An ACI Technical Publication

SYMPOSIUM VOLUME

Cracking and Durability in Sustainable Concretes

SP-336

Editors:
Ralf Leistikow and Kimberly Waggle Kramer

American Concrete Institute
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Cracking and Durability in Sustainable Concretes

Sponsored by
ACI Committees 130, Sustainability of Concrete
and 224, Cracking

The Concrete Convention and Exposition
October 15-19, 2017
Anaheim, California, USA

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First printing, December 2019

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Printed in the United States of America

Editorial production: Susan K. Esper

ISBN-13: 978-1-64195-088-6

PREFACE

Cracking and Durability in Sustainable Concretes

ACI Committees 130 and 224 sponsored and moderated two sessions at The ACI Concrete Convention and Exposition – Fall 2017, held in Anaheim, California. The objective of the sessions was to review the use of innovative mixture designs which incorporated sustainable admixtures and supplemental cementitious materials, and the effect these sustainable technologies have on the cracking performance and durability of these concretes. In particular, cracking behavior in sustainable concretes or practices for mitigation of cracking in sustainable concretes was reviewed. This information was shared based on completed research and case studies of sustainable concrete mixture designs. The learning objectives of the two sessions follow:

1) Learn about innovative mixture designs that incorporate sustainable admixtures and supplemental cementitious materials;
2) Learn about the effect these sustainable technologies have on the cracking performance and durability of these concrete mixes;
3) Gain an understanding of the cracking behavior of sustainable concrete mixtures; and
4) Learn about practices used to mitigate cracking in sustainable concrete.

Twelve presentations were given, and the presenters came from all over the world. Following the sessions, some of the presenters authored papers that provided more extensive information about their research. This SP include copies of these seven research papers.

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SP-336-1

Internal Curing and Supplementary Cementitious Materials in Bridge Decks

James Lafikes, Rouzbeh Khajehdehi, Muzai Feng, Matthew O'Reilly, David Darwin

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

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

INTRODUCTION

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

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

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

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

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

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

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

RESEARCH SIGNIFICANCE

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

CRACK SURVEY PROCEDURE

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

Procedure

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

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

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

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

BRIDGES

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

Table 1—Bridge properties

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

IN-IC

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

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

IN-Control

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

IN-IC-HPC-1

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

IN-IC-HPC-2

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

IN-IC-HPC-3

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

IN-IC-HPC-4

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