal-weight aggregates, and when pre-saturated, can provide moisture transfer to the concrete during hydration and drying. Although there are other technologies available to provide IC in concrete, the use of FLWA has been the most common (Bentz & Weiss, 2011).

Significant research on concrete with IC has been conducted for high-performance mixtures with low water-to-cementitious material (*w/cm*) ratios that are subject to self-desiccation and autogenous shrinkage (Castro, Spragg, & Weiss, 2011; Barrett et al., 2015a; Jones, House, & Weiss, 2014). Limited experimental work has been conducted, however, on IC for concrete with moderate *w/cm* ratios (including values of 0.43 to 0.45, as used in LC-HPC construction), where autogenous shrinkage is not a concern (Khayat, Meng, Valipour, & Hopkins, 2018). The use of IC for concrete with *w/cm* ratios above 0.42 has been shown to provide benefits in reducing both drying shrinkage and early-age cracking (Schlitter et al., 2010; Browning, Darwin, Reynolds, & Pendergrass, 2011; Pendergrass & Darwin, 2014; Khajehdehi & Darwin, 2018). In addition to evaluating early-age drying shrinkage, Khajehdehi and Darwin (2018) developed procedures for free shrinkage testing to observe the swelling effects of IC and SCMs after final set in a series of concrete mixtures, and demonstrated that the addition of one or both resulted in more swelling than control mixtures without IC or SCMs. This increased swelling can offset subsequent shrinkage of concrete and reduce cracking.

Although mixtures with IC at moderate *w/cm* ratios (0.42 to 0.45) have exhibited less early-age drying shrinkage compared to mixtures without IC, there is still some debate on the overall performance of concrete with IC, particularly with regard to durability. In a study by Schlitter et al. (2010), mortars with IC did not show any significant reduction in freeze-thaw durability; however, the amount of IC water relative to the cement content was significantly lower than that recommended by Bentz and Weiss (2011) and ASTM C1761. Work by Jones, House, and Weiss (2014) demonstrated that for a series of concrete mixtures with moderate *w/cm* ratios, including an excessive amount of IC water (more than the amount lost during early hydration of cement) led to freeze-thaw damage in significantly fewer cycles than mixtures without IC or mixtures with only enough IC water to counteract chemical and autogenous shrinkage.

Another benefit of including IC in concrete mixtures is in its improvement of the transport properties of concrete, defined as the ability of ions and solution to move through a medium.

Concrete transport properties are heavily influenced by the concrete pore structure and are characterized by permeability, diffusion, and absorption (Castro et al., 2011).

Castro et al. (2011) showed that IC increased the degree of hydration for a series of concrete mixtures, especially as the *w/cm* decreased. Along with an increased degree of hydration, Castro et al. (2011) also observed that concrete with IC also had a denser pore structure, which in turn improves durability performance. In another study, Khayat et al. (2018) varied the amount of FLWA/IC water in a series of bridge deck and paving mixtures and found that higher amounts resulted in higher surface and bulk resistivity values, indicating improved durability, particularly when specimens received shorter durations of wet curing.

Bridge decks with IC and SCMs have been constructed in other states but have shown mixed results to date in terms of cracking in the years after construction. Di Bella, Schlitter, Carboneau, and Weiss (2012); Guthrie et al. (2014); and Barrett et al. (2015a) discussed implementation of IC in bridge decks in Indiana and Utah. For these projects, concrete mixture proportions and the amount of IC water was somewhat dependent on the handling and storage of the FLWA. For some of the IC decks in Indiana, handling and storage procedures resulted in a higher amount of IC water than originally planned; in some cases, the IC water exceeded design amounts by almost 50%. In a study comparing cracking of these bridge decks, Lafikes, Khajehdehi, Feng, O'Reilly, and Darwin (2018) noted minimal cracking in the first one to three years after construction for decks cast with concretes with paste contents of 26% or less. Lafikes et al., however, also noted the potential for durability issues, such as scaling and freeze-thaw damage, in decks with higher amounts of IC water.

1.3 Objectives and Scope

The purpose of this study is to implement internal curing (IC) and supplementary cementitious materials (SCMs) in conjunction with LC-HPC specifications to improve bridge deck service life through reduction of cracking. The goals of this report include identifying practical mixture proportioning procedures for internally-cured LC-HPC (IC-LC-HPC) and FLWA handling and storage. Construction procedures are also examined and correlated with cracking performance for the IC-LC-HPC bridge decks. The work involves cooperation between state DOTs, material suppliers, contractors, and designers.

This report focuses on the construction of four IC-LC-HPC bridge decks in Minnesota and crack surveys through the first two years after placement. For IC-LC-HPC bridge decks, the Minnesota Department of Transportation (MnDOT) adopted many of the provisions from the Kansas LC-HPC specifications along with the addition of slag cement and IC in concrete mixtures. This report also describes the performance of two bridge decks that followed MnDOT specifications for high-performance concrete (HPC), which serve as controls. Two of the four IC-LC-HPC bridge decks are paired with MnDOT HPC Control (MN-Control) decks constructed during the same construction season, have similar geometries, and were placed by the same contractor with concrete from the same supplier. Construction of the IC-LC-HPC and MN-Control decks is discussed in Chapter 2. The crack survey results to date are presented and compared to Indiana IC-HPC bridge decks and Kansas LC-HPC bridge decks in Chapter 3. Lessons during this study will be used to improve construction of future IC-LC-HPC decks in Minnesota and Kansas.

Chapter 2: Internally-Cured Low-Cracking High-Performance Concrete Bridge Deck Construction

2.1 General

This chapter describes the construction of four bridge decks placed from 2016 to 2018 in Minnesota that incorporate internal curing (IC) in low-cracking high-performance concrete (LC-HPC), as well as two bridge decks that followed current Minnesota Department of Transportation (MnDOT) specifications for high-performance concrete (HPC) that serve as controls. Two IC-LC-HPC decks are paired with control decks that were constructed during the same construction season, have similar geometries, and were placed by the same contractor with concrete from the same supplier. Contract documents include a special provision for including IC concrete for mixture proportioning, required concrete properties, and construction. Future IC-LC-HPC projects by MnDOT are also planned. This chapter focuses on the implementation of IC-LC-HPC mixture proportioning, batching, and placement. The specifications developed for IC-LC-HPC projects remained substantially the same throughout the three years. During the period covered by this report, however, changes were made to the specifications based on experience gained from prior projects, including increasing the maximum slump and removing the upper limit on compressive strength.

IC water was provided using pre-wetted fine lightweight aggregate (FLWA). The FLWA used on the four bridge decks in this study is an expanded clay, sold as Riverlite fine lightweight aggregate sourced from Erwinville, Louisiana. To effectively implement IC in concrete mixtures, specific procedures were followed for handling and storage of the FLWA at the ready-mix plants to ensure that the stockpiles had a uniform moisture content that was high enough to provide internal curing. Lightweight aggregate has a very high absorption capacity relative to normal-weight aggregate, and full saturation of lightweight aggregate is difficult to achieve in field applications. Accordingly, while normal-weight coarse and fine aggregates in concrete mixtures are described as being in a saturated surface dry (SSD) condition, FLWA is proportioned based on a pre-wetted surface dry (PSD) condition, since the material is not fully saturated.

Establishing FLWA properties, moisture content (absorption and free surface moisture), and specific gravity in the field are important when implementing IC for concrete mixtures and quantifying results in laboratory testing. For the 2016 IC-LC-HPC projects, mixture proportions were developed solely by the concrete supplier. For the 2017 and 2018 IC-LC-HPC projects, University of Kansas (KU) researchers worked with MnDOT, the concrete suppliers, and the suppliers' testing laboratories to develop mixture proportions. KU researchers traveled to the concrete ready-mix plant prior to placement to provide assistance in establishing aggregate moisture contents and record FLWA material properties for each IC-LC-HPC deck.

IC-LC-HPC mixtures in this study include a partial replacement of portland cement with Grade 100 slag cement ranging from 27 to 30% (actual contents as batched) by weight of cementitious material/binder. The amount of cementitious material in IC-LC-HPC mixtures ranged from 550 to 582 lb/yd^3 (326 to 345 kg/m^3). The as-placed paste contents (volume of cementitious material and water expressed as a percentage of concrete volume) for IC-LC-HPC decks ranged from 25.0 to 25.7%. The concrete mixtures for the IC-LC-HPC bridge decks were proportioned to provide a quantity of IC water equal to 8% by total weight of binder (often expressed as 8 lb per hundred weight or 8 lb/cwt). This report describes the amount of IC water as a percentage of the total weight of binder rather than in lb or kg per hundred weight. The MN-Control decks mixtures include a partial replacement of portland cement with Class F fly ash. One of the control decks in this study (MN-Control-2) also included 4 lb/yd^3 (2.4 kg/m^3) of polypropylene-polyethylene macrofibers. The amount of cementitious material in the MN-Control decks ranged from 580 to 595 lb/yd^3 (344 to 353 kg/m^3), with paste contents from 25.1 to 25.8%.

The bridge decks included in this study have different surface finishes, depending on the year of construction. Decks placed in 2016 are on pedestrian bridges and had a broom finish. Decks placed in 2017 had a 7-in. (178-mm) IC-LC-HPC subdeck and a 2-in. (50-mm) low-slump wearing course (overlay) that did not incorporate IC. The bridge deck placed in 2018 was tined during construction, followed by the application of a curing compound prior to application of wet burlap for curing. All decks were cured under wet burlap for a minimum of 7 days after placement.

A second bridge placed in 2016 was originally slated to have an IC-LC-HPC deck. Placement of the IC-LC-HPC on this deck was abandoned during construction when difficulties in pumping could not be resolved and concrete properties were not within MnDOT specifications.

After rejecting multiple trucks within the first few hours of construction, the concrete supplier did not have enough FLWA on hand to complete the deck. Problems during construction also included:

1. The use of incorrect moisture contents for the FLWA when batching the concrete,
2. Using a different size pump in test placements than was used in construction, and thus, not checking the pumpability of the mixture, and
3. Not adding the viscosity modifying admixture, as designed, at the time of batching.

Crack surveys for the bridge decks in this study were planned for up to three years after placement. To date, the decks cast in 2016 have been surveyed twice within two years of placement, while those cast during the 2017 projects were surveyed within one year of placement. Survey results (described in Chapter 3) show relatively low cracking one and two years after construction. Previous surveys (Yuan et al., 2011; Pendergrass & Darwin, 2014; Darwin et al., 2016; Khajehdehi & Darwin, 2018) show that surveys performed three years after construction are more indicative of long-term performance.

2.2 MnDOT Specifications for IC-LC-HPC

All concrete bridge decks in this study follow MnDOT Specification 2461, "Structural Concrete," and MnDOT Specification 2401, "Concrete Bridge Construction." For the IC-LC-HPC projects, a special provision for Section 2401.2.A, "Concrete," includes modifications in the requirements on materials, mixture proportions, concrete properties, and construction. The MnDOT IC-LC-HPC specifications are shown in Appendix A.

2.2.1 Aggregates

The normal-weight coarse and fine aggregates used for all decks satisfied the MnDOT bridge construction and material specifications. The special provisions were applied for FLWA in IC-LC-HPC decks. FLWA was required to pass a $^{3}/_{8}$-in. (9.5-mm) sieve, and a maximum replacement of 10% of the total aggregate volume was imposed. The latter limit, however, was not followed, with actual replacements ranging from 10.1 to 12.8% to ensure that the target quantity of IC water (8%) was provided. Other provisions for FLWA included requirements for pre-wetting, handling, and stockpiling. For pre-wetting, the MnDOT specifications only noted that the material be pre-wetted to attain an acceptable quantity of absorbed moisture at the time of batching and that absorbed water would not be considered as mix water. For handling and stockpiling, the specifications noted that the material should be protected from segregation, contamination, and conditions of non-uniform moisture.

In addition to the MnDOT special provisions, KU researchers provided recommendations for the handling and storage of FLWA. These recommendations followed similar procedures that were used for a series of IC bridge decks in Indiana (Barrett et al., 2015a; Lafikes et al., 2018) and were designed to ensure that the aggregate was consistently and uniformly pre-wetted. It was recommended that pre-wetting of FLWA be achieved by sprinkling stockpiles for a minimum of 48 to 72 hours or until no more water is absorbed by the aggregate. If a steady rain of comparable intensity to the sprinkler system occurs, the sprinkler system may be turned off. To further promote uniform wetting of the FLWA during storage, it was recommended that the piles be turned several times (at least twice a day) during pre-wetting. The absorption of the FLWA needs to be measured several times during pre-wetting to ensure a constant value is reached. If the resulting absorption and amount of FLWA do not provide IC water in the desired range (7 to 9% by total weight of binder for IC-LC-HPC projects), mixture proportions should be adjusted.

For the quantity of FLWA required on the IC-LC-HPC decks, an ordinary lawn sprinkler was sufficient to pre-wet the material. Use of a sprinkler system in lieu of submerging or vacuum-saturating the material was recommended because vacuum saturation forces water into small pores where it may not be readily available for IC, and its presence may result in damage to the aggregate when it is subjected to freezing.

Variability of the surface moisture of FLWA within the stockpile can cause problems during batching. Thus, a number of steps are needed to ensure that the stockpile of FLWA has a uniform surface moisture. To this end, it was recommended that prior to batching, sprinkling the FLWA stockpiles should be stopped 12 to 15 hours prior to batching to allow the surface moisture to drain. It was also recommended that the height of the pile be limited to 5 ft (1.5 m) to allow the majority of the surface moisture to drain during this period, and that stockpiles be turned and remixed just prior to loading the material into bins for batching to obtain a homogeneous moisture content. Even when following these procedures, the aggregate at the bottom of the piles can have a substantially higher moisture content than aggregate in the rest of the pile, so it was recommended that the bottom 4 to 6 in. (100 to 150 mm) of aggregate not be used in batching.

Determination of the specific gravity and moisture content of the FLWA is needed for accurate batching of IC concrete. Following procedures in ASTM C1761 or New York State DOT test procedures (NY 703-19E), which involve drying FLWA samples with paper towels to a PSD condition, has been shown to produce highly variable results because the FLWA sample is susceptible to loss of fine particles (smaller than the No. 100 sieve) (Schlitter et al., 2010; Barrett et al., 2015a). This drawback can be overcome by using a centrifuge, which has proven to provide significantly greater precision in obtaining the PSD condition (Miller, Barrett, Zander, & Weiss, 2014). For this reason, a centrifuge was used to place the FLWA in a PSD condition for determining FLWA free-surface moisture on the IC-LC-HPC projects. The procedure and worksheet used for computing FLWA properties using a centrifuge are shown in Appendix B.

For all types of aggregate, the MnDOT IC-LC-HPC specifications also stipulate that the actual gradation of the aggregates used in batching be within a specified percentage of the gradations submitted in the original mixture proportion. Table HPC-6 in Section 2.A.7 in the special provision (as shown in Appendix A) lists the specific limits for the difference in gradations submitted to MnDOT and aggregate samples taken during construction. For the FLWA used in this study, high variability in particle size distribution between samples caused the material to be outside of this range for a majority of tests, which MnDOT allowed.

2.2.2 Concrete

The IC-LC-HPC specifications require that concrete mixture proportions be submitted to the agency at least 21 calendar days prior to trial placement. The specifications include a maximum paste content (the total volume of cementitious material and water) of 27% by volume of concrete and a water-to-cementitious material (*w/cm*) ratio of 0.43 to 0.45. For the IC-LC-HPC decks placed in 2016 and 2017, the mixtures had a *w/cm* of 0.45; the IC-LC-HPC deck placed in 2018 had a *w/cm* of 0.43. The MnDOT specifications required air contents between 6.5 and 9.5% in 2016. For subsequent years, the upper limit on air content was raised to 10%. Slump for 2016 projects was specified to be between 1 and 3½ in. (25 and 90 mm). The upper limit for slump range was increased to 4 in. (100 mm) in 2017 and 5½ in. (140 mm) in 2018. Ongoing research has found good performance of IC decks in Indiana despite having slumps as high as 5¾ in. (145 mm) (Lafikes et al., 2018), suggesting that slumps above 3½ in. (90 mm) are not detrimental for IC concrete.

Slag cement and silica fume were permitted in IC-LC-HPC mixtures, with upper limits of 28 and 2% by total weight of total cementitious material, respectively. In 2016, the IC-LC-HPC contained 30% slag cement, while in 2017 and 2018, the IC-LC-HPC included 27.3 and 28.2% slag cement, respectively. Silica fume was not used.

The MnDOT specifications for hardened concrete properties are shown in Table 2.1. These include compressive strength, permeability, shrinkage, freeze-thaw, and scaling. The tests are performed in accordance with applicable ASTM procedures. The requirements are discussed in Section 2.3 of this report. The requirements for 28-day compressive strength (ASTM C31) included a range from 4,000 to 5,500 psi (27.6 to 37.9 MPa). Shrinkage was limited to 400 microstrain at 28 days following ASTM C157. Rapid chloride permeability (RCP) readings (ASTM C1202) were limited to 2,500 coulombs at 28 days and 1,500 coulombs at 56 days. Freeze-thaw testing (ASTM C666 – Procedure A) requires that specimens maintain at least 90% of their initial dynamic modulus of elasticity through 300 freeze-thaw cycles. The limit for scaling tests included a maximum visual rating of 1 after 50 cycles for specimens tested in accordance with ASTM C672.

Table 2.1: MnDOT Specification Requirements for Hardened Concrete Properties

HPC Mixtures		
Test	**Requirement**	**Test Method**
Required Strength (Average of 3 cylinders)	4,000 psi min. at 28 days, 5,500 psi max. at 28 days	ASTM C31
Rapid Chloride Permeability	≤ 2,500 coulombs at 28 days (For Preliminary Approval)	ASTM C1202
	≤ 1,500 coulombs at 56 days	
Freeze-Thaw Durability	Greater than 90% at 300 cycles	ASTM C666 Procedure A
Shrinkage	No greater than 0.040 percent at 28 days	ASTM C157
Scaling	Visual rating not greater than 1 at 50 cycles	ASTM C672

2.2.3 Construction

For IC-LC-HPC decks, MnDOT specifications require the successful completion of a trial placement of at least two 10 yd^3 (7.6 m^3) loads at least 14 calendar days prior to deck placement. For trial placements, contractors were required to use the same materials, ready-mix plant, mixture proportions, and means of placement that would be used on the actual placement. In particular, the same pump must be used during the bridge deck placement and the trial placement to ensure the concrete can be pumped successfully. Sections of approach slabs, abutments, footings, and other projects in the vicinity of the bridge deck are allowed to serve as the trial placements.

The maximum allowable evaporation rate per MnDOT specifications is 0.2 $lb/ft^2/hr$ (1 $kg/m^2/hr$). The contractor must provide weather forecast verification prior to bridge deck placement to be within this limit and to ensure there would be no rain during construction. The evaporation rate was well within the maximum specified limit for the IC-LC-HPC bridge decks in this study.

The deck type dictated the final finishing and curing regime for IC-LC-HPC projects. Table 2.2 summarizes the types of deck and required curing methods for the projects included in this study. The pedestrian bridges constructed in 2016 had sidewalk finishes, the 2017 projects received a low slump wearing course (overlay), and the 2018 project received a tined texture finish.

Table 2.2: Required Curing Method Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Required Curing Method*
Bridge structural subdeck	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks	Tined Texturing**	Conventional wet curing after tined texturing, prior to applying AMS curing compound
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)*	Conventional wet curing after applying transverse broom finish, AMS curing compound after wet cure period

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

Conventional wet curing via pre-wetted burlap was used for the projects in this study. MnDOT specifications require that the burlap be soaked for at least 12 hours prior to application, applied within 20 minutes after final strike-off of the concrete surface, and be covered with a layer of plastic sheeting to prevent rapid evaporation. Continuous wetting of the burlap for at least seven days after construction is also required. The exception to the 20-minute limit for wet burlap placement was needed for the 2018 IC-LC-HPC deck, which received a tined finish. Here, the specifications permitted a Poly-Alpha-Methylsytrene (AMS) membrane curing compound to be applied within 30 minutes of concrete placement, with wet burlap applied upon the completion of deck placement–up to seven hours after placement in this case.

2.3 Deck Construction

The bridge decks included in this study are summarized in Table 2.3. All decks are supported by prestressed concrete I-girders. The 2016 projects are pedestrian bridges while all others carry vehicular traffic. The decks are either in the Twin Cities area or between Rochester and St. Paul, MN. The failed IC-LC-HPC deck placement was located north of the Twin Cities and will be discussed in Section 2.5. All decks used removable wooden forms. IC-LC-HPC-1, MN-Control-1, and MN-Control-2 were placed in September. The other IC-LC-HPC decks were placed between May and July, which provided a longer time between placement and the deck being exposed to freezing temperatures, giving more time for the IC water in the FLWA to evaporate. Overlays on the IC-LC-HPC-2, IC-LC-HPC-3, and MN-Control-2 subdecks were placed over two days, with half of the deck width placed each day.

Table 2.4 lists the concrete suppliers and construction contractors for the decks in this study. All concrete was placed via pump, with two pumps used per deck. All subdecks were placed in a single placement.

Table 2.3: Minnesota IC-LC-HPC and MN-Control Project Descriptions

Project ID	MnDOT Bridge No.	Location	Structure Type	Deck Finish	Subdeck Placement Date	Overlay Placement Dates*
IC-LC-HPC-1	62892	Mackubin St. over I-94; St. Paul, MN	Prestressed I-Girder	Finished Sidewalk	9/22/2016	-
IC-LC-HPC-2	25036	S.B. T.H. 52 near Cannon Falls, MN		Low Slump Wearing Course	7/6/2017	9/7/2017, 9/9/2017
IC-LC-HPC-3	25037	T.H. 58 over T.H. 52; Zumbrota, MN		Low Slump Wearing Course	6/29/2017	7/21/2017, 7/24/2017
IC-LC-HPC-4	9619	38th St. over I-35W, Minneapolis, MN		Tined Texturing	5/15/2018	-
MN-Control-1	62800	Grotto St. over I-94; St. Paul, MN		Finished Sidewalk	9/28/2016	-
MN-Control-2	25032	N.B. T.H. 52 near Cannon Falls, MN		Low Slump Wearing Course	9/15/2017	9/28/2017, 9/30/2017

*Overlays were placed over two days, after the subdeck was cured and then shot blasted

Table 2.4: Minnesota IC-LC-HPC and MN-Control Project Contractors

Project ID	Concrete Supplier	Construction Contractor
IC-LC-HPC-1	Cemstone	Kraemer North America
IC-LC-HPC-2	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.
IC-LC-HPC-3	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.
IC-LC-HPC-4	Aggregate Industries US	Lunda Construction Co.
MN-Control-1	Cemstone	Kraemer North America
MN-Control-2	Ready-Mix Concrete Company, L.L.C.	Lunda Construction Co.

Table 2.5 summarizes the bridge deck geometry for the projects in this study. None of the decks were skewed. The number of spans ranges from one to four. Bridge deck lengths and widths listed are the outermost dimensions and include barriers and sidewalks (where applicable). Sidewalk concrete, which did not incorporate IC, was placed separately on top of a portion of the deck on IC-LC-HPC-3 and IC-LC-HPC-4 well after deck placement.

Table 2.5: Minnesota IC-LC-HPC and MN-Control Deck Geometry

Project ID	Skew (deg.)	No. of Spans	Length (ft)	Width (ft)
IC-LC-HPC-1	0	2	182.5	14.3
IC-LC-HPC-2	0	1	153.6	45.3
IC-LC-HPC-3	0	2	215.7	48.9
IC-LC-HPC-4	0	4	213.5	56.0
MN-Control-1	0	2	237.0	14.3
MN-Control-2	0	1	153.6	45.3

Note: 1 ft = 0.305 m

2.3.1 Aggregates

Aggregate properties and gradations submitted to MnDOT for normalweight coarse and fine aggregates used for both IC-LC-HPC and MN-Control decks are listed in Table 2.6a and Table 2.6b, respectively. The FLWA properties, including the amount of IC water for IC-LC-HPC decks, are listed in Table 2.6c.

The FLWA in the IC-LC-HPC decks is an expanded clay. All samples were provided by the same manufacturer; however, variations in the manufacturing process produced samples with different physical properties. The absorptions and resulting quantities of IC water listed in Table 2.6c are based on measurements by KU researchers on the day of deck placement after the FLWA had been pre-wetted for at least 72 hours and allowed to drain for 12 to 15 hours. The FLWA samples were obtained in accordance with ASTM D75 (2014) after the stockpiles had been turned. The absorption (OD basis) ranged from 23.1 to 30.3%, while the specific gravity (PSD basis) ranged from 1.64 to 1.67. The amount of IC water provided in a concrete mixture is controlled by the quantity of FLWA per cubic yard and amount of water absorbed by the material. Given the variation in FLWA absorption, the subsequent amount of IC water can be significantly higher or lower than the target. This can lead to incorrect amounts of mix water being added or withheld during batching unless free-surface moisture is measured just before batching. Free surface moisture on the FLWA ranged from 5 to 8% just prior to batching. As for gradation, MnDOT observed that even within the same stockpile, particle size varied substantially.

Table 2.6a: Coarse Aggregate Properties

Bridge Deck Designation	MnDOT Submitted		
	IC-LC-HPC-1, MN-Control-1	IC-LC-HPC-2, -3, MN-Control-2	IC-LC-HPC-4
Specific Gravity (SSD)	2.72	2.65	2.71
Absorption (%)*	0.4	0.3	1.4
Fineness Modulus	6.50	6.50	6.47
Sieve Size	**Percent Retained on Each Sieve**		
3/4-in. (19-mm)	0	0	0
1/2-in. (12.7-mm)	25	25	22
3/8-in. (9.5-mm)	32	32	30
No. 4 (4.75-mm)	36	36	43
No. 8 (2.38-mm)	7	7	5
No. 16 (1.18-mm)	0	0	0
No. 30 (0.60-mm)	0	0	0
No. 50 (0.30-mm)	0	0	0
No. 100 (0.15-mm)	0	0	0
No. 200 (0.075-mm)	0	0	0
Pan	0	0	0

* Oven-dry basis

Table 2.6b: Fine Aggregate Properties

Bridge Deck Designation	MnDOT Submitted		
	IC-LC-HPC-1, MN-Control-1	IC-LC-HPC-2, -3, MN-Control-2	IC-LC-HPC-4
Specific Gravity (SSD)	2.65	2.61	2.66
Absorption (%)*	0.5	0.7	0.5
Fineness Modulus	2.69	2.69	2.59
Sieve Size	**Percent Retained on Each Sieve**		
3/8-in. (9.5-mm)	0	0	0
No. 4 (4.75-mm)	0	1	0.1
No. 8 (2.38-mm)	11	12	4.5
No. 16 (1.18-mm)	14	16	15.8
No. 30 (0.60-mm)	25	22	29.2
No. 50 (0.30-mm)	34	33	36.1
No. 100 (0.15-mm)	15	14	13.3
No. 200 (0.075-mm)	0.8	1.3	0.8
Pan	0.2	0.7	0.2

* Oven-dry basis

Table 2.6c: FLWA Properties

Bridge Deck Designation		MnDOT Submitted			
		IC-LC-HPC-1	IC-LC-HPC-2	IC-LC-HPC-3	IC-LC-HPC-4
Specific Gravity (PSD)		1.68	1.67		1.64
Absorption (%)[ǁ]	**Design**	25.6[a]	23.5[b]		30.3[c]
	Actual[d]	23.1	24.5	24.9	30.3
Fineness Modulus		4.06	4.06		3.94
LWA Content (% Aggregate Volume)		10.1	12.8		10.9
IC Water Provided[d] **(% of total binder weight)**		6.5	8.5	8.6	7.9
Sieve Size		**Percent Retained on Each Sieve**			
3/8-in. (9.5-mm)		0	0		0
No. 4 (4.75-mm)		10	10		14.5
No. 8 (2.38-mm)		32	32		28.5
No. 16 (1.18-mm)		29	29		25.5
No. 30 (0.60-mm)		15	15		14.5
No. 50 (0.30-mm)		8	8		8
No. 100 (0.15-mm)		3.6	3.6		2.5
No. 200 (0.075-mm)		2	2		2.9
Pan		0.4	0.4		3.6

[a] Based on FLWA producer report
[b] Based on 72-hour soak time in laboratory testing
[c] Based on testing during trial placement one week before deck placement
[d] Values listed are based on measurements on the day of batching IC-LC-HPC bridge decks
[ǁ] Oven-dry basis

2.3.2 Concrete Mixture Proportions

Total cementitious material and water contents are listed in Table 2.7. While the mixtures were designed to provide an IC water content nominally equal to 8% of the weight of cementitious materials, actual IC water content ranged from 6.5% (for IC-LC-HPC-1) to 8.6% (for IC-LC-HPC-3). Water contents reported as "Actual" are based on the average of values from trip tickets. As shown in Table 2.7, the actual *w/cm* ratios were lower than the design values. This was due to the concrete producers withholding water on a majority of batches, particularly on the MN-Control decks. The design *w/cm* ratios for the IC-LC-HPC decks were either 0.45 or 0.43, with actual *w/cm* ratios ranging from 0.422 to 0.437. The design *w/cm* ratio for the MN-Control decks was 0.42, with actual values ranging from 0.371 to 0.395. The lower water contents also subsequently lowered the paste contents in each of the concrete mixtures. IC-LC-HPC-1 had a design paste content of 25.4% and an actual paste content of 25.0%, the lowest in this study. All other IC-LC-HPC decks had design paste contents of 26%, with actual paste contents listed as much as 0.8% less. IC-LC-HPC-4 had the smallest deviations in *w/cm* ratio and paste content. Design paste contents for the MN-Control decks were slightly below 27%, with actual paste contents below 26%. The 2-in. (50-mm) overlays followed mixture proportions defined by MnDOT 3U17A "Low Slump Concrete" and contain only portland cement as a binder (836 lb/yd^3, 496 kg/m^3), a 0.37 *w/cm* ratio, and a paste content of 34.3%. The low paste contents of both the IC-LC-HPC and MN-Control decks should yield good cracking performance; lower *w/cm* ratios and significantly higher paste contents as used in the overlays have tended to result in extensive cracking in previous studies (Lindquist, Darwin, & Browning, 2005, 2006; Darwin et al., 2016). The overlay concrete on IC-LC-HPC-2, MN-Control-2, and IC-LC-HPC-3 was mixed on-site, and thus, trip ticket was not available. For this reason, overlay concrete is considered to have been batched as designed.

Table 2.8 lists the cementitious material percentages and aggregate proportions for the bridge decks in this study. The quantity of FLWA varies as a function of cementitious material content and FLWA absorption.

Table 2.7: Cementitious Material Content, Water Content, *w/cm* Ratio, and IC Water Contents for Minnesota IC-LC-HPC and MN-Control

Project ID	Cementitious Material Content (lb/yd³)		Water Content (lb/yd³)		*w/cm* Ratio		Paste Content (%)		IC Water (% Binder Weight)	
	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]	Design	Actual[a]
IC-LC-HPC-1	550	551	248	241	0.451	0.437	25.4	25	8	6.5
IC-LC-HPC-2	564	565	254	245	0.45	0.432	26	25.4	8	8.5
IC-LC-HPC-3	564	568	254	239	0.45	0.422	26	25.2	8	8.6
IC-LC-HPC-4	582	581	250	245	0.43	0.422	26	25.7	8	7.9
MN-Control-1	595	594	250	220	0.421	0.371	26.9	25.1	-	
MN-Control-2	580	582	245	230	0.422	0.395	26.7	25.8	-	
2-in. Overlays[b]	836		312		0.373		34.3		-	

[a] Values listed are based on the average of trip tickets
[b] Overlay construction records do not indicate actual amounts of materials used on the day of placement
Note: 1 lb/yd^3 = 0.593 kg/m^3

Table 2.8: Cementitious Material Percentages and Aggregate Proportions (SSD/PSD Basis)

Project ID	Cementitious Material Percentages[c]	Coarse Aggregate (lb/yd³)		Fine Aggregate (lb/yd³)		FLWA (lb/yd³)	
		Design	Actual[a]	Design	Actual[a]	Design	Actual[a]
IC-LC-HPC-1	70% C, 30% S	1,655	1,649	1,106	1,101	194	190
IC-LC-HPC-2	72% C, 28% S	1,411	1,415	1,141	1,143	238	243
IC-LC-HPC-3	72% C, 28% S	1,411	1,414	1,141	1,143	238	244
IC-LC-HPC-4	72% C, 28% S	1,701	1,708	970	973	201	198
Control-1	75% C, 25% F-FA	1,719	1,719	1,318	1,318	-	
Control-2	65% C, 35% F-FA	1,736	1,740	1,243	1,277	-	
2-in. Overlays[b]	100% C	1,411		1,373		-	

[a] Values listed are based on the average of trip tickets
[b] Overlay construction records do not indicate actual amounts of materials used on the day of placement
[c] Percentages by total weight of cementitious material; C = portland cement; S = Grade 100 slag cement; F-FA = Class F fly ash
Note: 1 lb/yd^3 = 0.593 kg/m^3

2.4 Bridge Decks

Table 2.9 lists the average slump, concrete temperature, air content, and 28-day compressive strength for each deck in this study. The projects are discussed in greater detail in Section 2.4.1 through Section 2.4.6. The average slump for the IC-LC-HPC decks was allowed to increase each year based on the good performance of the IC decks in Indiana (Lafikes et al., 2018) as discussed in Section 2.2.2. The most recent project (IC-LC-HPC-4) had both the greatest average and the greatest range of slumps in the study (as will be discussed in Section 2.4.6). The air contents and *w/cm* ratios of IC-LC-HPC projects were all greater than the concrete used in the control decks. Concrete temperatures were within 5 °F (3 °C) for the IC-LC-HPC and MN-Control pairs. Although IC-LC-HPC and MN-Control deck pairs did not use the same *w/cm* ratio or binder composition, compressive strengths were within 360 psi (2.5 MPa) for IC-LC-HPC-1 and MN-Control-1 and 580 psi (4.0 MPa) for IC-LC-HPC-2 and MN-Control-2.

Table 2.9: Average Minnesota IC-LC-HPC and MN-Control Concrete Properties

Project ID	Slump	Temperature	Air Content	28-Day Compressive Strength
	(in.)	(°F)	(%)	(psi)
IC-LC-HPC-1	3¼	67	7.5	7,090
IC-LC-HPC-2	3½	78	9.1	4,560
IC-LC-HPC-3	3½	75	8.3	5,140
IC-LC-HPC-4	4¾	64	8.9	5,540
MN-Control-1	4	66	6.1	6,730
MN-Control-2	3¼	73	6.3	5,140

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

2.4.1 IC-LC-HPC 1 – St. Paul Pedestrian Bridge (2016)

The first IC-LC-HPC bridge deck placed in Minnesota was the Mackubin St. pedestrian bridge over I-94 in St. Paul within the MnDOT Metro District. The bridge has two spans with lengths of 92 ft and 90 ft, 6 in. (28.0 m and 27.6 m), a 12-ft (3.7-m) wide walkway, and a 1-ft, 2 in. (0.4-m) barrier on each side, for a total deck width of 14 ft, 4 in. (4.4 m). The nominal deck thickness is 7 in. (178 mm). The end spans/approaches for this bridge are cast-in-place T-beams, where the top flanges serve as the deck surface. The T-beams did not incorporate IC-LC-HPC and were placed at a later date.

Kraemer North America was the contractor, and Cemstone was the concrete supplier. Prior to batching, the FLWA used in IC-LC-HPC-1 was stored outdoors at the ready-mix plant. The aggregate was wetted by a lawn sprinkler placed on top of the aggregate pile. The pile was turned one to two times per day with the sprinkler head being moved each time to fully cover the pile in its spray pattern. With the relatively small volume of concrete needed for this bridge (requiring less than 10 tons of FLWA), there were no issues with storage, and the stockpile height remained below the recommended maximum of 5 ft (1.5 m). The sprinkler was turned off on the morning of deck placement, allowing the material to drain approximately 12 hours before batching that evening. The stockpile was remixed before a composite sample was collected for the absorption and free surface moisture tests. Figure 2.1 shows the FLWA stockpile during pre-wetting.

Figure 2.1: FLWA Storage for IC-LC-HPC-1

The mixture proportions for IC-LC-HPC-1 are listed in Table 2.10. IC-LC-HPC-1 included a 30% replacement by total weight of binder with Grade 100 slag cement, slightly higher than the 28% upper specification limit. The design *w/cm* ratio was 0.45. During construction, approximately 1 gallon per yd^3 (8 lb/yd^3, 5 kg/m^3) of water was withheld from the concrete batches, which dropped the average *w/cm* ratio to 0.437. Individual *w/cm* ratios on the trip tickets ranged from 0.423 to 0.449. The design and average paste contents were 25.4 and 25.0%, respectively. Based on the trip tickets, individual paste contents ranged from 24.4 to 25.4%. Granite was used as the coarse aggregate and river sand was used as the fine aggregate. The FLWA used in IC-LC-HPC-1 had an absorption of 23.1% (OD basis). The concrete supplier designed the mixture to include FLWA as approximately 10% of the total aggregate volume. With a lower than anticipated absorption (23.1% vs. 25.6%) and unchanged mixture proportions, the amount of IC water provided was 6.5% by total weight of binder.

Table 2.10: IC-LC-HPC-1 Mixture Proportions

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual
Type I/II Cement	385	387
Gr. 100 Slag Cement	165	164
Water	250	241
Coarse Aggregate	1,655	1,649
Fine Aggregate	1,106	1,101
FLWA	194	190
Chemical Admixtures		
BASF	**Type**	**Dosage (oz/cwt)**
MasterAir AE 90	Air Entraining	0.58
VMA 358	Viscosity Modifier	3
MasterPolyheed 1020	Mid-Range Water Reducer	5

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths for the accepted trucks are listed in Table 2.11. Three tests for slump and air content were performed and were within the MnDOT specification limits for IC-LC-HPC. The slump ranged from 2½ to 3½ in. (65 and 90 mm) with an average of 3¼ in. (85 mm). Three tests for air content ranged from 7 to 8.1% with an average of

7.5%. Concrete temperatures ranged from 65 to 68 °F (18.5 to 20 °C) with an average of 67 °F (19.5 °C). One set of three cylinders was tested for compressive strength on IC-LC-HPC-1. Individual strengths ranged from 6,990 to 7,200 psi (48.2 to 49.6 MPa) with an average of 7,090 psi (48.9 MPa), which was above the specified limit of 5,500 psi (37.9 MPa).

Table 2.11: IC-LC-HPC-1 Concrete Test Results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-1	**in.**	**%**	**°F**	**psi**
Average	3¼	7.5	67	7,090
Minimum	2½	7.0	65	6,990
Maximum	3½	8.1	68	7,200

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

Placement began on the evening of September 22, 2016, at 10:30 pm at the north end of the deck and ended shortly before 1:00 am on September 23, 2016, at the south end with final strike-off being completed at 1:19 am. Time between placement and strike-off ranged from 6 to 52 minutes. The time between strike-off and application of wet curing (wet burlap) ranged from 13 to 77 minutes. The last section of the bridge experienced the longest delay in burlap placement; the concrete in the final truck appeared to be wetter than in previous trucks and the contractor waited to apply curing in an attempt to avoid marring the finish for this area. During placement, wind speeds at the deck ranged from 4.6 to 8.1 mph (7.4 to 13.0 km/hr). Relative humidity at the deck remained high and ranged between 82 and 86%. Ambient air temperature during construction ranged from 60 to 63 °F (15.5 to 17 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.03 to 0.05 lb/ft^2/hr (0.15 to 0.24 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

The concrete in the first truck had a 6-in. (150-mm) slump at the point of placement, well above the 3½-in. (90-mm) specified limit, and was rejected. Both slump and air content were within specification limits in subsequent tests, and the remaining trucks were accepted. Because IC-LC-HPC-1 is a pedestrian walkway, MnDOT specifications required that the deck surface receive a transverse broom finish before applying wet curing. The first accepted load of concrete had a slump of 2½ in. (65 mm), and while it could be pumped, some difficulty in finishing was observed in the first 15 ft (4.3 m) of the deck. The deck was consolidated with a single spud vibrator and finished with a vibrating screed. Within the first 15 ft (4.3 m) of the deck, workers followed the vibrating screed with a 2×4 manual screed because of imperfections left in the surface. Trowels were used at the abutments and along the edges, and bull floats were used elsewhere on the deck. A transverse broom finish was applied as the final finishing operation before placement of the wet burlap. Figure 2.2a and Figure 2.2b show finishing operations on the deck. Placement proceeded with minimal difficulty. KU personnel were not present during the trial placement, but the mixture was approved by MnDOT. MnDOT personnel indicated that for the trial placement, a smaller pump was initially on site; however, the MnDOT representatives required the concrete supplier to use the same size pump as would be used during deck placement before the trial placement was approved. The issue of using the same size equipment for trial placements as for construction also rose during the failed placement of the second IC-LC-HPC deck slated for 2016, as discussed in Section 2.5.

(a) Surface imperfections at the north end of the deck after first screed pass

(b) Bull floating the north end of the deck

Figure 2.2: Finishing the IC-LC-HPC-1 Deck Surface

2.4.2 MN-Control 1 – St. Paul Pedestrian Bridge (2016)

The control deck for IC-LC-HPC-1 is also a pedestrian bridge that spans over I-94 in St. Paul (Bridge No. 62800), also placed in September 2016. MN-Control-1 is along Grotto St., approximately 0.5 miles (0.3 km) from IC-LC-HPC-1. The bridge has two spans, each 118 ft-6 in. in length, supported by two prestressed I-girders. The walkway is 12 ft (3.7 m) wide with a 1-ft-2 in. (0.4-m) barrier on each side for a total deck width of 14 ft-4 in. (4.4 m), the same as IC-LC-HPC-1. The nominal deck thickness is also 7 in. (178 mm) and has similar end spans/approaches (cast-in-place T-beams) to IC-LC-HPC-1. As with IC-LC-HPC-1, Kraemer North America and Cemstone served as the contractor and concrete suppler, respectively.

The mixture proportions for MN-Control-1 are listed in Table 2.12. MN-Control-1 had a 25% replacement by total weight of binder with Class F fly ash and a design *w/cm* ratio of 0.42. During construction, approximately 33 lb/yd^3 (20 kg/m^3) of water were withheld throughout concrete batching, dropping the actual *w/cm* ratio to an average of 0.371. Individual *w/cm* ratios from trip tickets ranged from 0.364 to 0.381. The corresponding design and actual average paste contents were 26.9 and 25.1%, respectively. Based on trip tickets, individual paste contents ranged from 24.8 to 25.6%. The granite coarse aggregate and river sand used in IC-LC-HPC-1 were the same as used in MN-Control-1.

Table 2.12: MN-Control-1 Mixture Proportions

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual*
Type I/II Cement	446	445
Class F Fly Ash	149	149
Water	250	220
Coarse Aggregate	1,719	1,716
Fine Aggregate	1,318	1,359
Chemical Admixtures		
BASF	Type	Dosage (oz/cwt)
MasterAir AE 90	Air Entraining	0.43
VMA 358	Viscosity Modifier	3
MasterPolyheed 1020	Mid-Range Water Reducer	1

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

The plastic concrete properties and compressive strengths, listed in Table 2.13, were within MnDOT HPC specification limits. Three tests for slump were performed, with values of 3¾ or 4 in. (95 or 100 mm). Four tests for air content were performed, with values from 5.6 to 6.8% and an average of 6.1%. Concrete temperatures ranged from 62 to 70 °F (16.5 to 21 °C) with an average of 66 °F (19 °C). One set of three cylinders was tested for compressive strength. Individual cylinders had 28-day compressive strengths that ranged from 6,360 to 6,820 psi (43.9 to 47.0 MPa) with an average of 6,630 psi (45.7 MPa).

Table 2.13: MN-Control-1 Concrete Test Results

Bridge No.	Slump	Air Content	Concrete Temperature	28-Day Compressive Strength
MN-Control-1	**(in.)**	**(%)**	**(°F)**	**(psi)**
Average	4	6.1	66	6,730
Minimum	3¾	5.6	62	6,360
Maximum	4	6.8	70	6,820

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

KU researchers were not present for the placement of MN-Control-1. According to the trip tickets, placement began on the evening of September 28, 2016, around 8:50 pm and ended around 11:30 pm.

2.4.3 IC-LC-HPC 2 – Cannon Falls (2017)

The second pair of IC-LC-HPC and MN-Control bridge decks were placed on bridges carrying southbound and northbound traffic, respectively, over the Little Cannon River along T.H. 52 near Cannon Falls in MnDOT District 6. Both are single span bridges, 153 ft, 7 in. (46.8 m) long and 45 ft, 4 in. (13.8 m) wide. The driving lanes are 42 ft (12.8 m) wide with an additional 1-ft, 8-in. (0.5-m) barrier on each side. The total deck thickness is 9 in. (229 mm), consisting of a 7-in. (178-mm) IC-LC-HPC subdeck and a 2-in. (51-mm) thick overlay that did not incorporate FLWA/IC. The overlay contained only portland cement as a binder and a nominal paste content of 34.3%, as indicated in Table 2.7. The overlays were placed well after construction of the IC-LC-HPC and control subdecks.

Lunda Construction Co. was the contactor and Ready-Mix Concrete Company, L.L.C., was the concrete supplier for IC-LC-HPC-2 and MN-Control-2. Prior to batching, the FLWA used in IC-LC-HPC-2 was stored outdoors at the ready-mix plant. The FLWA stockpile was pre-wetted using a lawn sprinkler placed on top of the concrete blocks used to separate aggregates. The height of the FLWA stockpile was kept under 5 ft (1.5 m). Although the sprinkler did not cover the entire FLWA stockpile, the material was thoroughly mixed one to two times per day and immediately before batching to provide a uniform moisture content. The sprinkler was turned off the evening before deck placement, allowing the material to drain for approximately 14 hours before batching. The FLWA was mixed immediately before KU researchers collected a composite sample for absorption and free-surface moisture tests. When the material was collected by the loader for placement into aggregate bins, the bottom several inches of the stockpile were left undisturbed, per recommendations by KU researchers. Figure 2.3 shows the FLWA stockpile for both IC-LC-HPC-2 and IC-LC-HPC-3.

Figure 2.3: FLWA Storage for IC-LC-HPC-2 and IC-LC-HPC-3

Mixture proportions for IC-LC-HPC-2 are listed in Table 2.14. IC-LC-HPC-2 included a 27.3% replacement by total weight of binder with Grade 100 slag cement. The design *w/cm* ratio was 0.45. During construction, approximately 8 lb/yd^3 (5 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.432. Individual *w/cm* ratios based on trip tickets ranged from 0.403 to 0.439. The design and actual average paste contents were 26 and 25.4%, respectively. Based on trip tickets, individual paste contents ranged from 24.6 to 25.7%. Granite was used as the coarse aggregate and river sand was used as the fine aggregate. The mixture proportions included a FLWA content of 12.8% of the total aggregate volume. The FLWA used in IC-LC-HPC-2 had an average absorption of 24.5% (OD basis) on the day of batching, slightly higher than the design absorption of 23.5% (OD basis), which resulted in an IC water content of approximately 8.5% by total weight of binder compared to a design value of 8%.

Table 2.14: IC-LC-HPC-2 Mixture Proportions

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual*
Type I/II Cement	410	411
Gr. 100 slag cement	154	154
Water	254	245
Coarse Aggregate	1,411	1,415
Fine Aggregate	1,141	1,143
FLWA	238	243
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.9
Polychem VMA	Viscosity Modifier	2
KB-1200	Mid-Range Water Reducer	3
Retarder - Polychem Renu	Set Retarder	2

* Actual values based on average of trip tickets

Note: 1 lb/yd^3 = 0.593 kg/m^3, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths, listed in Table 2.15, were within MnDOT specification limits for IC-LC-HPC. Three tests for slump and air content were performed. A slump of 3½ in. (90 mm) was measured in all three tests. Air contents ranged from 9 to 9.3% with an average of 9.1%. Concrete temperatures ranged from 76 to 81 °F (24.5 and 27 °C) with an average of 78 °F (25.5 °C). One set of three cylinders was tested for compressive strength. Individual strengths ranged from 4,370 to 4,670 psi (30.1 to 32.2 MPa) with an average of 4,560 psi (31.4 MPa), which was within the specification limit of 5,500 psi (37.9 MPa).

Table 2.15: IC-LC-HPC-2 Concrete Test Results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-2	(in.)	(%)	(°F)	(psi)
Average	3½	9.1	78	4,560
Minimum	-	9	76	4,370
Maximum	-	9.3	81	4,670

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

Subdeck placement began around 6:00 am on July 6, 2017, at the south end of the deck and ended shortly before 9:30 am at the north end with final strike-off being completed at 9:46 am. The time between placement and strike-off ranged from 1 to 3 minutes. The time between strike-off and application of wet curing (wet burlap) ranged from 4 to 13 minutes. Wind speeds at the deck ranged from 0 to 1.7 mph (0 to 2.7 km/hr). Relative humidity at the deck ranged from 65 to 75%. Ambient air temperature during construction ranged from 74 to 84 °F (23.5 to 29 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.01 to 0.03 lb/ft^2/hr (0.04 to 0.15 kg/m^2/hr), below the 0.2 lb/ft^2/hr (1 kg/m^2/hr) specification limit.

All concrete test results were within specification limits for slump and air content. No significant delays were experienced during construction. No difficulties in placement or finishing were indicated by MnDOT or construction personnel. A single operator with a spud vibrator followed the path of the pump to consolidate the freshly placed concrete. The vibrator was inserted at regularly spaced intervals. At times, however, the vibrator was rapidly pulled out of the concrete, leaving holes in the plastic concrete, and construction personnel were observed walking through areas that had been recently vibrated, resulting in deconsolidation of the concrete. Both of these actions have been correlated with cracking in Kansas bridge decks, as documented by Khajehdehi and Darwin (2018). The deck was finished using a pair of vibrating screeds placed side by side, each with a carpet drag, as shown in Figure 2.4. The screeds had to be moved laterally to finish the entire width of the deck. Construction personnel followed closely behind the screeds with bull floats and trowels. A work bridge followed behind finishing operations for application of wet curing. Tight control of the elevation of the concrete was not required because the final grade was adjusted during overlay placement.

Figure 2.4: Placement, Finishing, and Curing Setup for IC-LC-HPC-2

A single trial placement was used for IC-LC-HPC-2 and IC-LC-HPC-3, an abutment for IC-LC-HPC-2, since subdeck placement dates were within one week for these decks. KU personnel were not present during the trial placement. The trial placement concrete pumped easily and was within specification limits for slump and air content.

Overlay construction procedures were similar for the three decks placed in 2017 in this study. Prior to overlay placement, the subdecks surfaces were shot blasted and a mechanical screed was advanced along the length of the deck to verify clearance and grade elevations. The surface of subdeck then received a thin layer of slurry (water and portland cement). A mobile mixer was used to mix the overlay concrete on-site. Buggies deposited the concrete ahead of the finishing equipment machine. Construction personnel used shovels to evenly distribute concrete along with an auger attachment in the front of the screed. A pair of screeds was used to strike-off the freshly placed concrete at the correct grade. Workers used trowels at abutments and edges and bull floats to finish concrete behind the screeds. A carpet drag followed behind troweling and bull floating. A work bridge followed behind the carpet drag for a worker to tine the overlay. After tining, the overlay was sprayed with a curing compound. Figure 2.5a and Figure 2.5b show the overlay placement sequence. When the overlay could be walked on (approximately 2 hours after placement), wet burlap followed by plastic sheeting were applied on top of the curing compound to complete construction. A single cylinder was made and tested for a 28-day compressive strength for every 30 yd^3 of concrete placed.

The overlay for the right lane was placed on July 21, 2017, and the overlay for the left lane was placed on July 24, 2017. KU researchers were present to observe placement on July 24, 2017. The 28-day compressive strengths of the two cylinders from the July 24, 2017, placement were 7,130 and 8,450 psi (49.2 and 58.3 MPa), both above the 5,600 design compressive strength. Compressive strength data for cylinders cast on July 21, 2017, is not available.

(a) Overlay concrete placement

(b) Overlay concrete finishing

Figure 2.5: Overlay Placement Sequence

2.4.4 MN-Control 2 – Cannon Falls (2017)

The control deck for IC-LC-HPC-2 is a highway bridge with the same geometry, also along T.H. 52 near Cannon Falls in MnDOT District 6. The subdeck for MN-Control-2 was placed on September 15, 2017. Nominal deck thickness (subdeck and overlay) were the same as IC-LC-HPC-2. Lunda Construction Co. and Ready-Mix Company, L.L.C., also served as the contractor and concrete supplier for this bridge.

Mixture proportions for MN-Control-2 are listed in Table 2.16. MN-Control-2 had a 35% replacement by total weight of binder with Class F fly ash and a design *w/cm* ratio of 0.42. During construction, approximately 19 lb/yd^3 (10 kg/m^3) of water was withheld throughout concrete batching, dropping the average *w/cm* ratio to 0.395. Individual *w/cm* ratios based on trip tickets ranged from 0.379 to 0.412. The corresponding design and actual average paste contents were 26.7 and 25.8%, respectively. Based on trip tickets, individual paste contents ranged from 25.3 to 26.3%. The normalweight coarse and fine aggregates used in IC-LC-HPC-2 were used in MN-Control-2. The MN-Control-2 subdeck is also the only concrete in this study that contains fibers (only in the subdeck), dosed at 4 lb/yd^3 (2.4 kg/m^3).

The plastic concrete properties and compressive strengths, listed in Table 2.17, were within MnDOT HPC specification limits for control decks. Three tests for slump and air content were performed. The slump ranged from 3 to 3½ in. (75 to 90 mm) with an average of 3¼ in. (85 mm). Air contents ranged from 5.5 to 7.2% with an average of 6.3%. Concrete temperatures ranged from 72 to 75 °F (22 and 24 °C) with an average of 73 °F (22.5 °C). Two sets of three cylinders were tested for compressive strength with averages of 4,950 and 5,320 psi (34.1 and 36.7 MPa). Individual strengths ranged from 4,520 to 5,580 psi (31.2 to 38.4 MPa).

Table 2.16: MN-Control-2 Mixture Proportions

Material	Mixture Proportions (lb/yd^3)	
	Design	Actual*
Type I/II Cement	377	379
Class F Fly Ash	203	203
Water	245	230
Coarse Aggregate	1736	1740
Fine aggregate	1243	1277
Macrofibers[a]	4	4
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.5
KB-1200	Mid-Range Water Reducer	3
Polychem SPC	Superplasticizer	2
Polychem Renu	Set Retarder	3

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

Table 2.17: MN-Control-2 Concrete Test Results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
MN-Control-2	(in.)	(%)	(°F)	(psi)
Average	3¼	6.3	73	5140
Minimum	3	5.5	72	4520
Maximum	3½	7.2	75	5580

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

KU researchers were not present for the subdeck or overlay placements of MN-Control-2. According to trip tickets, placement began on September 15, 2017, at approximately 11:00 am and ended shortly after 2:00 pm. The overlay was placed following the procedure outlined in Section 2.4.3. The overlay for the right lane was placed on September 28, 2017, and the overlay for the left lane was placed on September 30, 2017. The 28-day compressive strengths of the two cylinders cast on September 30, 2017, were 7,760 and 8,650 psi (53.5 and 59.6 MPa). Compressive strength data for cylinders cast on September 28, 2017, is not available.

2.4.5 IC-LC-HPC 3 – Zumbrota (2017)

IC-LC-HPC-3 is a two-lane bridge along T.H. 58 in Zumbrota, MN, carrying traffic over T.H. 52, also in MnDOT District 6. Although IC-LC-HPC-3 was placed a week prior to IC-LC-HPC-2, numbering was assigned to keep the IC-LC-HPC and MN-Control pairs sequential. IC-LC-HPC-3 has two spans, each 106 ft (32.3 m) long and 48 ft, 11 in. (14.9 m) wide. The bridge includes a 34-ft (10.4-m) wide roadway, barriers on each side (1 ft., 8 in. [0.5 m] and 1 ft, 3 in. [0.4 m] wide) and a 12-ft (3.7-m) wide sidewalk placed on the deck (which did not incorporate IC) on the north side. Similar to IC-LC-HPC-2, the total deck thickness is 9 in. (229 mm), consisting of a 7-in. (178-mm) IC-LC-HPC subdeck and a 2-in. (51-mm) overlay that did not include IC.

As for IC-LC-HPC-2 and MN-Control-2, Lunda Construction Co. was the contractor and Ready-Mix Concrete Company, L.L.C., was the concrete supplier. The same materials were used for IC-LC-HPC-3 as for IC-LC-HPC-2.

Mixture proportions for IC-LC-HPC-3 are listed in Table 2.18. IC-LC-HPC-3 had identical mixture proportions as IC-LC-HPC-2, including a design *w/cm* ratio of 0.45 and 27.3% replacement by total weight of binder with Grade 100 slag cement. During construction, approximately 15 lb/yd^3 (9 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.422. Individual *w/cm* ratios based on trip tickets ranged from 0.398 to 0.434. The corresponding design and actual average paste contents were 26 and 25.2%, respectively. Based on trip tickets, individual paste contents ranged from 24.5 to 25.6%. The FLWA in IC-LC-HPC-3 had a slightly higher absorption than the material used for IC-LC-HPC-2, an average of 24.9% (OD basis) vs. 24.5% for IC-LC-HPC-2. The design absorption was 23.5% (OD basis). The mixture proportions also included a FLWA content of 12.8% of the total aggregate volume. With a slightly higher absorption of the FLWA on-site, the amount of IC water content was approximately 8.6% of the total binder weight.

Table 2.18: IC-LC-HPC-3 Mixture Proportions

Material	Mixture Proportions (lb/yd³)	
	Design	Actual*
Type I/II Cement	410	414
Gr. 100 slag cement	154	154
Water	254	239
Coarse Aggregate	1,411	1,414
Fine Aggregate	1,141	1,143
FLWA	238	244
Chemical Admixtures		
GRT	**Type**	**Dosage (oz/cwt)**
Polychem SA-50	Air Entraining	0.8-0.9
Polychem VMA	Viscosity Modifier	2
KB-1200	Mid-Range Water Reducer	3
Polychem Renu[a]	Set Retarder	0-3

[a] Set retarder dosage stepped down from 3 to 0 oz/cwt throughout placement
* Actual values based on average of trip tickets
Note: 1 lb/yd³ = 0.593 kg/m³, 1 oz/cwt = 0.652 mL/kg

The plastic concrete properties and compressive strengths are listed in Table 2.19. Six tests for slump and air content were performed and the results were within MnDOT specification limits for IC-LC-HPC. Slumps ranged from 2½ to 4 in. (65 to 100 mm) with an average of 3½ in. (90 mm). Air contents ranged from 8 to 9.1% with an average of 8.3%. Concrete temperatures ranged from 73 to 77 °F (23 to 25 °C) with an average of 75 °F (24 °C). Two sets of cylinders were tested for compressive strength with averages of 4,420 and 5,850 psi (30.5 and 40.3 MPa). Individual strengths ranged from 4,160 to 6,250 psi (28.7 to 43.1 MPa). One set exceeded the 5,500 psi (37.9 MPa) MnDOT specification limit for 28-day compressive strength.

Table 2.19: IC-LC-HPC-3 Concrete Test Results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-3	(in.)	(%)	(°F)	(psi)
Average	3½	8.4	75	5,140
Minimum	3	7.5	73	4,160
Maximum	4	9.1	77	6,250

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

Placement began at approximately 9:00 am on June 29, 2017, at the north end of the deck with final strike-off being completed at 12:20 pm at the south end. The time between placement and strike-off ranged from 3 to 14 minutes. The time between strike-off and application of wet curing (wet burlap) ranged from 3 to 28 minutes. Wind speeds at the deck ranged from 1 to 5 mph (1.6 to 8 km/hr). Relative humidity at the deck ranged from 59 to 71% of the subdeck. Ambient air temperature during construction ranged from 69 to 79 °F (20.5 to 26 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.03 to 0.06 lb/ft^2/hr (0.15 to 0.29 kg/m^2/hr).

All concrete tests were within specification limits for slump and air content. No significant delays were experienced during construction. No difficulties in placement or finishing were indicated by MnDOT or construction personnel. The placement and finishing operations were similar to IC-LC-HPC-2, including the issues with consolidation observed on IC-LC-HPC-2 (with contractors walking through consolidated concrete [Figure 2.6] and rapid removal of the spud vibrator). Minimal finishing was performed on the north side of the deck where the sidewalk would be placed. The placement, finishing, and application of curing for IC-LC-HPC-3 are shown in Figure 2.7.

(a) Footprints left in the deck

(b) Re-finishing

Figure 2.6: IC-LC-HPC-3 Deck Consolidation and Finishing Problems

Figure 2.7: Placement, Finishing, and Curing Setup for IC-LC-HPC-3

KU personnel were not present during the trial or overlay placements. One of the abutments for IC-LC-HPC-2 served as the trial placement for IC-LC-HPC-2 and IC-LC-HPC-3. The overlay was placed following the procedure outlined in Section 2.4.3. The overlay placement dates were September 7, 2017, and September 9, 2017. The 28-day compressive strengths of the two cylinders from September 7, 2017, placement were 9,030 and 9,270 psi (62.3 and 63.9 MPa). Compressive strength data for cylinders cast on September 9, 2017, is not available.

2.4.6 IC-LC-HPC 4 – Minneapolis (2018)

The fourth and most recently constructed IC-LC-HPC bridge deck in this study is a two-lane bridge carrying traffic along 38th St. over I-35W in Minneapolis in the MnDOT Metro District. The bridge has four spans, with lengths of 27 ft, 1 in. (8.3 m), 31 ft, 1 in. (9.5 m), and two at 77 ft, 8 in. (23.7 m), for a total length of 213 ft, 6 in. (65.1 m). The total width of the deck is 56 ft (17.1 m), including a roadway width of 36 ft (11 m) plus sidewalks and barriers totaling 10 ft (3.0 m) on each side. Sidewalk concrete was placed on the deck at a later date and did not incorporate IC. The deck is 9 in. (229 mm) thick and composed of IC-LC-HPC. The finished IC-LC-HPC deck surface serves as the final driving surface. The deck was tined during construction. In addition, project specifications also indicated that an AMS curing compound be placed on the deck after tining, prior to application of wet curing.

Lunda Construction Co. was the contractor, and Aggregate Industries U.S. served as the concrete supplier. Prior to batching, the FLWA was stored in a garage at the ready-mix plant and pre-wetted using a lawn sprinkler placed on top of the stockpile. The sprinkler was moved periodically to ensure all of the aggregate was pre-wetted uniformly. The stockpile was turned one to two times per day. The stockpile had a height over 10 ft (3 m) at its tallest point, which was greater than the recommended 5-ft (1.5-m) limit. The sprinkler was turned off about 14 hours prior to batching the bridge deck concrete, allowing the material to drain. When the material was collected by the loader for placement into the aggregate bins, the bottom several inches of the stockpile were left undisturbed.

Two batches of concrete were used in the first unsuccessful trial placement, attempted on May 3, 2018, using mixture proportions based on an FLWA absorption value that had been determined after soaking for 24 hours in a laboratory. The concrete used in these attempts could not be pumped. The contractor and pump operator blamed the problem on the slump limitations (1½ to 4 in. [40 to 100 mm]). The actual problem was the use of incorrect moisture values in establishing the batch weights. The absorption established in the laboratory for the FLWA was 23.6% (OD basis). Tests for absorption or specific gravity were not performed for the first trial placement, and moisture corrections were made based on the total moisture content by subtracting the "laboratory" absorption from the total moisture content. The total moisture reported during attempted trial placements was 36.4%, resulting in a calculated free-surface moisture of 12.8%. On May 8, 2018, KU researchers measured an absorption of 30.3% (OD basis) and a 7.7% free-surface moisture for a total of 38% total moisture. Based on the incorrect free-surface moisture calculated during the first trial placement, around 16 lb/yd^3 (9.5 kg/m^3) of water was withheld. An additional gallon of trim water per yd^3 (8 lb/yd^3, 5 kg/m^3) was also withheld from these batches for a total of over 24 lb/yd^3 (14 kg/m^3). The differences between the assumed and actual FLWA material properties caused considerable changes in the water and, subsequently, the paste content between the original and final mixture proportions. The paste content was lowered from 25.5% to around 24% and *w/cm* ratio was lowered from 0.43 to below 0.39 for the first trial placement. The second trial placement included concrete with the correct FLWA moisture content, along with a modified paste content and VMA dosage, as discussed below, and was easily pumped.

A key observation from the trial placements is that FLWA properties need to be measured shortly before batching the concrete. Batch weights based on the correct absorption and free-surface moisture are needed to produce the concrete. In addition to using the correct moisture contents, increases were made to the design paste content (25.5% to 26%) and VMA dosage (3 to 5 oz/cwt [2 to 3 mL/kg]) to further aid pumping. The maximum slump allowed on this deck was increased from 4 to 5½ in. (100 to 140 mm). The increase in slump was justified based on experience with IC-HPC decks in Indiana, which included concretes with paste contents similar to those used in the IC-LC-HPC decks and slumps ranging from 4¾ to 5¾ in. (120 to 145 mm), that exhibited minimal cracking up to three years after placement (Lafikes et al., 2018).

The mixture proportions for IC-LC-HPC-4 are listed in Table 2.20. IC-LC-HPC-4 included a 28.1% replacement by total weight of binder with Grade 100 slag cement. Initial mixture proportions were used during the first attempted trial batch. The final mixture proportions were used during the successful trial placement and with deck placement. The mixture proportions, particularly the amount of FLWA, used in the initial trial placement would have provided a higher amount of IC water (9.7% by total weight of binder) than the design value of 8%. Thus, the aggregate quantities were adjusted to meet the target IC water content. The cementitious material and water contents were also increased to raise the design paste content to 26%. The design *w/cm* ratio was 0.43 for both initial trials and the final design. During construction, approximately 5 lb/yd^3 (3 kg/m^3) of water was withheld from the concrete batches, which dropped the actual *w/cm* to an average of 0.422. Individual *w/cm* ratios based on trip tickets ranged from 0.417 to 0.428. The corresponding design and actual average paste contents were 26 and 25.7%, respectively. Based on trip tickets, individual paste contents ranged from 25.5 to 25.9%. Crushed gravel was used as the coarse aggregate and river sand was used as the fine aggregate. The mixture proportions included a FLWA content of 10.9% of the total aggregate volume. The FLWA used in IC-LC-HPC-4 had an average absorption of 30.3% (OD basis) on the day of batching, the same value determined during the trial placement the previous week. The amount of IC water provided was approximately 7.9% by total weight of binder based on the average amount of FLWA indicated on trip tickets.

Table 2.20: IC-LC-HPC-4 Mixture Proportions

<table>
<tr><th colspan="2" rowspan="2">Material</th><th colspan="3">Mixture Proportions (lb/yd^3)</th></tr>
<tr><th>Initial</th><th>Final Design</th><th>Actual*</th></tr>
<tr><td colspan="2">Type I/II Cement</td><td>410</td><td>418</td><td>416</td></tr>
<tr><td colspan="2">Gr. 100 slag cement</td><td>160</td><td>164</td><td>165</td></tr>
<tr><td colspan="2">Water</td><td>245</td><td>250</td><td>245</td></tr>
<tr><td colspan="2">Coarse Aggregate</td><td>1,731</td><td>1,701</td><td>1,708</td></tr>
<tr><td colspan="2">Fine Aggregate</td><td>908</td><td>970</td><td>973</td></tr>
<tr><td colspan="2">FLWA</td><td>239</td><td>201</td><td>198</td></tr>
<tr><th colspan="5">Chemical Admixtures</th></tr>
<tr><th>Sika</th><th>Type</th><th>Initial Trial Dosage (oz/cwt)</th><th colspan="2">Actual Dosage* (oz/cwt)</th></tr>
<tr><td>Air-260</td><td>Air Entraining</td><td>0.21</td><td colspan="2">0.28-0.33</td></tr>
<tr><td>Stabilizer-4R</td><td>Viscosity Modifying</td><td>3</td><td colspan="2">5</td></tr>
<tr><td>ViscoCrete®-1000</td><td>Water Reducing</td><td>2.5</td><td colspan="2">1.75-2.75</td></tr>
<tr><td>SikaTard 440</td><td>Set Retarding</td><td>1</td><td colspan="2">0</td></tr>
</table>

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

KU personnel were present for the second trial placement for IC-LC-HPC-4, which was conducted at the ready-mix plant on May 8, 2018, and used the revised mixture proportions. Table 2.21 lists the slump and air content measurements during the trial batch. The first truck was tested immediately after batching and again after being sent out to drive around the ready-mix plant for approximately 15 minutes to simulate the haul time to the bridge deck. MnDOT inspectors required that the concrete be tested after pumping with both horizontal and vertical boom positions to simulate construction conditions. After pumping, the slump dropped 1 to 1¼ in. (25 to 30 mm). Air contents were not significantly affected. The first test on the second truck was performed after the simulated 15-minute haul time. In this case, the concrete was sampled from the pump hopper instead of the truck chute and was dropped into a wheelbarrow about 5 ft (1.5 m) below. The high drop likely resulted in a loss of air, as the air content for this test was 1.6 to 2.4% lower than after pumping. Similar to the first truck, the slump dropped 1 to 1¼ in. (25 to 30 mm) after pumping.

Table 2.21: IC-LC-HPC-4 Trial Batch Properties for Second Trial Placement

IC-LC-HPC-4 Trial Batch	Concrete Properties	
	Slump (in.)	Air Content (%)
Truck No. 1		
Immediately after batching	5¾	9.2
15 min. haul time	4½	8.2
Vert. Pump Boom	3¼	8.5
Horz. Pump Boom	3½	8.5
Truck No. 2		
15 min. haul time	6	7.2[a]
Vert. Pump Boom	5	9.6
Horz. Pump Boom	4¾	8.8

[a] Concrete sample was dropped from 5 ft (1.5 m) height
Note: 1 in. = 25.4 mm

On May 9, 2018, a new shipment of FLWA was delivered to the ready-mix plant to ensure that enough material would be available when the bridge deck concrete was batched. The aggregate properties did not change from the previous shipment of FLWA. Rain in the Minneapolis area caused weather delays for bridge deck placement until the following week on May 15, 2018.

The plastic concrete properties and compressive strengths are listed in Table 2.22. A total of 12 tests for slump and air content were performed. Slump test results ranged from 3½ to 6 in. (90 to 150 mm) with an average of 4¾ in. (120 mm). Air contents ranged from 7.4 to 11.2% with an average of 8.9%. During the first two hours of placement, two of the concrete tests exceeded specification limits with a 6 in. (152 mm) slump and air content of 11.0 and 11.2%. No trucks were rejected, but subsequent batches included a 0.25 oz/cwt (0.16 mL/kg) reduction of water-reducing admixture and withheld 5 lb/yd^3 (3 kg/m^3) of water. Concrete temperatures ranged from 58 to 70 °F (14.5 to 21 °C) with an average of 64 °F (18 °C). Three sets of three cylinders were tested for 28-day compressive strength with averages of 4,780, 5,720, and 6,130 psi (33.0, 39.4, and 42.3 MPa). Individual strengths ranged from 4,570 to 6,280 psi (31.5 to 43.3 MPa). One set exceeded the 5,500 psi (37.9 MPa) MnDOT specification limit for 28-day compressive strength.

Table 2.22: IC-LC-HPC-4 Concrete Test Results

Bridge No.	Slump	Air Content	Temperature	28-Day Compressive Strength
IC-LC-HPC-4	(in.)	(%)	(°F)	(psi)
Average	4¾	8.9	64	5,540
Minimum	3½	7.4	58	4,570
Maximum	6	11.2	70	6,280

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

Placement began on the evening of May 15, 2018, at 9:50 pm at the east end of the deck and ended at 2:48 am on May 16, 2018, on the west end, with final strike-off being completed at 3:00 am. The deck had curing compound applied within an hour after tining. Between 4:30 and 6:00 am, wet curing was applied. The subdecks under the sidewalks on each side did not receive any curing compound or finishing; wet burlap was placed on these sections during construction within an hour after being consolidated. The time between placement and bull floating for the roadway ranged from 17 minutes to 1 hour, 10 minutes. The average time between bull floating and tining ranged from 14 to 32 minutes. The time between bull floating and curing compound application ranged from 28 to 64 minutes. Wind speeds at the deck during construction were relatively low, with only one of the readings as high as 1 mph (1.6 km/hr). Relative humidity at the deck ranged from 37 to 58%. Ambient air temperature during construction ranged from 52 to 63 °F (11 to 17 °C). These environmental conditions resulted in relatively low evaporation rates, ranging from 0.02 to 0.03 lb/ft^2/hr (0.08 to 0.15 kg/m^2/hr).

Early on during placement, between the first 18 and 30 ft (5.5 and 9.2 m), a wheel on the roller screed broke and needed to be replaced, causing a nearly 50-minute delay. This delay is what accounted for the 1 hour and 10-minute delay between placement and bull floating at this section. No other significant delays were experienced for the remainder of construction, including when pumps were switched midway through placement. No difficulties in placement or finishing occurred. As for the other IC-LC-HPC decks placed by Lunda Construction Co., concrete consolidation was achieved with a single operator with a spud vibrator. Similar to consolidation observed during subdeck placement for IC-LC-HPC-2 and IC-LC-HPC-3, the vibrator was inserted at regularly spaced intervals. At times, however, the vibrator was rapidly pulled out of the concrete, leaving holes in the plastic concrete, and construction personnel were observed walking through areas that had been recently vibrated, resulting in deconsolidation of the concrete.

The concrete was finished with a Bid-Well roller screed. The attachments on the screed included a strike-off auger, followed by a Rota-Vibe® (a vibrating roller with ridges). It should be noted that the Rota-Vibe® attachment is not permitted during placement of LC-HPC bridges in Kansas. Its intention is to provide a more uniform concrete surface that is easier to finish. Concern with this attachment in Kansas LC-HPC construction is that this piece of equipment forces coarse aggregate below the surface of concrete, leaving a higher paste content at the surface, which can subsequently lead to more cracking. Immediately after the Rota-Vibe® attachment, the concrete was finished with a roller screed, followed by metal pan and burlap drags. Figure 2.8 shows these attachments in order from left to right. The finishing equipment was advanced in 1-ft (0.3-m) increments at a rate of approximately 1 ft (0.3 m) per minute. For most of the bridge deck, the strike-off auger was usually within 3 ft (0.9 m) of the most recently placed concrete. The sidewalks on either side of the bridge were only consolidated; no Bid-Well equipment was used to finish these surfaces. The 6-in. (150-mm) sidewalk was placed at a later date. Bull floats were used on the roadway following the burlap drag. A work bridge was used for workers to tine the deck. The work bridge and tining operation were skewed by approximately 15° with respect to the width of the deck. Figure 2.9 shows the roadway being tined near the east end. A single layer of curing compound was applied shortly after tining. Although the compound appeared to be applied evenly, over time, some bleed water and blotches were observed in different areas on the deck. Figure 2.10 shows the completed deck prior to application of wet burlap.

Figure 2.8: IC-LC-HPC-4 Finishing Equipment

Figure 2.9: Consolidation and Finishing of IC-LC-HPC-4 Sidewalk Sections

Figure 2.10: Finished IC-LC-HPC-4 Deck Showing Spots of Uneven Curing Compound Application

2.5 Failed IC-LC-HPC Bridge Deck Placement (Hinckley, MN)

This section describes the failed placement of an IC-LC-HPC bridge deck. This placement was the second of two IC-LC-HPC bridge decks planned for 2016. The deck is located along southbound I-35 near Hinckley (MnDOT Bridge No. 58821) in MnDOT District 1. The lessons learned from this failed placement include the need for determination of FLWA properties on the day of batching, using the same equipment to place concrete as used in trial batches, and including all admixtures (particularly VMA) at the time of batching.

The placement was attempted on the morning of October 6, 2016. Cemstone was the concrete supplier, and materials and mixture proportions were to be the same as those used to construct IC-LC-HPC-1. KU researchers arrived at the Cemstone ready-mix plant in Rock Creek on the morning of October 5, 2016, to determine FLWA properties. Upon arriving, it was discovered that the plant was not storing any of the material; the FLWA would be delivered that afternoon. The FLWA was being stored offsite but was still being pre-wetted. The FLWA was delivered to the ready-mix plant around 2:00 pm on October 5th. The quantity of material delivered was about 10% more than the volume needed to complete the entire bridge deck. When tested, the absorption was found to be 26.0% (OD basis) vs. 25.6% based on results reported by the aggregate producer several months prior. While KU researchers sampled the FLWA, Cemstone employees also took a sample for testing at a Cemstone laboratory in the Twin Cities-area.

The FLWA samples tested on the afternoon of October 5, 2016 (15 hours before deck placement) had a free surface moisture content of 7.5% (corresponding to a total moisture content of 33.5%). The test performed at the Cemstone laboratory yielded a 34% total moisture content; no additional tests for moisture content were performed by Cemstone, even though batching was scheduled for the following morning. During this time, although none of the absorbed water in the FLWA was expected to be lost, the material would still continue draining until batching, resulting in a decreased free-surface moisture. Cemstone loaded FLWA into the aggregate hopper at the ready-mix plant on the afternoon of October 5, 2016, where it would sit for more than 15 hours until batching began.

On the morning of October 6, 2016, KU researchers arrived at the ready-mix plant prior to batching the bridge deck concrete. The free surface moisture of the FLWA in the stockpile, stored and covered outdoors was found to be 4.3%, 4.1% lower than the value Cemstone was using for moisture correction. The material placed in the bin was not available for sampling; as a result, the FLWA used in batching had an unknown moisture content, one likely to be lower than the 34% assumed. The water withheld from batching was based on the difference between 34% and 25.6% (8.4%). Because the actual free-surface moisture was 4.3%, excess water was withheld from the mixture. To prevent this error, IC-LC-HPC batch weights should be based on free surface moisture contents measured within an hour of batching.

The first IC-LC-HPC load was batched at 6:31 am. At this time, bridge approach slabs were still being placed and deck placement could not begin. As a result, the first load was held at the ready-mix plant for nearly 40 minutes before being transported to the construction site, a trip that required approximately 15 minutes. No tests for air content were performed at the ready-mix plant by Cemstone before sending trucks to the bridge. Upon arriving at the construction site around 7:40 am, the first batch of concrete was barely able to be pumped. The slump was 1¾ in. (45 mm); the contractor (Redstone Construction Co.) urged MnDOT and Cemstone to modify the concrete to provide a higher slump. Cemstone, however, had continued batching at the ready-mix plant after the first truck had left but before it was tested at the construction site. Five IC-LC-HPC loads had been batched at the time of the first test. One gal/yd^3 (8 lb/yd^3, 5 kg/m^3) of water had been withheld from the first five batches. In an attempt to bring the concrete properties within specification limits and improve pumpability, adjustments were made to the concrete after arriving at the bridge, including adding back the trim water initially withheld. VMA had also unintentionally been withheld at the time of batching from the first five trucks. The original IC-LC-HPC mixture proportions included 3 oz/cwt (2 mL/kg) of VMA, which was used for IC-LC-HPC-1. The maximum dosage per the manufacturer's (BASF's) recommendations was 6 oz/cwt (4 mL/kg). After the first truck (which did not contain any VMA) was rejected, VMA was added to the four other trucks at the construction site. The last two trucks to arrive at the job site had the maximum manufacturer's recommended dosage (6 oz/cwt [3.9 mL/kg]) added. The adjustments in mix water and VMA made after the first truck was rejected also did not account for the large amount of elapsed time between batching and testing (approximately 75 minutes). Each truck thereafter was discharged and tested in substantially less time but still had pumping issues and inconsistent air contents. Despite these changes, the inconsistent and out-of-specification concrete properties led to the rejection of all five trucks.

Acceptance tests for slump and air content were performed at the point of placement (after pumping). The mixture pumped, but with difficulty and never achieved a steady flow through the pump. Concrete was also being discharged from the pump 5 ft (1.5 m) above the deck. A portion of the low air content may have been due to a high freefall of the concrete, as most air contents were below the 6.5% minimum specified air content after pumping. The second truck was rejected after the air content was below 5%. The third truck was rejected when the slump exceeded the maximum slump limit of 3½ in. (90 mm) with 4¼ in. (110 mm) and was not tested for air content. The fourth truck had a 4½ in. (115 mm) slump and a 5% air content and was also rejected. For the fifth and final truck, the slump and air content prior to pumping was 3¼ in. (85 mm) and 9.5%, respectively. After pumping, however, the air content dropped below 5% and was rejected.

While some of these issues could have been rectified in subsequent batches, Cemstone personnel indicated the deck placement could not be completed with IC-LC-HPC concrete due to lack of sufficient FLWA at the ready-mix plant. Placement of IC-LC-HPC concrete was abandoned after the contractor obtained approval from MnDOT to switch to the standard MnDOT HPC bridge deck mixture proportions.

It was later learned from the MnDOT inspector on-site that the trial placement was performed with a smaller pump than the one on site for deck placement. The smaller pump used during trial placement would have resulted in less friction and head losses and made pumping easier than when a larger pump was used.

The failed placement of this bridge deck was precipitated by problems in preparation and concrete batching. Due to errors in the moisture correction, the first rejected batch had a paste content well below the design value of 25.4%. The lower paste content coupled with a low slump, long delays before placement, and a lack of VMA resulted in the difficulties encountered during pumping and placement. Ultimately, the concrete batched and tested that day differed significantly from the design mixture proportions and the IC-LC-HPC used by the same concrete supplier in St. Paul two weeks prior in IC-LC-HPC-1. These observations reinforce the need to determine FLWA properties within a short time prior to batching, but also points to a greater need for proper planning and control during ready-mix operations, practices that were followed during placement of the completed IC-LC-HPC decks.

Chapter 3: Crack Surveys and Results

3.1 General

Crack surveys were performed on the two pedestrian bridges (IC-LC-HPC-1 and MN-Control-1) in June 2017, approximately 9 months after placement, and again in May 2018, approximately 19 months after construction. The first surveys for the 2017 projects (IC-LC-HPC-2, IC-LC-HPC-3, and MN-Control-2), which have 2-in. (50-mm) overlays, were also conducted in May 2018, 7.8 to 10.4 months after placement of the subdecks. The crack survey procedure is presented in Appendix C. Crack surveys for bridge decks in this study will be continued for at least three years after placement. The results of the crack surveys are compared with cracking in the LC-HPC and matching control decks in Kansas constructed from 2005 to 2011 and a series of internally-cured HPC (IC-HPC) decks placed in Indiana between 2013 and 2015.

3.2 Cracking During the First Two Years After Placement

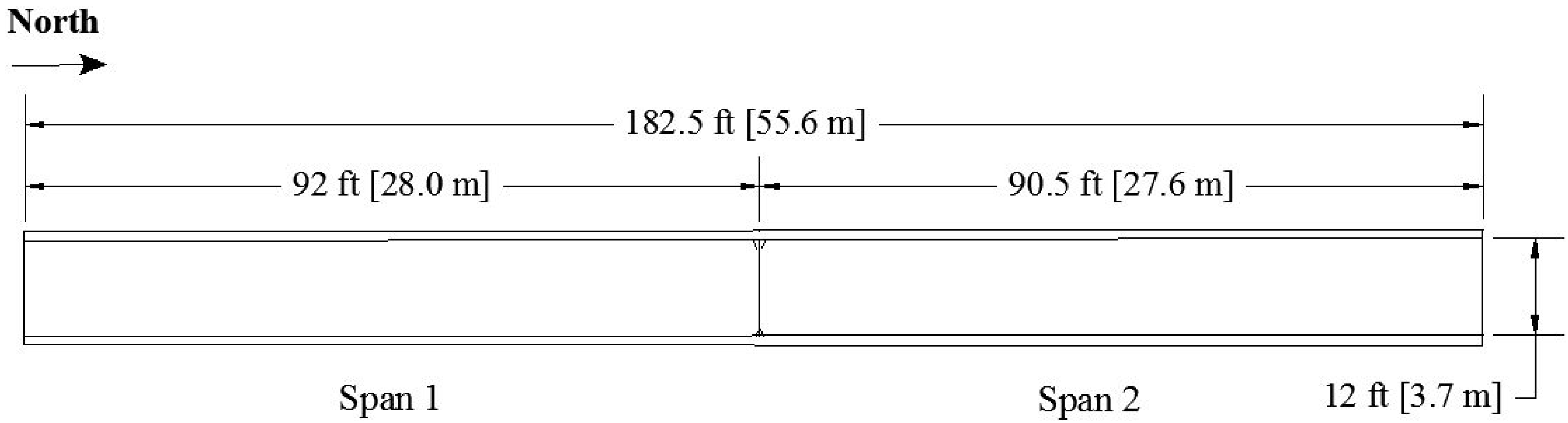
Crack densities, expressed in m/m^2, for the bridge decks in this study are listed in Table 3.1. The crack densities for the pedestrian bridges remained relatively constant within the first two years. IC-LC-HPC-1 had crack densities of 0.009 and 0.007 m/m^2, while MN-Control-1 had crack densities of 0.030 and 0.032 m/m^2 for the first two surveys. Neither IC-LC-HPC-3 nor MN-Control-2 exhibited any cracking in the first year after construction. The greatest crack density was observed on IC-LC-HPC-2 (0.165 m/m^2) 10.1 months after placement. An important detail to note for the MN-Control decks in this study is that specifications for high-performance concrete (HPC) were used, which differ from Kansas control decks. This includes the use of an SCM (fly ash) and paste contents below 26% for the two MN-Control decks. The low paste content is expected to result in significantly lower crack densities than observed in the control decks in the Kansas LC-HPC study (Darwin et al., 2016). Future surveys (three years and more after construction) will provide a better indicator of long-term performance and cracking. Individual crack surveys will be discussed below, in order from first to most recent placement. At the time of this report, IC-LC-HPC-4 has not yet been surveyed and is not included in this section.

Pedestrian bridges IC-LC-HPC-1 and MN-Control-1 were surveyed during the first and second year after construction, with the most recent surveys completed on May 8, 2018. Cracking patterns included a few short (under 2 ft [0.6 m]) cracks on either side of the contraction joint over the center pier. Figure 3.1 shows highlighted cracks on one side of the deck at the center pier for IC-LC-HPC-1. The average crack width for both surveys of IC-LC-HPC-1 was 0.003 in. (0.076 mm). Slightly more cracking over the center pier was observed during the 2017 survey than in the 2018 survey, which accounted for the decrease in crack density. The crack map from the latest survey at 19.6 months after construction is shown in Figure 3.2. Cracking patterns on MN-Control-1 included multiple cracks on either side of the contraction joint over the center pier along the entire width of the deck. The average crack width for both surveys was 0.005 in. (0.127 mm). The crack map from the latest survey at 19.3 months after construction is shown in Figure 3.3.

Table 3.1: Minnesota IC-LC-HPC and MN-Control Crack Survey Results

Project ID	Survey No. 1 Crack Density (m/m^2)	Survey No. 2 Crack Density (m/m^2)	Age at Latest Survey (months)
IC-LC-HPC-1	0.009	0.007	19.6
IC-LC-HPC-2	0.165	-	10.1
IC-LC-HPC-3	0	-	10.4
MN-Control-1	0.030	0.032	19.3
MN-Control-2	0	-	7.8

Figure 3.1: IC-LC-HPC-1 Typical Crack Pattern

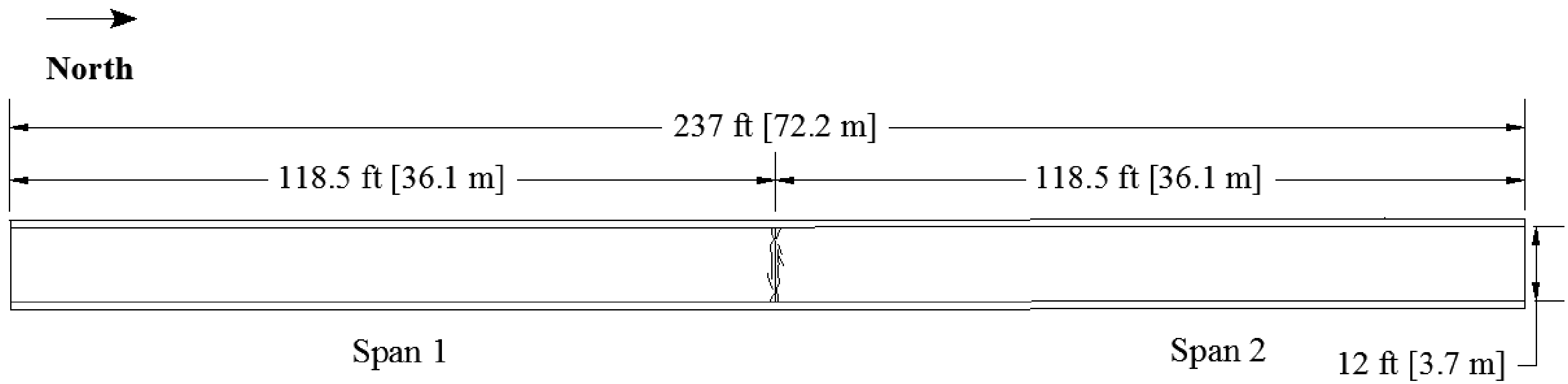


Bridge ID: IC-LC-HPC-1
Bridge Number: 62892
Bridge Location: Mackubin St. over I-94
Construction Date: 9/21/2016
Crack Survey Date: 5/8/2018

Bridge Length: 185.2 ft (56.4 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 92.0 ft (28.0 m)
Span 2: 90.5 ft (27.6 m)
Number of Placements: 1

Bridge Age: 19.6 months
Crack Density: 0.007 m/m^2
Span 1: 0.006 m/m^2
Span 2: 0.009 m/m^2
Crack Length: 4.9 ft
Span 1: 2.1 ft
Span 2: 2.9 ft

Figure 3.2: Crack Map for IC-LC-HPC-1 (Survey 2)



Bridge ID: MN-Control-1
Bridge Number: 62800
Bridge Location: Grotto St. over I-94
Construction Date: 9/28/2016
Crack Survey Date: 5/8//2018

Bridge Length: 237 ft (72.2 m)
Bridge Width: 12.0 ft (3.7 m)
Skew: 0 °
Number of Spans: 2
Span 1: 118.5 ft (36.1 m)
Span 2: 118.5 ft (36.1 m)
Number of Placements: 1

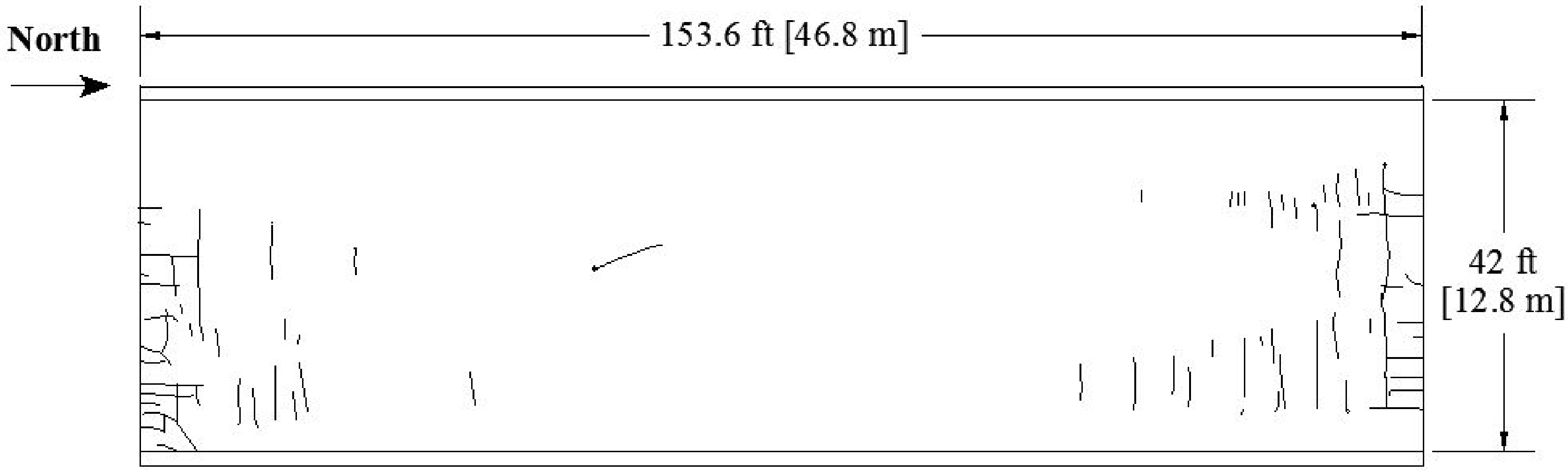
Bridge Age: 19.3 months
Crack Density: 0.032 m/m^2
Span 1: 0.031 m/m^2
Span 2: 0.034 m/m^2
Crack Length: 28.1 ft
Span 1: 13.5 ft
Span 2: 14.6 ft

Figure 3.3: Crack Map for MN-Control-1 (Survey 2)

IC-LC-HPC-2 was surveyed on May 10, 2018, 10.1 months after subdeck placement (9.6 months after overlay placement). The deck on IC-LC-HPC-2, along with those for MN-Control-2 and IC-LC-HPC-3, have a 2-in. (50-mm) overlay. The undersides of the decks were also examined with no cracks observed in any of the decks. The crack density in the overlay on IC-LC-HPC-2 was 0.165 m/m^2, which is the highest to date among projects in this study. The crack map is shown in Figure 3.4. The majority of cracks observed were within 15 ft (4.6 m) of the abutments. Cracks at the abutments were longitudinal in orientation. A majority of the cracks that were located more than 3 ft (0.9 m) from each end of the deck were transverse and varied in length from less than 1 ft (0.3 m) to more than 20 ft (6.1 m). Crack widths ranged from 0.003 in (0.076 mm) to 0.008 in. (0.203 mm) with an average of 0.004 in. (0.102 mm). Cracks did not appear to reflect through to the underside of the deck. It is assumed that with the overlay being placed late-July 2017, cracking due to restrained drying shrinkage of the overlay, made worse by high temperatures, was the primary cause of cracking.

MN-Control-2 was surveyed on May 10, 2018, 7.8 months after subdeck placement (7.3 months after overlay placement). No cracks (0 m/m^2 crack density) were observed during the survey. The effect of including fibers in the subdeck concrete cannot be evaluated because of the overlay. Placing the overlay later in the construction season may have helped due to milder early environmental conditions. While the overlay for IC-LC-HPC-2 was placed in July, a September placement for MN-Control-2 overlay would have helped mitigate rapid drying shrinkage worsened by higher summer temperatures. With no cracking in this deck, no crack map is presented in this report. The bridge geometry is identical to IC-LC-HPC-2.

IC-LC-HPC-3 was surveyed on May 10, 2018, 10.4 months after subdeck placement (8.1 months after overlay placement). No cracks (0 m/m^2 crack density) were observed during the survey. Only the 34-ft (10.4-m) wide roadway was surveyed. The sidewalk on the north side of the deck was placed well after the IC-LC-HPC subdeck and did not incorporate IC. Figure 3.5 shows bridge deck geometry for reference. The overlay for this deck was placed in early-September, well after the late-June placement of the subdeck. Allowing the overlay to cure in cooler ambient temperatures likely reduced the amount of drying shrinkage cracking within the first year after placement.

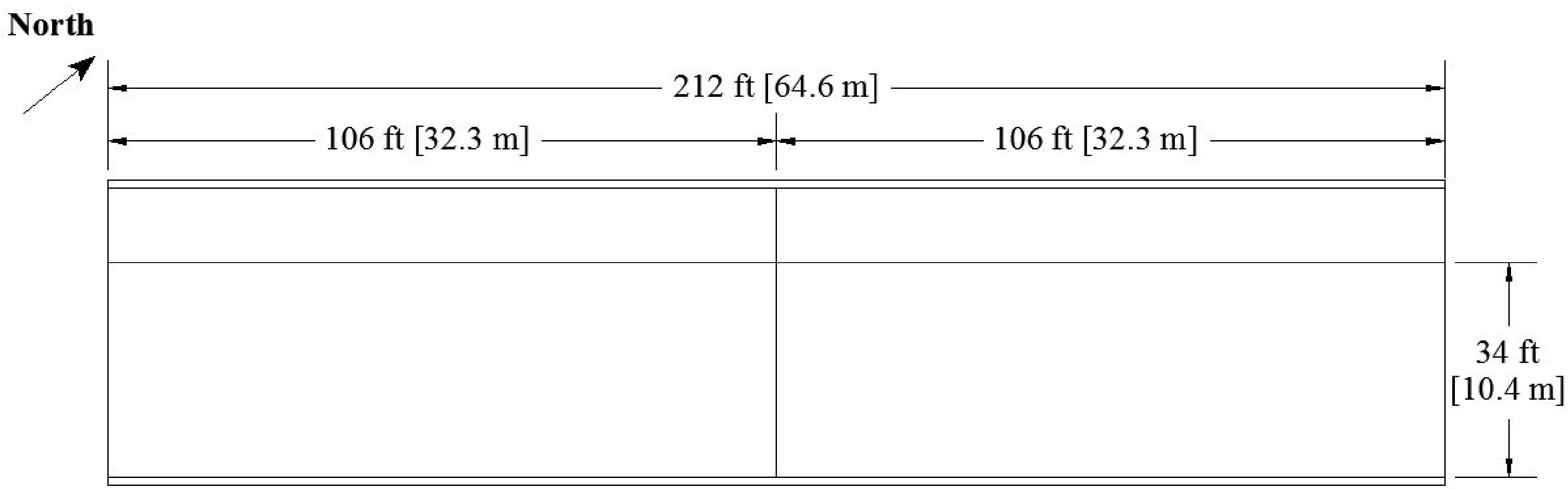


Bridge ID: IC-LC-HPC-2
Bridge Number: 25036
Bridge Location: S.B TH 52 over Little Cannon River
Construction Date: 7/6/2017
Crack Survey Date: 5/10/2018

Bridge Length: 153.6 ft (46.8 m)
Bridge Width: 42 ft (12.8 m)
Skew: 0°
Number of Spans: 1
Number of Placements: 1

Bridge Age: 10.1 months
Crack Density: 0.165 m/m^2
Crack Length: 325.0 ft

Figure 3.4: Crack Map for IC-LC-HPC-2 [w/ Overlay] (Survey 1)



Bridge ID: IC-LC-HPC-3
Bridge Number: 25037
Bridge Location: T.H. 58 over T.H. 52
Construction Date: 6/29/2017
Crack Survey Date: 5/10/2018

Bridge Length: 212 ft (64.6 m)
Bridge Width: 34 ft (10.4 m)
Skew: 0 °
Number of Spans: 1
Number of Placements: 1

Bridge Age: 10.4 months
Crack Density: 0 m/m^2
Span 1: 0 m/m^2
Span 2: 0 m/m^2
Crack Length: 0 ft
Span 1: 0 ft
Span 2: 0 ft

Figure 3.5: Crack Map for IC-LC-HPC-3 [w/ Overlay] (Survey 1)

3.3 Comparisons of Cracking

For the two bridge decks placed in 2016 (IC-LC-HPC-1 and MN-Control-1), crack surveys have shown similar results during the first two years after placement. Of the three decks with overlays placed in 2017, one (IC-LC-HPC-2) exhibited significant cracking within the first year after placement. All projects in this study should be surveyed through at least three years to establish an estimate for long-term cracking behavior. Figure 3.6 shows crack densities as a function age for the IC-LC-HPC and MN-Control decks.

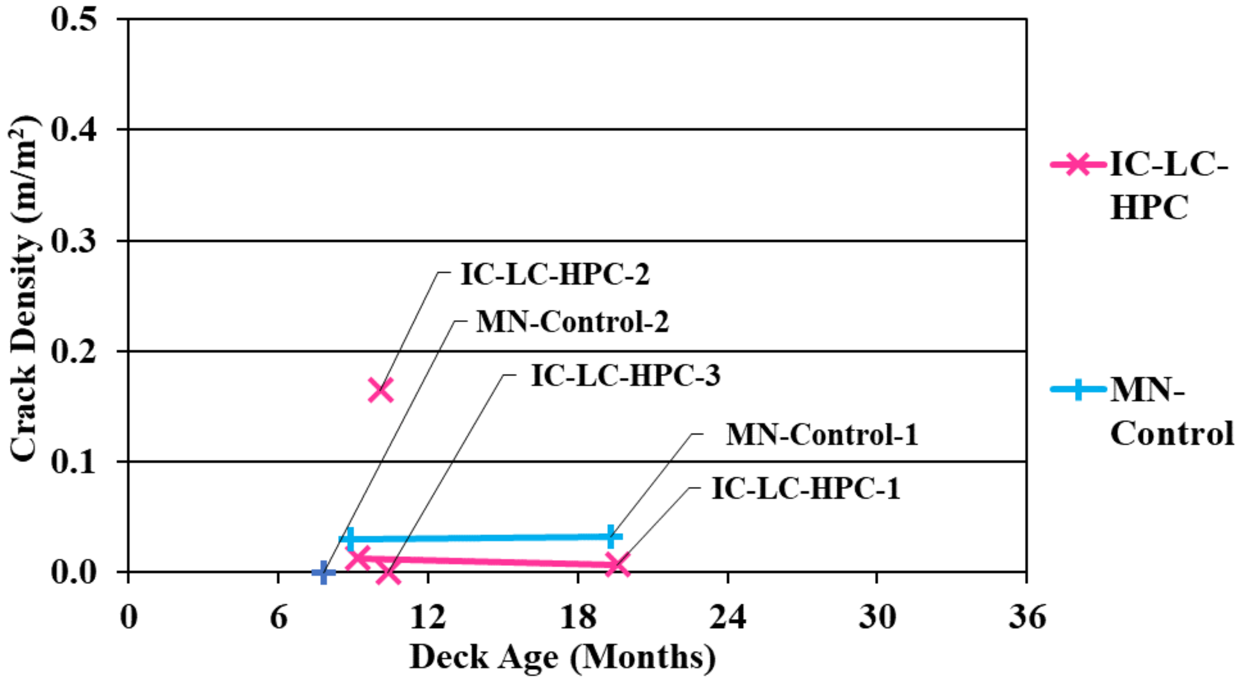


Figure 3.6: Crack Densities of Minnesota IC-LC-HPC and MnDOT HPC Control Decks vs. Deck Age

Cracking in the Minnesota IC-LC-HPC decks is compared to cracking in bridge decks from the Kansas LC-HPC study (Darwin et al., 2016) and bridge decks in Indiana (IN) that followed specifications for IC-HPC in Figure 3.7. The Kansas LC-HPC study included a series of bridge decks that followed the Kansas Department of Transportation (KDOT) specifications for LC-HPC bridge decks and were constructed alongside a series of control decks that followed conventional KDOT bridge deck specifications. Unlike the MnDOT bridges in the current study, the LC-HPC bridge decks in Kansas contained portland cement as the only cementitious material. All decks were surveyed by KU researchers and contain paste contents below 26%. Both the Minnesota and the Indiana decks had IC provided using a pre-wetted FLWA. The Indiana decks contained ternary blends of portland cement, silica fume, and either Class C fly ash or slag cement as binder.

Crack densities for IC-LC-HPC-1 and IC-LC-HPC-3 are among the lowest in these studies. The crack density for IC-LC-HPC-2, while higher than the other IC-LC-HPC decks, is still within the spread of Kansas LC-HPC data one year after construction. Most of IC-HPC decks in Indiana also exhibited significantly lower crack densities than most Kansas LC-HPC decks between three and five years after placement.

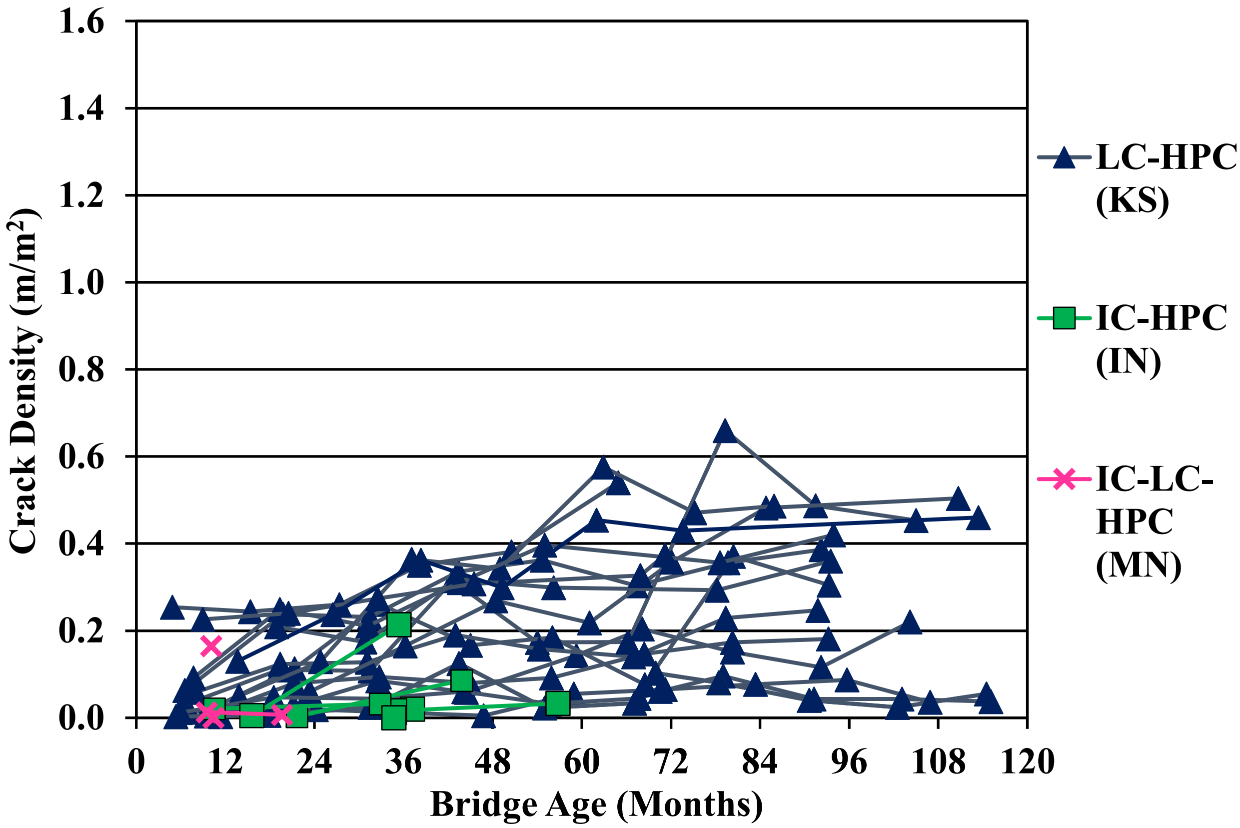


Figure 3.7: Crack Densities of Kansas LC-HPC, Minnesota IC-LC-HPC, and Indiana IC-HPC Decks vs. Deck Age

Figure 3.8 shows the crack densities of the control decks from both the Kansas and Minnesota projects. Compared to the control (KS) decks, the MN-Control (HPC-Control (MN)) decks are exhibiting significantly less cracking through the first one or two years after construction.

Although the MN-Control and IC-LC-HPC bridge decks contain different mixture proportions, including binder composition and *w/cm* ratio, the paste contents are significantly lower than the majority of Kansas control decks. As indicated above, the Minnesota control decks have a combination of low paste contents (25.1 to 25.8% by volume) and a partial replacement of cement with Class F fly ash (25 to 35% by weight of binder). The Kansas control decks have design paste contents ranging from 25.6 to 29% by volume. Although some of the Kansas control decks also include a 20% replacement of cement with fly ash by weight, the paste content for these bridge decks (29%) was significantly higher than any of the Minnesota bridge decks included in this study. The Kansas control decks with design paste contents between 25.6 and 27.1% only include portland cement as binder. Most KS-Control decks have a low *w/cm* ratio (0.37) overlay containing silica fume. These differences are expected to result in significantly higher cracking than the Minnesota control decks.

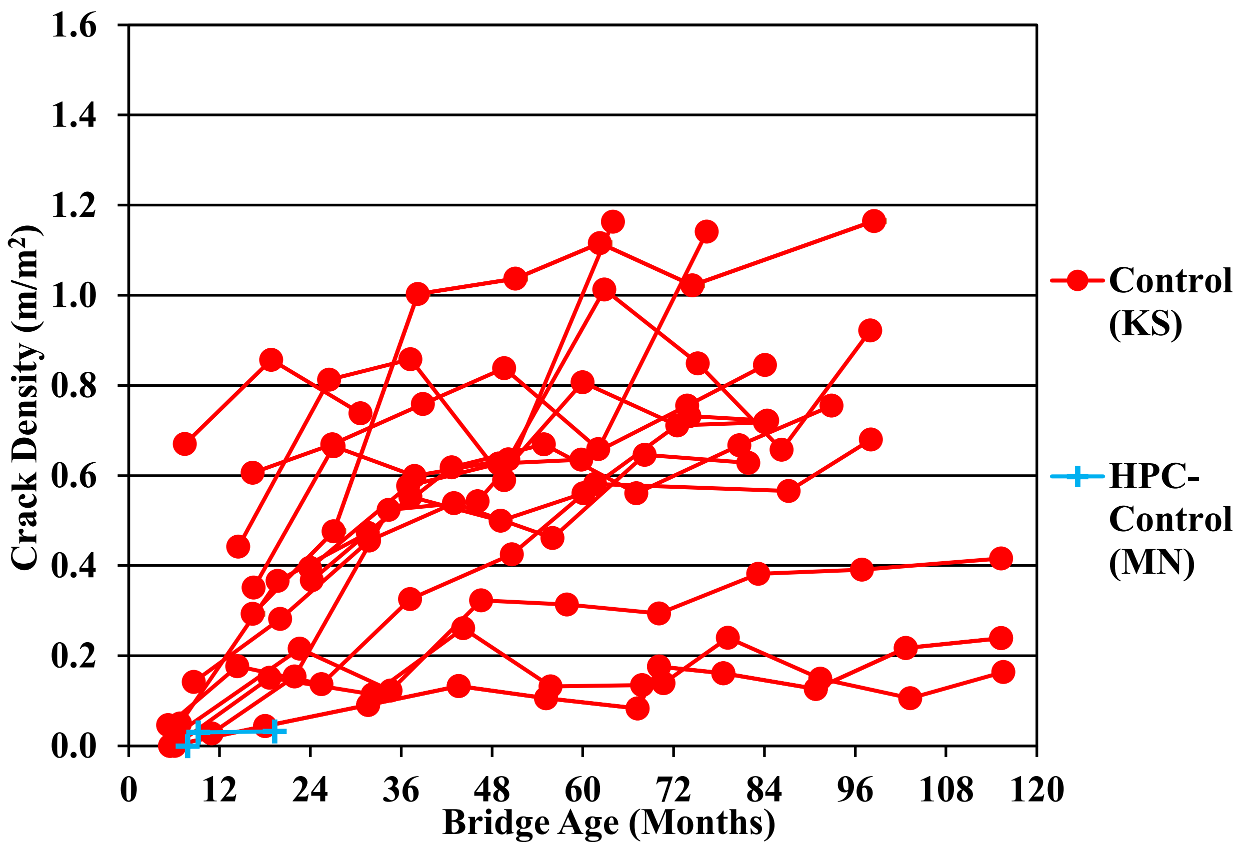


Figure 3.8: Crack Densities of Kansas Control decks and MnDOT HPC Control Decks vs. Deck Age

Chapter 4: Summary, Conclusions, And Recommendations

4.1 Summary

The first four decks implementing specifications for Internally-Cured Low-Cracking High-Performance Concrete (IC-LC-HPC) were placed in Minnesota during this study. Two control decks that followed Minnesota specifications for high-performance concrete (HPC) were paired with IC-LC-HPC decks to compare long-term cracking following placement. IC was provided via a pre-wetted fine lightweight aggregate (FLWA), which was proportioned based on its absorption to provide a target amount of IC water of 8% by total weight of cementitious material. The IC-LC-HPC mixture proportions contained slag cement as part of the binder system (27 to 30% by total weight) while the control mixture proportions included Class F fly ash (25 or 35% by total weight of binder). University of Kansas (KU) researchers worked with the Minnesota Department of Transportation (MnDOT), the concrete suppliers, and the testing laboratories to develop recommendations for handling, storing, and testing FLWA. Placement of one IC-LC-HPC deck in 2016 had to be abandoned after errors in FLWA moisture corrections and concrete batching led to consecutive rejections of batches when concrete was not within specification limits and the remaining FLWA was not enough to complete the deck. For the deck placed in 2018, mixture proportions, namely the quantity of FLWA, needed to be modified after the FLWA delivered to the ready-mix plant had a significantly higher absorption than the FLWA used in the initial design.

KU researchers observed the construction of the IC-LC-HPC decks. Crack surveys were performed within one and two years after construction on the IC-LC-HPC and control decks placed in 2016 and 2017. The IC-LC-HPC and control deck placed in 2016 exhibited low crack densities through the first two surveys. The two IC-LC-HPC and one control decks placed in 2017 had 2-in. (50-mm) overlays with high cement paste contents, which tend to cause high amounts of cracking. Within one year of placement of the 2017 decks, no cracking was observed on the overlays that were placed in September; however, the IC-LC-HPC deck with an overlay placed in July exhibited significant cracking within one year of placement. The crack survey results of the IC-LC-HPC decks are, to date, similar to or better than the spread of data for the low-cracking high-performance concrete (LC-HPC) bridge decks in Kansas and a series of internally-cured high-performance concrete (IC-HPC) decks in Indiana. Future crack surveys are planned.

4.2 Conclusions

The goal of this project is to serve as a foundation for implementing IC-LC-HPC specifications to improve bridge deck service life through a reduction of cracking. Based on the observations during planning, construction, and early-age crack surveys of the first four IC-LC-HPC decks, the following conclusions can be drawn:

1. The FLWA used throughout this study has shown to be highly variable in its properties (absorption, specific gravity, and gradation). Individual FLWA shipments should be tested for specific gravity and absorption and should be stored and pre-wetted until a uniform, constant moisture content is achieved.
2. Final IC-LC-HPC mixture proportions should be contingent on test results for FLWA absorption determined 1 hour before batching and adjusted to provide the correct amount of IC water.
3. Enforcing specification requirements for trial placements of IC-LC-HPC mixtures is critical in identifying any concrete issues prior to construction. For projects that have concrete placed via pump, the same size pump should be used during trial placements as will be used on the deck.
4. Crack survey results of the IC-LC-HPC and control decks included in this study serve as positive indicators for low amounts of long-term cracking.
5. It appears that bridge deck overlays placed later in the construction season exhibit less cracking than those subjected to high temperature within the first month of curing, but future surveys are needed to establish long-term behavior.

4.3 Recommendations

The experience gathered from the construction and evaluation within the first two years after IC-LC-HPC bridge deck placement, along with other studies of IC concrete (Lafikes et al., 2018), provide the basis for the recommendations that follow for future IC-LC-HPC decks.

Recommendations 1–5 address handling, storage, testing, and proportioning FLWA. Recommendations 6–8 address IC-LC-HPC properties.

1. IC-LC-HPC mixture proportions submitted to a Department of Transportation for approval and the final batch weights on the day of placement should be based on providing the desired quantity of IC water. For the IC-LC-HPC decks placed to date, the desired quantity of IC water was 8% of the total weight of binder. Providing lower than this target amount of IC water potentially reduces the benefits from IC while an excessive amount of IC water may pose a potential for freeze-thaw damage in concrete subject to freezing prior to drying out.
2. FLWA for use in IC-LC-HPC projects should be delivered to ready-mix plants well in advance of batching. The same material should be used in the completion of trial and bridge deck placements with enough available to account for up to 20% of batches being rejected during construction. The material should be pre-wetted until the material reaches a constant absorption. Pre-wetting should stop 12 to 15 hours prior to batching to allow the material to drain.
3. Additional requirements for turning stockpiles twice per day and again immediately before determining the moisture contents used for batching should be added to the current IC-LC-HPC specifications.
4. Use of a centrifuge to place FLWA in a pre-wetted surface dry (PSD) condition is recommended for IC-LC-HPC projects. The procedure used by KU researchers closely follows one developed by Miller, Spragg et al. (2014) and is provided in Appendix B.
5. Ready-mix suppliers should be authorized to adjust the batch weights of the FLWA and normalweight fine aggregate to maintain the target amount of IC water.
6. The paste content (volume of cementitious material and water) in an IC-LC-HPC mixture should be limited to 26% of the total concrete volume. Paste

content has shown to be the driving factor affecting bridge deck cracking and is more critical than slump or compressive strength (Khajehdehi & Darwin, 2018). Provided this trend continues to be verified through crack surveys beyond three years after construction, IC-LC-HPC specifications may include a 5½ in. (140 mm) maximum slump and have the 5,500 psi (37.9 MPa) cap on 28-day compressive strength removed.

7. The use of overlays on bridge decks has not been shown to be beneficial in reducing cracking (Miller & Darwin, 2000; Lindquist, Darwin, & Browning, 2008; Yuan et al., 2011; Pendergrass & Darwin, 2014; Darwin et al., 2016; Khajehdehi & Darwin, 2018). Based on crack survey results of the two IC-LC-HPC bridge decks with an overlay in this study, the potential for high amounts of cracking remain despite inclusion of an IC-LC-HPC subdeck. It is recommended that future IC-LC-HPC decks not contain an overlay.
8. Khajehdehi and Darwin (2018) identified consolidation and early application of wet curing as variables that should be controlled during construction. For IC-LC-HPC bridge decks, concrete should receive thorough consolidation and be left undisturbed throughout the remainder of construction.

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Appendix A: Minnesota Department of Transportation Specifications for Internally-Cured Low-Cracking High-Performance Concrete

SB-10 STRUCTURAL CONCRETE – INTERNALLY CURED HIGH PERFORMANCE CONCRETE BRIDGE DECKS (CONTRACTOR CONCRETE MIX DESIGN)

Delete the contents of 2401.2.A, "Concrete," and replace with the following:

Design an internally cured concrete mixture that will minimize cracking by incorporating saturated lightweight fine aggregate. Perform the work in accordance with the applicable requirements of MnDOT 2401, "Concrete Bridge Construction," 2461, "Structural Concrete," and the following:

2.A.1 Fine Aggregate Requirements

Provide fine aggregates complying with quality requirements of 3126.2.D, "Deleterious Material," 3126.2.E, "Organic Impurities," and 3126.2.F, "Structural Strength."

2.A.1.a Fine Aggregate Lightweight Requirements

Incorporate fine lightweight aggregate as a means to provide internal curing water for concrete. The requirements of ASTM C1761 and C330 shall apply, except as modified in this specification.

(1) Size all lightweight aggregate to pass a 3/8 in. sieve.

(2) Proportion the volume of lightweight aggregate such that is does not exceed 10 percent of total aggregate volume. Lightweight aggregate used as a replacement for normal weight aggregate shall be made on a volume basis.

(3) Pre-wet lightweight aggregate prior to adding at the time of batching. Recommendations for pre-wetting made by the lightweight aggregate supplier shall be followed to ensure that the lightweight aggregate has achieved an acceptable absorbed moisture content at the time of batching. Mixture proportions shall not be adjusted based on the absorbed water in the lightweight aggregate.

(4) Handling and Stockpiling Lightweight Aggregates:

Keep aggregates from different sources, with different gradings or with a significantly different specific gravity separated.

Transport aggregate in a manner that insures uniform grading.

Do not use aggregates that have become mixed with earth or foreign material.

Stockpile or bin all washed aggregate produced or handled by hydraulic methods for 12 hours (minimum) before batching. Rail shipment exceeding 12 hours is acceptable for binning provided the car bodies permit free drainage.

Provide additional stockpiling or binning in cases of high or non-uniform moisture.

2.A.1.b Fine Aggregate Alkali Silica Reactivity (ASR) Requirements

The Department will routinely test fine aggregate sources for alkali silica reactivity (ASR) in accordance with the following:

(1) Multiple sources of certified portland cement in accordance with ASTM C 1260 MnDOT Modified; and

(2) Multiple combinations of certified portland cement and supplementary cementitious materials in accordance with ASTM C 1567 MnDOT Modified.

The Concrete Engineer, in conjunction with the Engineer, will review the 14-day fine aggregate expansion test results to determine the acceptability of the proposed fine aggregate and cement combination in accordance with the following:

(1) For fine aggregate and cement combinations previously tested by the Department, the Concrete Engineer will use the average of all 14-day unmitigated test results for an individual source to determine necessary mitigation in accordance with Table HPC-1.

(2) If the previously tested proposed fine aggregate and cement combination requires less mitigation than the average 14-day unmitigated test result, the Concrete Engineer will allow mitigation at the lesser rate in accordance with Table HPC-1.

(3) Alkali silica reactivity (ASR) ASTM C1260 and ASTM C1567 test results are available on the MnDOT Concrete Engineering Unit website.

<table>
<tr><th colspan="8">Table HPC-1
Fine Aggregate ASR Mitigation Requirements</th></tr>
<tr><th>14-day Fine Aggregate Unmitigated Expansion Limits</th><th>Class F Fly Ash</th><th>Class C Fly Ash</th><th>Slag</th><th>Slag/Class F Fly Ash</th><th>Slag/Class C Fly Ash</th><th>IS(20)/Class F Fly Ash</th><th>IS(20)/Class C Fly Ash</th></tr>
<tr><td>≤ 0.150</td><td colspan="7">No mitigation required</td></tr>
<tr><td>>0.150 - 0.200</td><td>Not Allowed</td><td>Not Allowed</td><td>35%</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td><td rowspan="2">Not Allowed</td></tr>
<tr><td>> 0.200 – 0.300</td><td>Not Allowed</td><td>Not Allowed</td><td>35%</td></tr>
<tr><td>> 0.300</td><td colspan="7">The Department will reject the fine aggregate</td></tr>
</table>

The Concrete Engineer may reject the fine aggregate if mortar bar specimens exhibit an indication of external or internal distress not represented by the expansion results. The Concrete Engineer will make the final acceptance of the aggregate.

2.A.2 Intermediate Aggregate Requirements

Provide intermediate aggregates complying with the quality requirements of 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure," except as modified in Table HPC-2. If the intermediate aggregate is from the same source as the ¾ in- fraction, the aggregate quality is determined based upon the composite of the ¾ in- and intermediate aggregate.

The Concrete Engineer classifies intermediate aggregate in accordance with Table HPC-2.

Table HPC-2 **Intermediate Aggregate for Use in Concrete**			
If the gradation meets the following:	**Classify material type as:**	**Gradation Test Procedures**	**Quality Test Requirements**
100% passing the 1/2" and ≤90% passing #4	Intermediate Aggregate	Coarse Aggregate (+4 Portion)	Spec. 3137.2.D.2 except 3137.2.D.2(i) modified to maximum 40% carbonate
		Fine Aggregate (-4 Portion)	Shale in Sand (-4 Portion)
100% passing the 1/2" and >90% passing #4	Intermediate Aggregate	Fine Aggregate (Minimum 1000 g sample)	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)
100% passing the 3/8" and ≤90% passing #4	Coarse Sand	Fine Aggregate	Shale Content Test by AASHTO T113 MnDOT Modified (+4 Portion)
			Shale in Sand (-4 Portion)

For any intermediate aggregate size not previously tested by the Department, the Concrete Engineer reserves the right to test for alkali silica reactivity, in accordance with ASTM C1260, prior to allowing incorporation into the concrete mix design.

2.A.3 Coarse Aggregate Requirements

Provide Class A, B or C coarse aggregate meeting the quality requirements in accordance with 3137.2.D.2, "Coarse Aggregate for Bridge Superstructure."

When providing Class B aggregate, the maximum absorption percent by weight is 1.10%.

2.A.3.a Coarse Aggregate Alkali Silica Reactivity (ASR) Requirements

When using coarse aggregate identified as quartzite or gneiss, the Concrete Engineer will review ASTM C1293 testing to determine the necessary ASR mitigation requirements in accordance with Table HPC-3.

ASR ASTM C1293 test results are available on the MnDOT Concrete Engineering Unit website.

Table HPC-3 Coarse Aggregate ASR Mitigation Requirements*							
ASTM C1293 Expansion Results	**Class F Fly Ash**	**Class C Fly Ash**	**Slag**	**Slag/Class F Fly Ash**	**Slag/Class C Fly Ash**	**IS(20)/Class F Fly Ash**	**IS(20)/Class C Fly Ash**
≤ 0.040	No mitigation required						
>0.040	Not Allowed	Not Allowed	35%	Not Allowed	Not Allowed	Not Allowed	Not Allowed
* The Engineer will allow the Contractor to substitute a portion of the minimum required supplementary cementitious material with up to 2% silica fume by weight for mitigation purposes.							

2.A.4 Cementitious Materials

Provide only cementitious materials from the Approved/Qualified Products List.

2.A.4.a Cement

Use Type I or Type I/II cement complying with Specification 3101, "Portland Cement," or blended cement in accordance with Specification 3103, "Blended Hydraulic Cement."

(1) Total alkalis (Na_2Oe) no greater than 0.60 percent in the portland cement, and
(2) Total alkalis (Na_2Oe) no greater than 3.0 lb per yd^3 of concrete resulting from the portland cement.

2.A.4.b Ground Granulated Blast Furnace Slag

Use ground granulated blast furnace slag conforming to Specification 3102, "Ground Granulated Blast-Furnace Slag."

2.A.4.c Silica Fume

Use silica fume conforming to ASTM C 1240.

2.A.4.d Ternary Mixes

Ternary mixes are defined as portland cement and two other supplementary cementitious materials, or blended cement and one other supplementary cementitious material with a maximum replacement of 40% by weight.

2.A.5 Allowable Admixtures

Use any of the following admixtures on the MnDOT Approved/Qualified Products as listed under "Concrete Admixtures A-S":

(A) Type A, Water Reducing Admixture,
(B) Type B, Retarding Admixture,
(C) Type C, Accelerating Admixture,
(D) Type D, Water Reducing and Retarding Admixture,
(E) Type F, High Range Water Reducing Admixture, and
(F) Type S, Specific Performance Based Admixture

Obtain a written statement from the manufacturer of the admixtures verifying:

(1) Compatibility of the combination of materials, and
(2) Manufacturer recommended sequence of incorporating the admixtures into the concrete.

The manufacturer will further designate a technical representative to dispense the admixture products.

Utilize the technical representative in an advisory capacity and have them report to the Contractor any operations or procedures which are considered as detrimental to the integrity of the placement. Verify with the Engineer whether the Manufacturer's technical representative's presence is required during the concrete placement.

2.A.6 Concrete Mix Design Requirements

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department's website at least 21 calendar days before the initial concrete placement. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

2.A.6.a Concrete Mix Design Requirements

Design and produce 3YHPCIC-M or 3YPHCIC-S concrete mixes based on an absolute volume of 27.0 ft^3 [1.0 m^3] in accordance with the Table HPC-4 and the following requirements:

Table HPC-4
High Performance Bridge Deck Concrete Mix Design Requirements

Concrete Grade	Mix Number *	Intended Use	w/c ratio	Target Air Content	Maximum %SCM (Fly Ash/Slag/ Silica Fume/ Ternary) ‖	Slump Range †, *inches*	Minimum/Maximum Compressive Strength, f'c (28-day)	3137 Spec.
HPC	3YHPCIC-M	Bridge Deck – Monolithic	0.43-0.45	6.5% to 10%	0/28/2/30	1 1/2" to 4 "	4000psi/5500 psi	2.D.2
	3YHPCIC-S	Bridge – Structural Slab						

* Provide a Job Mix Formula in accordance with 2401.2.A.7. Use any good standard practice to develop a job mix formula and gradation working range by using procedures such as but not limited to 8-18, 8-20 gradation control, Shilstone process, FHWA 0.45 power chart or any other performance related gradation control to produce a workable and pumpable concrete mixture meeting all the requirements of this contract.
‖ The individual limits of each SCM shall apply to ternary mixtures.
† Keep the consistency of the concrete uniform during entire placement.
Limit volume of water plus cementitious materials to a maximum of 27% of total concrete volume.
Add all mix water at the plant. No water will be allowed to be added on site.

2.A.6.b Required Preliminary Testing

Prior to placement of any 3YHPCIC-M or 3YHPCIC-S Concrete, the Engineer will require preliminary batching and testing of the concrete mix design.

Submit the concrete mixes using the appropriate MnDOT Contractor Mix Design Submittal Workbook available on the Department's website at least 14 calendar days prior to the beginning of preliminary laboratory mixing and testing of the proposed mix designs. Any changes or adjustments to the material or mix design require a new Contractor mix design submittal. For mix design calculations, the Engineer, in conjunction with the Concrete Engineer, will provide specific gravity and absorption data.

The Concrete Engineer, in conjunction with the Engineer, will review the mix design submittal for compliance with the contract.

Batch the concrete and place in mixing truck for the max anticipated delivery time. Test the concrete for the following hardened concrete properties in accordance with Table HPC-5:

Table HPC-5 Required Hardened Concrete Properties for Mixes 3YHPCIC-M and 3YHPCIC-S		
Test	Requirement	Test Method
Required Strength (Average of 3 cylinders)	4000 psi min. at 28 days, 5500 psi max. at 28 days	ASTM C31
Rapid Chloride Permeability	≤ 2500 coulombs at 28 days (For Preliminary Approval) ≤ 1500 coulombs at 56 days	ASTM C1202
Freeze-Thaw Durability	Greater than 90% at 300 cycles	ASTM C666 Procedure A
Shrinkage	No greater than 0.040 percent at 28 days	ASTM C157
Scaling	Visual rating not greater than 1 at 50 cycles	ASTM C672

The Engineer will allow the maturity method for subsequent strength determination. Perform all maturity testing in accordance with ASTM C1074 and the MnDOT Concrete Manual.

If a mix is approved, the Concrete Engineer will consider the mix design and testing as acceptable for a period of 5 years provided the actual concrete mixed and placed in the field meets the Contract Requirements. The Concrete Engineer will not require new testing within that 5-year period as long as all the constituents (including the aggregates) of the proposed mix design are the same as the original mix design.

The Engineer determines final acceptance of concrete for payment based on satisfactory field placement and performance.

2.A.7 Job Mix Formula

A Job Mix Formula (JMF) contains the following:

(a) Proportions for each aggregate fraction,
(b) Individual gradations for each aggregate fraction, and
(c) Composite gradation of the combined aggregates including working ranges on each sieve in accordance with Table HPC-6.

Table HPC-6 Job Mix Formula Working Range	
Sieve Sizes	**Working Range, %***
1 in [25 mm] and larger	±5
¾ in [19 mm]	±5
½ in [12.5 mm]	±5
⅜ in [9.5 mm]	±5
No.4 [4.75 mm]	±5
No.8 [2.36 mm]	±4
No.16 [1.18 mm]	±4
No.30 [600 µm]	±4
No.50 [300 µm]	±3
No.100 [150 µm]	±2
No.200 [75 µm]	≤ 1.6
* Working range limits of the composite gradation based on a moving average of 4 tests (N=4).	

2.A.7.a Verification of JMF

Prior to beginning placements of bridge deck concrete, perform gradation testing to ensure current materials comply with the approved JMF. Perform gradation testing in accordance with the Schedule of Materials Control.

(1) Take samples at the belt leading to the weigh hopper or other locations close to the incorporation of the work as approved by the Engineer.
(2) Add fill-in sieves as needed during the testing process to prevent overloading.

The Producer and Engineer will test and record the individual gradation results using the Concrete Aggregate Worksheet.

(1) Using the JMF Moving Average Summary Worksheet, calculate the moving average of Producer aggregate gradation test results during production.
(2) The Engineer will randomly verify Producer combined aggregate gradation results as defined in the Schedule of Materials Control.

If, during production, the approved JMF falls outside of the allowable working range immediately sample and test additional gradation and continue production.

2.A.7.b JMF Adjustment

If it is determined that the current aggregates do not meet the approved JMF, submit a new mix design including JMF to the Concrete Engineer in accordance with 2401.2.A.7.

2.A.7.c JMF Acceptance

The Engineer will make monetary adjustments for the quantity of bridge deck concrete represented by the JMF Working Range failure, from the failing test to the next passing test, at a minimum rate of $500.00 or $5.00 per cubic yard, whichever is greater.

2.A.8 Laboratory batching, testing requirements and submittals:

To determine the characteristics of the Contractor proposed mix design, the Concrete Engineer will require the Contractor to prepare test batches and do laboratory testing. Conduct all batching and testing of concrete at a **single** AMRL certified laboratory using the exact materials proposed in the mix design.

Lab testing requirements:

(a) Slump and air content at <5 minutes, 15 minutes, and 30 minutes after the completion of mixing,
(b) Compressive strength (Make cylinders in accordance with AASHTO T126 and tested in accordance with AASHTO T22) at 1, 3, 7, 28, 56 days (sets of 3),
(c) Hardened air content (ASTM C457) at a minimum of 7 days,
(d) Rapid chloride permeability (ASTM C1202) at 28 days and 56 days (2 specimens for 28 day test and 2 test specimens for 56 day test (Take 2 specimens from each batch of a 2 batch mix)),
(e) Concrete Durability (ASTM C666, Procedure A) at 300 cycles, and
(f) Concrete Shrinkage (ASTM C157) at 28 days.

The Contractor is required to contact the MnDOT Concrete Engineering Unit a minimum of 2-days prior to any mixing so that a MnDOT representative can observe the process. This same 2-day notification is required prior to any physical testing on hardened concrete samples. Additionally, retain any hardened concrete test specimens for a minimum of 90 days and make available for MnDOT to examine.

Perform all testing for plastic concrete after all admixtures additions to the concrete mixture.

After completion of the laboratory testing specified herein and, at least, 15 working days prior to the trial placement, submit the laboratory test data to the MnDOT for review and acceptance.

Include the following information in the laboratory reports of the design mixes:

(a) Exact batch weights and properties of all ingredients used and all aggregate gradations

(b) Slump and air content
(c) Cylinder identification, including mix designation
(d) Date and time of cylinder preparation
(e) Date and time cylinder specimen was tested
(f) Compressive strength of each cylinder specimen at 1, 3, 7, 28, and 56 day (sets of 3)
(g) A graphic plot of age, from 0 to 56 days, vs. strength for each mix design
(h) Hardened air content at a minimum of 7 days
(i) Rapid chloride permeability at 28 days and 56 days
(j) Concrete Durability at 300 cycles and
(k) Concrete Shrinkage at 28 days.

2.A.9 Prior to Actual Bridge Deck Placement

2.A.9.a Trial Placement

A minimum of 14 calendar days prior to the actual placement of the bridge deck slab concrete, successfully complete a separate trial placement utilizing a minimum of two (2) - 10 yd^3 loads.

The Engineer may allow the incorporation of the concrete for trial batches into the bridge footings, abutments or end diaphragms. The Contractor may also choose to incorporate the trial batches into residential /commercial construction in the immediate vicinity of the project. In any case, the Engineer will require mixing, transporting, and placing the concrete using the same methods as the actual placement of the bridge deck.

If the concrete is incorporated into the permanent work, the Engineer will test the plastic concrete in accordance with the Schedule of Materials Control. The Engineer may require additional trial batches if the concrete delivered to the project does not comply with the plastic concrete requirements of the Contract.

The concrete mix design, laboratory batching and mixing, and the trial placement is incidental to the concrete furnished and placed.

Use the same materials, same supplier, and same supplier's manufacturing plant, and proportions in the permanent work as in the trial placement. Strength requirements specified for each mix are applicable to the cylinder tests taken during the production work.

2.A.9.b Slab Placement and Curing Plan

At least 14 calendar days prior to slab placement, provide a slab placement and curing plan for each bridge to the Engineer for approval. Include the following information in the placement and curing plan:

(1) Anticipated concrete delivery rates
(2) Estimated start and finish time
(3) Material, labor and equipment proposed for placing, finishing, and curing including placement of wet burlap, soaker hose, or other system to maintain the deck in a moist condition during the curing period
(4) Number of work bridges proposed for use
(5) Number of people responsible for the various tasks and
(6) Bulkheading methods and materials proposed for use if the Contractor cannot maintain the proposed concrete placement rates.

For full depth monolithic decks, the finishing machine will consist of a cylindrical finisher mated with horizontal adjustable augers, both of which are mounted on a transversely moving carriage unless otherwise approved by the State Bridge Construction Engineer.

A 10 ft [3 m] bull float is required for full-depth decks prior to carpet dragging regardless of whether texture planing is specified for the final ride surface. Float slab in accordance with MnDOT Construction Manual 5-393.358 to ensure the final surface does not vary by greater than ⅛ in [3 mm] within a 10 ft [3 m] straightedge laid longitudinally on the final surface. This surface tolerance includes areas near expansion devices and other breaks in the continuity of the bridge slab.

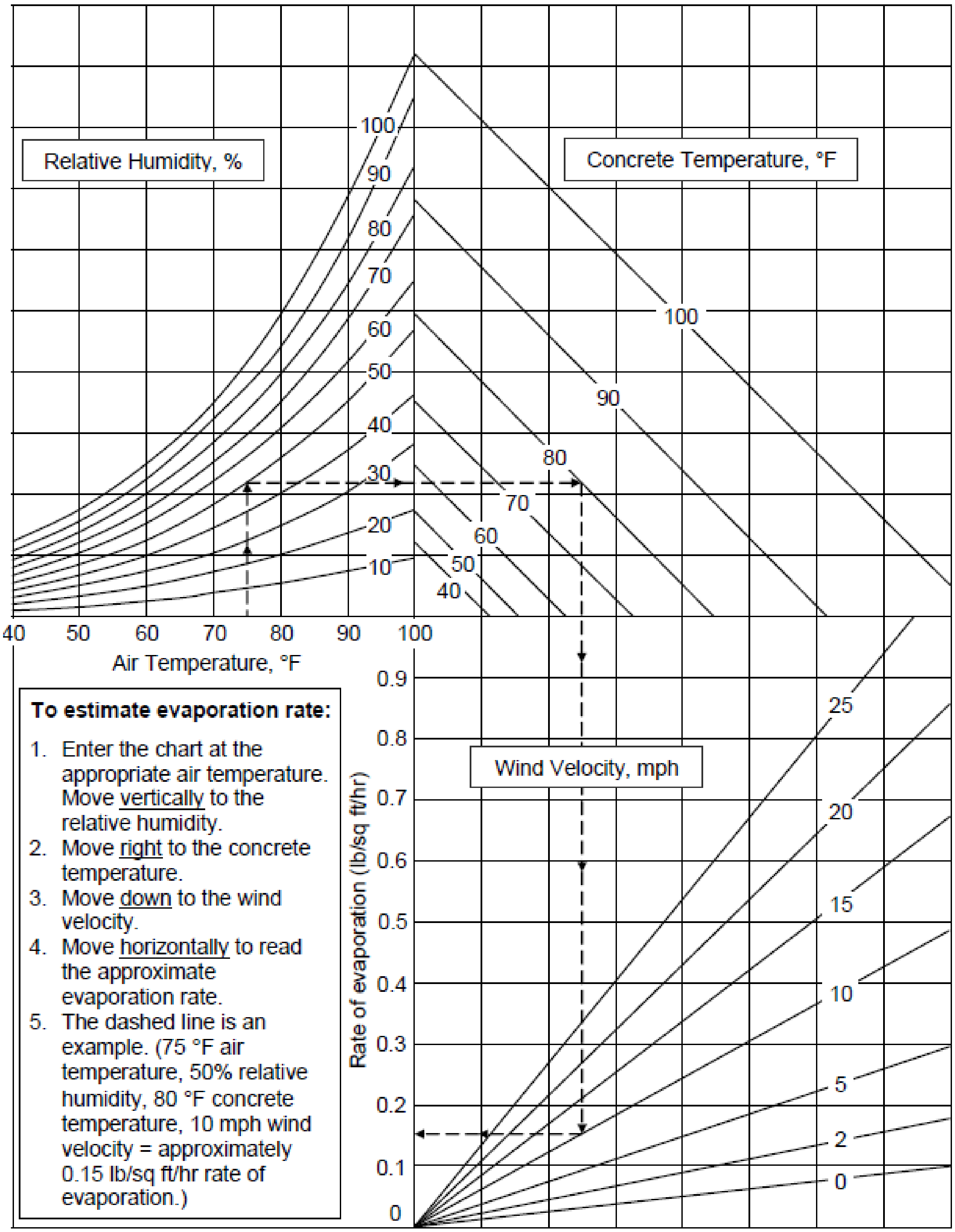
Attend a pre-placement meeting 10 days to 15 days before the slab placement to review the information and details provided in the placement and curing plan. The following project personnel are required to attend the pre-placement meeting:

(1) Contractor
(2) Engineer
(3) Concrete supplier and
(4) If required by the Engineer, the concrete pump supplier.

2.A.9.c Three (3) Hours Prior to Beginning Bridge Deck Concrete Placement

The Engineer requires the Contractor to comply with all of the following conditions prior to allowing the Contractor to begin the bridge deck concrete placement:

(1) Provide a forecast to the Engineer three (3) hours before placement. The Engineer will review the forecast for the following:
   (a) No forecasted precipitation two (2) hours prior to the scheduled placement duration, nor up to two (2) hours after the anticipated completion of the placement, and
   (b) Less than 30% chance of precipitation for the entire placement window and
(2) Only if the combination of air temperature, relative humidity, concrete temperature and wind velocity produces an evaporation rate of less than 0.20 pounds per square foot of surface area per hour, according Figure HPC-1:



[1] Based on ACI 305 R, "Hot Weathering Concreting"

FIGURE HPC-1

SB-10.1 Delete the 16th paragraph through 18th paragraphs of 2401.3.G, "Concrete Curing and Protection," and replace with the following:9

2.A.9.d Actual Bridge Deck Placement and Curing Requirements

In addition to the requirements set forth in 2461.3.G.4, "Field Adjustments," if any adjustments are necessary on site, comply with the following:

(1) The Engineer will only allow the addition of admixtures originally incorporated into the mix, except Viscosity Modifying Admixture (VMA) is allowed to adjust slump even if they were not used in the original testing

(2) The Engineer will allow a maximum of 1 gal of water additions per yd^3 of concrete on site provided additional water is available to add per the Certificate of Compliance, including any water necessary to dilute admixtures and

(3) Mix the load a minimum of 5 minutes or 50 revolutions after any additions.

The Engineer will not allow finishing aids or evaporation retarders for use in finishing of the concrete.

The Contractor is fully responsible for curing methods. Comply with the following curing methods unless other methods are approved by the Engineer in writing.

Table HPC-7
Required Curing Method Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Required Curing Method ‖
Bridge structural slab curing (3YHPCIC-S)	Low Slump Wearing Course	Conventional wet curing after carpet drag
Bridge deck slab curing for full-depth decks (3YHPCIC-M)	Epoxy Chip Seal Wearing Course or Premixed Polymer Wearing Course	Conventional wet curing after carpet drag
	Bridge Deck Planing	Conventional wet curing after carpet drag.
	Tined Texturing*	Conventional wet curing after tine texturing AMS curing Compound after wet cure period
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)*	Conventional wet curing after applying transverse broom finish AMS curing Compound after wet cure period

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

Use conventional wet curing consisting of pre-wetted burlap covered with white plastic sheeting in accordance with the following. Presoak the burlap for a minimum of 12 hours prior to application:

(1) Place the burlap to cover 100 percent of the deck area without visible openings

(2) Place the wet curing within 20 min after the finishing machine completes the final strike-off of the concrete surface

(3) If the Contractor fails to place the wet curing within 20 min, the Department will monetarily deduct $500 for every 5 min period, or any portion thereof, after the initial time period until the Contractor places the wet curing as approved by the Engineer, the Department may assess the deduction more than once

(4) Keep the slab surface continuously wet for an initial curing period of at least 7 calendar days

(5) Use a work bridge to follow the finish machine and
(6) Provide an additional center rail on wide bridges, if necessary.

Where marring of the broomed finish or tined texturing surface finish is a concern, the Engineer may authorize curing as follows:

(1) Apply a membrane curing compound meeting the requirements of 3754, "Poly-Alpha Methylsytrene (AMS) Membrane Curing Compound"
(2) Apply curing compound using approved power-operated spray equipment
(3) Provide a uniform, solid white, opaque coverage of membrane cure material on exposed concrete surfaces (equal to a white sheet of paper)
(4) Place the membrane cure within 30 min of concrete placement unless otherwise directed by the Engineer
(5) Provide curing compound for moisture retention until the placement of a conventional wet curing
(6) Apply conventional wet curing when walking on the concrete will not produce imprints deeper than $^{1}/_{16}$ in [1.6 mm]
(7) Keep the deck slab surface continuously wet for an initial curing period of at least 7 calendar days including weekends, holidays, or both if these fall within the 7-calendar-day curing period
(8) The Engineer will not allow placement of membrane curing compound on any concrete surface that expects future placement of additional concrete on that surface and
(9) If the Contractor fails to meet these requirements, the Department may reduce the contract unit price for the concrete item in accordance with 1512, "Conformity with Contract Documents."

SB-10.2 Delete 2401.3.I.2, "Crack Sealing," and replace with the following:

The Contractor is fully responsible for crack sealing all cracks identified by the Engineer in accordance with Table HPC-8.

Table HPC-8
Required Crack Sealing Requirements Based on Final Bridge Deck Surface

Bridge Deck Type	Final Bridge Deck Surface	Crack Sealing Requirements
Bridge structural slab (3YHPCIC-S) *	Low Slump Wearing Course	Seal cracks in accordance with 2401.3.I.2
Bridge deck slab for full-depth decks (3YHPCIC-M)	Epoxy Chip Seal Wearing Course or Premixed Polymer Wearing Course	See wearing course special provision
	Bridge Deck Texture Planing	Seal cracks in accordance with 2401.3.I.2 after texture planing
	Tined Texturing	Seal cracks in accordance with 2401.3.I.2
	Finished Sidewalk or Trail Portion of Deck (without separate pour above)	Seal cracks in accordance with 2401.3.I.2
* Shotblast the surface in preparation for low slump wearing course. Prior to placing the low slump wearing course, the Engineer will visually inspect the bridge structural slab, and will mark cracks that require sealing appearing on the top surface. Control the application of the crack sealer such that the maximum width of crack sealant does not exceed 1 in [25 mm]. If exceeding the permitted width of 1 in [25 mm], remove excess by means of surface grinding to prevent debonding of concrete wearing course. The Engineer requires the sealer to cure completely prior to pre-wetting of the deck, as required for placement of a low slump concrete wearing course.		

SB-10.3 Method of Measurement

If measuring bridge slab concrete by area, the Engineer will base the measurement on end-of-slab stationing and out-to-out transverse dimensions of the slab.

SB-10.4 Basis of Payment

Payment for Item No. 2401.618 "BRIDGE SLAB CONCRETE (3YHPCIC-M)" will be made at the Contract price per square foot and shall be compensation in full for all costs of forming, placing, finishing, curing, crack sealing, and all associated incidentals necessary to construct the bridge deck and end diaphragms as detailed in the Plans in accordance with these specifications.

Appendix B: Determining the Absorption, Surface Moisture, and Total Moisture of Fine Lightweight Aggregates Using a Centrifuge

The centrifuge used is the Houghton HM-E5 Centrifuge Extractor with a 9 in. bowl diameter. Note that similar models with variable speed control and the same bowl diameter are expected to yield the same results*. To obtain the absorption using centrifuge, the following series of steps should be performed:

1. Soak the aggregates for 72 hours and drain a sample using a No. 200 sieve before testing. After aggregates are drained, mix them with a scoop before taking the sample.
2. Measure the mass of the empty centrifuge bowl and record it as $\mathbf{M_1}$.
3. Tare the scale with centrifuge bowl placed on it. Add 600 grams (± 5 grams) of drained pre-wetted lightweight aggregate to the bowl. Record the resulting mass as $\mathbf{M_2}$.
4. Make sure that the material is evenly distributed inside the bowl by shaking it horizontally. This will avoid any vibration during centrifugation. Place the bowl in the centrifuge. After the filter paper ring and the lid are placed on top of the bowl, secure the assembly.
5. Run the centrifuge selecting 2000 rpm for the testing speed for a period of three minutes.
6. Remove the centrifuge bowl measure the mass of centrifuge bowl plus the aggregate inside (which now is in pre-wetted surface-dry condition), record it as $\mathbf{M_3}$.
7. By subtracting the mass of empty centrifuge bowl ($\mathbf{M_3}$) from $\mathbf{M_1}$, obtain the mass of pre-wetted surface-dry aggregate (PSD), record it as $\mathbf{M_4}$.
8. Record the weight of an empty pan for oven drying the aggregate, record it as $\mathbf{M_5}$.
9. Carefully transfer all the material to the pan, place it in an oven at 110 ± 5 ˚C (230 ± 10 ˚F) until constant mass is reached. Once aggregate is oven-dried, measure the mass of pan plus oven-dried aggregate and record it as $\mathbf{M_6}$.
10. By subtracting $\mathbf{M_5}$ from $\mathbf{M_6}$ obtain the mass of oven-dried aggregate, call it $\mathbf{M_7}$.
11. Using the equations in the results section of the provided spreadsheet, obtain the surface moisture and 72-hour absorption.

Note: The attached excel spreadsheet will automatically calculate $\mathbf{M_4}$, $\mathbf{M_7}$, Absorption, Surface Moisture, and Total Moisture when $\mathbf{M_1}$, $\mathbf{M_2}$, $\mathbf{M_3}$, $\mathbf{M_5}$, and $\mathbf{M_6}$ are entered in the cells highlighted yellow.

*****If the centrifuge has a different bowl radius, keeping the spinning time at 3 minutes, the appropriate spinning speed can be calculated from the formula below with a known bowl radius (*R*):

$R\omega^2 = 5000$ (m·radians/sec.)

Where,

R= bowl radius (meters), ω= spinning speed (radians/sec), 1 radian/sec=9.55 RPM

Absorption, Surface Moisture, and Total Moisture

Procedure	Measurement	Value
Measure mass of empty centrifuge bowl	M_1	
Measure mass of pre-wetted LWA added tared centrifuge bowl (600±5 g)	M_{WET}	
Measure mass of centrifuge bowl and PSD aggregate after centrifugation	M_2	
Calculate mass of PSD, M_{PSD}	$M_{PSD}= M_2-M_1$	
Measure mass of empty pan used for oven drying aggregate	M_3	
Measure mass of pan and oven-dry aggregate	M_4	
Calculate mass of oven dry aggregate, M_{OD}	$M_{OD}=M_4-M_3$	

Results

Calculate desired properties	Result	Value
Absorption (%)= $(M_{PSD}-M_{OD})/M_{OD}*100$	Absorption	
Surface Moisture(%)= $(M_{WET}-M_{PSD})/M_{PSD}*100$	Surface Moisture	
Total Moisture(%)= $(M_{WET}-M_{OD})/M_{OD}*100$	Total Moisture	
Water Content(%)= $(M_{PSD}-M_{OD})/M_{PSD}*100$	Water Content	

Relative Density

Procedure	Measurement	Value
Measure mass of filled pycnometer	M_{PW}	
Measure mass of PSD LWA added to tared empty pycnometer (600±5 g)	M_{PSD}	
Measure mass of pycnometer and PSD aggregate filled with water	M_{PS}	
Measure mass of empty pan used for oven drying aggregate	M_5	
Measure mass of pan and oven-dry aggregate	M_6	
Calculate mass of oven dry aggregate, M_{OD}	$M_{OD}=M_6-M_5$	

Results

Calculate desired properties	Result	Value
Relative Density (PSD)= $M_{PSD}/(M_{PW}+M_{PSD}-M_{PS})$	(PSD) Relative Density	
Relative Density (OD)= $M_{OD}/(M_{PW}+M_{PSD}-M_{PS})$	(OD) Relative Density	

Appendix C: Bridge Deck Survey Specification

1.0 DESCRIPTION.

This specification covers the procedures and requirements to perform bridge deck surveys of reinforced concrete bridge decks.

2.0 SURVEY REQUIREMENTS.

a. Pre-Survey Preparation.

(1) Prior to performing the crack survey, related construction documents need to be gathered to produce a scaled drawing of the bridge deck. The scale must be exactly 1 in. = 10 ft (for use with the scanning software), and the drawing only needs to include the boundaries of the deck surface.

NOTE 1 – In the event that it is not possible to produce a scaled drawing prior to arriving at the bridge deck, a hand-drawn crack map (1 in.= 10 ft) created on engineering paper using measurements taken in the field is acceptable.

(2) The scaled drawing should also include compass and traffic directions in addition to deck stationing. A scaled 5 ft by 5 ft grid is also required to aid in transferring the cracks observed on the bridge deck to the scaled drawing. The grid shall be drawn separately and attached to the underside of the crack map such that the grid can easily be seen through the crack map.

NOTE 2 – Maps created in the field on engineering paper need not include an additional grid.

(3) For curved bridges, the scaled drawing need not be curved, i.e., the curve may be approximated using straight lines.

(4) Coordinate with traffic control so that at least one side (or one lane) of the bridge can be closed during the time that the crack survey is being performed.

b. Preparation of Surface.

(1) After traffic has been closed, station the bridge in the longitudinal direction at ten feet intervals. The stationing shall be done as close to the centerline as possible. For curved bridges, the stationing shall follow the curve.

(2) Prior to beginning the crack survey, mark a 5 ft by 5 ft grid using lumber crayons or chalk on the portion of the bridge closed to traffic corresponding to the grid on the scaled drawing. Measure and document any drains, repaired areas, unusual cracking, or any other items of interest.

(3) Starting with one end of the closed portion of the deck, using a lumber crayon or chalk, begin tracing cracks that can be seen while bending at the waist. After beginning to trace cracks, continue to the end of the crack, even if this includes portions of the crack that were not initially seen while bending at the waist. Areas covered by sand or other debris need not be surveyed. Trace the cracks using a different color crayon than was used to mark the grid and stationing.

(4) At least one person shall recheck the marked portion of the deck for any additional cracks. The goal is not to mark every crack on the deck, only those cracks that can initially be seen while bending at the waist.

NOTE 3 – An adequate supply of lumber crayons or chalk should be on hand for the survey. Crayon or chalk colors should be selected to be readily visible when used to mark the concrete.

c. Weather Limitations.

(1) Surveys are limited to days when the expected temperature during the survey will not be below 60°F.

(2) Surveys are further limited to days that are forecasted to be at least mostly sunny for a majority of the day.

(3) Regardless of the weather conditions, the bridge deck must be completely dry before the survey can begin.

3.0 BRIDGE SURVEY.

a. Crack Surveys.

Using the grid as a guide, transfer the cracks from the deck to the scaled drawing. Areas that are not surveyed should be marked on the scaled drawing. Spalls, regions of scaling, and other areas of special interest need not be included on the scale drawings but should be noted.

b. Delamination Survey.

At any time during or after the crack survey, bridge decks shall be checked for delamination. Any areas of delamination shall be noted and drawn on a separate drawing of the bridge. This second drawing need not be to scale.

c. Under Deck Survey.

Following the crack and delamination survey, the underside of the deck shall be examined and any unusual or excessive cracking noted.

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