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SPECIFICATIONS TO REDUCE BRIDGE DECK CRACKING

JoAnn Browning and David Darwin, University of Kansas and Kenneth F. Hurst, Kansas Department of Transportation

Research over the past several decades has addressed the causes of cracking in cast-in-place reinforced concrete bridge decks in North America(1-3) including three detailed studies by the University of Kansas (KU).(4-6) Results of these studies have provided specific guidance on needed modifications in materials and construction techniques to reduce the amount of cracking in reinforced concrete bridge decks. This guidance has been put to use during the first phase of a pooled-fund study under the direction of the Kansas Department of Transportation (DOT) in conjunction with 14 other state DOTs and the Federal Highway Administration. New specifications have been developed for use in the construction of 20 low-cracking, high-performance concrete (LC-HPC) bridge decks (15 in Kansas and 5 in partner states), with an equal number of conventional control decks to evaluate the relative performance and cost.

Specifications

Material specifications were developed using crack survey results in conjunction with construction diaries and laboratory work at KU. It is well established that settlement cracks can be reduced with increased concrete cover, smaller bar sizes, and lower concrete slump. Shrinkage cracks can be reduced by decreasing the volume of water and cement and maintaining an air content above 6 percent. Concrete specified for LC-HPC bridge decks has a maximum cement content of 535 lb/yd^3 (317 kg/m^3), a maximum water-cement ratio of 0.42, an air content of 8.0 ± 1.0 percent, and a slump of 1.5 to 3 in. (38 to 75 mm). Cement is the only cementitious material permitted. The temperature of the concrete at point of placement must be between 55 and 70°F (13 and 21°C) to control the temperature differential between the concrete, as placed, and the supporting beams. Even on a hot day in June in Kansas, concrete was placed within these specification limits using ice in the concrete and casting at night. The lower temperature also slows the setting time and allows for easier finishing of the deck. EvapoRATE(7) software is available to evaluate and document evaporation rates expected at a site.

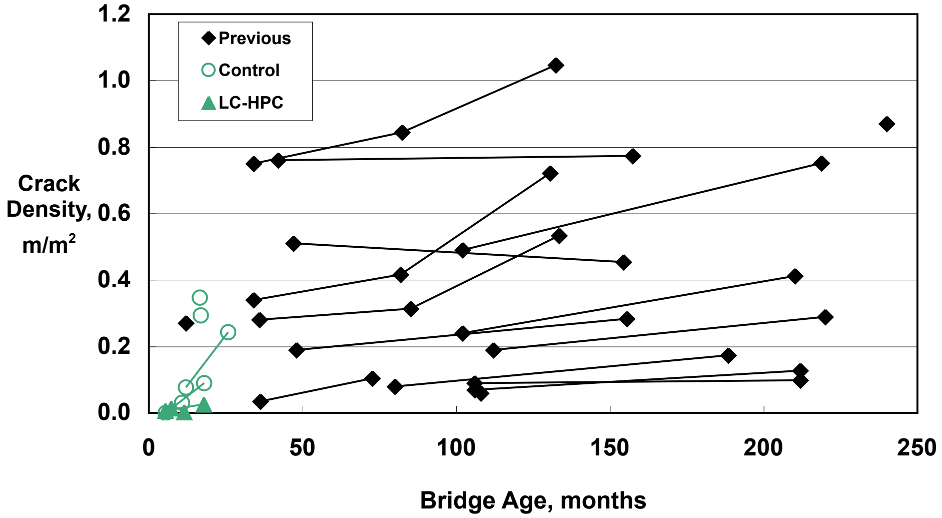
A key aspect in obtaining workable concretes with low cement contents is the use of optimized aggregate gradations (using a proven method such as the Shilstone Method,(8) or KU Mix(9)). Workability is enhanced using water-reducing and high-range water-reducing admixtures. A high-quality aggregate with a maximum absorption of 0.7 percent is specified. Bridges in Kansas have used granite from Arkansas and Oklahoma. The low absorption helps improve freeze-thaw resistance, but also helps maintain a constant slump through the pump. Concrete with a slump as low as 1.5 in. (38 mm) has been successfully pumped during this program.

To limit problems on the job, the construction specifications require that the concrete must be placed using buckets or conveyors, unless the contractor can demonstrate that low-slump concrete batched to satisfy the specifications can be pumped. Four out of the five LC-HPC bridge decks completed in Kansas have been placed using pumps, and the fifth was placed using a conveyor belt system only because the coarse aggregate had very elongated particles.

Plastic shrinkage cracking is minimized by controlling the rate of evaporation from the concrete surface. Windbreaks may be required on windy days. Fogging is required using devices mounted on the finishing equipment supplemented with hand-held fogging equipment, from time of concrete strikeoff until the concrete is covered. Fogging water, however, cannot accumulate on the concrete surface or be used as a finishing aid. Finishing is accomplished using a single-drum roller screed or a double-drum roller screed with one roller

(continued on pg. 2)

(continued from pg. 1)



Crack Densities on LC-HPC and Control Decks Compared with Crack Densities measured on Previous Crack Surveys.

removed (to minimize the cement paste that is worked to the concrete surface), with a supplementary pan/burlap drag and bullfloating, as required. In addition to fogging, contractors are required to place the first of two layers of pre-soaked burlap on the newly finished concrete within 10 minutes of strike-off and finishing. The second layer must be placed within another 5 minutes. Once the concrete has set enough to support foot traffic, soaker hoses are placed under white polyethylene sheeting for 14 days of wet curing.

One of the most significant modifications to the construction specifications has been the requirement for a qualification slab. The slab is 33 ft (10 m) long with the same design cross section as the actual deck, including the reinforcement. It is cast using the qualified concrete mix 15-45 days prior to placing concrete in the bridge deck. The motivation for requiring the qualification slab is to prevent experimentation on the bridge deck and to identify any problem areas. Meetings are held with the contractor, materials supplier, and state DOT representatives before and after placement of the qualification slab and after the placement of the bridge deck. Problems identified during qualification slab placements have included meeting material specifications for slump or temperature, accumulation of fogging water on the deck surface and use of this water as a finishing aid, handling and placement of the wet burlap, and general timing of the construction process. Lessons learned during these placements and follow-up discussions with DOT representatives and construction personnel have significantly improved the enthusiasm and participation of all parties to produce the best quality low-cracking bridge deck.

Results

Of 14 decks let in Kansas to date, construction costs for all but the first two have been about the same as those of the control decks. Crack surveys have been completed on the first three LC-HPC bridge decks in Kansas and on four control decks. The figure shows crack density, expressed in linear meters of cracking per square meter of bridge deck (m/m^2) versus the age of the deck at the time of the survey for three previous studies of monolithic bridge decks in Kansas (diamonds), new control decks (circles), and new LC-HPC decks (triangles). Symbols that are connected by lines indicate decks that have been surveyed multiple times. The amount of cracking on the LC-HPC decks is lower than that for any of the other decks and shows promise to continue the trend of low cracking for years to come.

To date, the study has been successful in identifying low-cracking portland cement concrete mixes. Several additional approaches, however, have been identified that have the potential to increase the benefits of the project, including using supplementary cementitious materials, new sources of aggregate, and new approaches to finishing. These approaches will continue to be evaluated during Phase II of this project.

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Fogging equipment is mounted on the finishing equipment.

Two layers of burlap must be placed within 15 minutes of finishing.

CONTROLLING BRIDGE DECK CRACKING IN INDIANA

Robert J. Frosch, Purdue University

Many bridges in Indiana have cracks in their concrete decks. Cracking has occurred in both negative and positive moment regions of bridges, on both the top and bottom surfaces, and can appear before or shortly after the opening of the structure to live loads. Various crack widths and amounts of cracking exist in different bridge systems including decks on both concrete and steel girders. To determine the factors affecting transverse and longitudinal bridge deck cracking as well as to develop design recommendations that minimize or prevent these types of bridge deck cracking, a research study(1) was initiated by the Indiana Department of Transportation (INDOT). The research focused on the design and construction of new bridge decks and included bridges designed by both the empirical and traditional methods.

Research

The research involved the following five phases: field evaluation; instrumentation of a typical bridge; laboratory investigation to study the effects of shrinkage and restraint on cracking, including stay-in-place forms; effect of formwork type; and effect of bar spacing and epoxy thickness on crack widths and spacings.

Based on the research, transverse deck cracking is caused by restrained shrinkage of the concrete deck. Restraint is primarily provided by composite attachment to the girders. Longitudinal deck cracking typically occurs above the edge of the girders and is caused by a combination of factors including restrained shrinkage, flexural response, and the use of a metal angle along the girder flange to support stay-in-place formwork. The angle usually has a 3-in. (75-mm) high leg turned up into an 8-in. (200-mm) thick deck and forms a crack initiation location. Since reduction of restraint is not possible due to the economic advantages of composite construction, recommendations were developed to minimize deck cracking.

Recommendations

The following recommendations were made:

A minimum 7-day wet curing process should be used to reduce overall shrinkage strains.

Drying shrinkage of the concrete mix should be minimized. This can be achieved through concrete mix design and materials selection. For example, proper aggregate selection and gradation can produce mixes with lower shrinkage.

Concrete compressive strength should be minimized. Strengths higher than specified by design are not required and can exacerbate deck cracking. Higher compressive strengths require additional cementitious materials that produce concretes with higher shrinkage, a higher tensile strength that can increase the likelihood of reinforcement yielding, and a higher modulus of elasticity that provides a larger internal restraint against shrinkage.

Additional reinforcement above current practice is required to control crack widths in concrete decks. The total amount of reinforcing steel recommended(1) is:

$$A_s = \frac{6\sqrt{f'_c}}{f_y} A_g$$

where:

A_g = gross area of section, in.^{2}

A_s = area of reinforcement in cross-section, in.^{2}

f'_c = specified compressive strength of concrete, psi.

f_y = specified yield strength of reinforcement, psi.

The purpose for this quantity of reinforcement is to prevent yielding of the reinforcement that can result in uncontrolled crack growth. For a 4000 psi (28 MPa) compressive strength concrete with a 60,000 psi (414 MPa) yield strength reinforcement, this requirement results in a reinforcement percentage of 0.63.

Closer bar spacings are required to control early age bridge deck cracking. To produce maximum crack widths in the range of 0.016 in. (0.41 mm), a maximum bar spacing of 6 in. (150 mm) was found necessary when using current cover requirements and currently accepted epoxy thicknesses of 0.006 to 0.012 in. (0.15 to 0.30 mm).

Alternatives to stay-in-place metal deck forms should be considered. These forms resulted in concrete curling that can exacerbate cracking on the top surface of the deck, provide for a crack initiation location due to the pan shape, and prevent visual inspection of the bottom deck surface. Removable formwork with a flat surface eliminates these problems.

Support of formwork through the use of an angle with a leg turned into the deck should be discontinued. As an alternative, the angle can be turned down to eliminate this discontinuity.

The recommendations outlined above have been implemented in several bridges in Indiana. Some of these projects have been accompanied by companion research studies to evaluate the performance of bridge decks incorporating the recommendations.(2) These studies clearly indicate that the proposed recommendations are effective in controlling bridge deck cracking. Furthermore, these projects demonstrate that proper control of bridge deck cracking requires consideration of materials selection, reinforcement design, and construction procedures. It should be noted that all bridge decks in Indiana now require a 7-day wet cure. While alternative deck forming methods were considered desirable, the original construction technique has been maintained at the present time due to contractor familiarity and economic considerations.

Additional research studies are ongoing to provide refinements to the recommendations and provide extension of the recommendations when fiber reinforced polymer reinforcement is specified. Preliminary findings indicate that the maximum reinforcement spacing can be increased to 9 in. (230 mm). Additional field implementations are planned with a major project being the reconstruction of I-465 around the west side of Indianapolis. It is anticipated that the results of this research and field implementation program will be integrated into design and construction specifications to enable widespread application and provide high performance bridge decks that are capable of extended service lives with lower life-cycle costs.

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CRACKING IN COLORADO BRIDGE DECKS

Yunping Xi, University of Colorado at Boulder

The presence of cracks in newly constructed concrete bridge decks in Colorado prompted the Colorado Department of Transportation (CDOT) to initiate a study to determine the extent and causes of the cracking and to identify changes needed in the material specifications, construction processes, and design specifications to alleviate the problem.

Investigation

An analysis of field inspection results collected in 2002 for 72 bridges built by CDOT between 1993 and 2000 revealed that 82 percent of the decks had defects including 37 percent with spalling and delaminations, 37 percent with unsealed cracks of either moderate size or density, and 5 percent with unsealed cracks of both moderate size and density. The analysis was confirmed with more detailed field inspections on nine newly constructed bridge decks that showed excessive cracking. The cracks widths varied from 0.01 to 0.10 in. (0.25 to 2.5 mm). The cracking was described as severe, widespread, and uniformly spaced. Typically, the cracks were oriented in the transverse and longitudinal directions. Occasionally, the cracks formed in random orientations.

The 1999 CDOT materials and construction specifications lists Class D concrete for new bridge decks, Class DT for deck topping rehabilitation, and Class SF for bridge deck overlays. The specified requirements for the concretes are shown in Table 1. In addition, the concretes were required to use an approved water-reducing admixture. Class DT concrete was required to contain at least 50 percent AASHTO M 43 No. 7 or No. 8 coarse aggregate. Class D concrete had been used since about 1976, although the original specified water-cement ratio was 0.48 maximum.

For construction, the air temperature at the deck surface was required to be between 40 and 90°F (4 and 32°C). A minimum curing period of 5 days was required.

Table 1. Concrete Requirements

Class	Minimum Compressive Strength, psi	Cementitious Content, lb/cu yd	Air Content, %	Water-Cementitious Materials Ratio
Previous Classes of Concrete				
D	4500(1)	615-660	5-8	0.44 maximum
DT	4500(1)	700 minimum	5-8	0.44 maximum
SF	5800(1)	660 minimum	4-8	0.35 maximum
New Classes of Concrete				
H	4500(2)	580-640	5-8	0.38-0.42
HT	4500(2)	580-640	5-8	0.38-0.42

1. At 28 days 2. At 56 days

Table 2. Cementitious Contents for Class H and HT Concretes

Material	Range	
	lb/cu yd	kg/cu m
Cement Type II	450-500	267-297
Fly Ash	90-125	53-74
Silica Fume	20-30	12-18
Total Cementitious	580-640	344-380

Implementation

As a result of the study, CDOT established two new classes of concrete for bridge decks without membranes—Class H concrete for exposed bridge decks and Class HT for overlays. The specified requirements for the new classes of concrete and their cementitious contents are shown in Tables 1 and 2, respectively. In addition, laboratory trial mixes for each class of concrete must have a rapid chloride permeability per AASHTO T 277 not exceeding 2000 coulombs at 56 days and must not exhibit a crack at or before 14 days in the cracking tendency test of AASHTO PP 34. The main difference in the two classes of concrete is the coarse aggregate content. Class H concrete contains a minimum of 55 percent AASHTO M 43 size No. 67 coarse aggregate, whereas, Class HT concrete contains a minimum of 50 percent size No. 7 or No. 8 coarse aggregate.

Both classes of concrete are to be placed only when the concrete temperature at time of delivery is between 50 and 80°F (10 and 27°C), the air temperature does not exceed 80°F (27°C), and the wind velocity does not exceed 10 mph (16 km/h). If it can be determined that the evaporation rate is less than 0.20 lb/sq ft/hr (1.0 kg/sq m/hr) in accordance with Fig. 2.1.5 of ACI 305, concrete placement is permitted.

During concrete placement and before final curing is started, the concrete surface is required to be kept moist at all times by fogging except fogging is not required from October 1 through April 30 if the evaporation rate is less than 0.10 lb/sq ft/hr (0.50 kg/sq m/hr). The new minimum curing period is 168 hours (7 days) and from May 1 through September 30, water curing must be used. Between November 1 and March 31, decks are to be cured by application of a membrane-forming curing compound followed by curing blankets. Decks placed in April or October may be cured by either of the above methods.

More Information

This article is based on the CDOT report entitled "Assessment of the Cracking Problem in Newly Constructed Bridge Decks in Colorado," Report No. CDOT-DTD-R-2003-3.

GREAT SALT LAKE CAUSEWAY RAILROAD BRIDGE

Anthony N. Kojundic, Silica Fume Association

The course of the Trans-Continental Railroad is virtually unchanged since surveyors originally selected the route more than 140 years ago. The only exception is a short-cut causeway that crosses the Great Salt Lake near Ogden, Utah. The earthen causeway splits the Great Salt Lake's water into two bodies. At mile marker 762.71, a 500-ft long bridge provides an opening to allow fresh water from mountain streams in the north to mix with the salt water, maintaining a uniform salinity in the lake. This is critical to the unique life there.

The causeway is a wide landfill carrying both the railroad track and an access road. The previous timber bridge was constructed in 1958. Estimated life spans of timber bridges are 30 to 50 years. For the railway bridge on the causeway, daily traffic averages 20 trains or 45 million gross tons per year. The conclusion was obvious—a replacement was needed and the decision was made to build the new bridge using concrete.

Environmental Conditions Call for High Performance Concrete

The project called for the removal of the timber bridge and replacing it with a 14-span, prestressed concrete bridge with a 100-year design service life, using high performance concrete (HPC).

Besides the significant dynamic loads from traffic, the bridge would be subject to severe exposure conditions. Freeze-thaw cycles in northern Utah, airborne salt, deicing salts, and salt water would all affect the concrete and these factors played a major role in the decision to use HPC.

HPC was selected to achieve a 100-year service life in the salty environment.

The HPC incorporated silica fume at 7 percent by weight of cement to reduce concrete permeability, slow the rate of chloride penetration, and increase electrical resistivity of the concrete. A corrosion inhibitor was used to increase the chloride threshold level at which reinforcing steel would begin to corrode. The entire Grade 60 deformed reinforcing steel was epoxy coated.

Challenging Site Logistics

A construction site in the middle of the Great Salt Lake wasn't the only logistical challenge. The project requirements included the need for the bridge and causeway to remain open to the major east-west rail traffic during the entire bridge reconstruction.

The road bridge was removed first and replaced. The track was then moved to the road bridge and the old track bridge removed and replaced. Finally, the track was moved back to the original alignment.

The wooden timber piles were replaced with 105 24-in. (610-mm) diameter steel piles, left in place, and filled with a locally produced HPC. The fifteen pile caps used cast-in-place concrete. The same mix proportions of the HPC, as shown in the table, were selected for use in the piles, pile caps, and box beams.

Precast, prestressed box beams for the superstructure were manufactured in the Dallas, TX, area and transported by rail to the construction site. The dual cell box beams with a width of 7 ft (2.0 m) ranged in length from 35 to 43 ft (10.7 to 13.1 m). Individual beams ranged in weight from 70 to 93.6 kips (32 to 42.4 Mg). The road bridge used three beams and the railroad bridge used four beams for total widths of 21 and 28 ft (6.4 and 8.5 m), respectively. The beam design allowed for track placement anywhere on the member, and was capable of supporting a Cooper E-80 live load with a maximum 30 in. (760 mm) depth of ballast. The prestressing strands were straight 1/2-in. (13-mm) diameter low-relaxation seven wire strands. The specified compressive strength of the HPC for the box beams was 4700 psi (32 MPa) at detensioning and 7000 psi (48 MPa) at 28 days.

Ready for the Next 100 Years

The causeway replacement project started in 2003 and was completed in early 2006. The Union Pacific inspects its bridges every two years, and expects that it will be 50 inspections from now until the end of the next century before another replacement bridge may be needed. This expected long life will be credited primarily to the use of HPC.

HPC Mix Proportions

Materials	Quantities	
	per yd^3	per m^3
Cement Type I	700 lb	415 kg
Silica Fume	50 lb	30 kg
Fine Aggregate$^{(1)}$	1300 lb	771 kg
Coarse Aggregate$^{(2)}$	1646 lb	977 kg
Water	233 lb	138 kg
Corrosion Inhibitor	5 gal	19 L
Retarding Admixture	21 fl oz	0.81 L
High-Range Water-Reducing Admixture	14-98 fl oz	0.5-3.8 L
Air Entraining Admixture	31.5 fl oz	12.2 L
Water-Cementitious Materials Ratio	0.31	0.31
Unit weight	145.5 lb/ft^3	2331 kg/m^3

(1) Natural river sand (2) 3/4-in. (19-mm) maximum size Class A limestone

HPC TESTS—UNRESTRAINED DRYING SHRINKAGE

Jerry Zemajtis, CTL Group

A major factor contributing to the cracking of concrete bridge decks is the shrinkage of the deck concrete. One test to measure the shrinkage of concrete is AASHTO T 160 (ASTM C 157)—Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete. This article describes the test method for concrete and its implications.

AASHTO T 160 covers the determination of length changes that are produced by causes other than externally applied forces and temperature changes in hardened mortar or concrete exposed to controlled conditions of temperature and humidity. The method is commonly referred to as the "shrinkage test," even though the measured changes may not be caused by drying shrinkage alone.

The method is useful for comparing different concrete mixtures. In such cases, the specimens must have the same dimensions. Comparing results obtained on specimens of different sizes may be difficult due to the influence of specimen size on length change. If specifications list any limits, the specimen size should also be listed.

The size of the concrete shrinkage specimens depends on the maximum aggregate size. For all aggregate passing a 2-in. (50-mm) sieve, 4x4-in. (100x100-mm) prisms are used. If all aggregate passes a 1-in. sieve (25-mm), 3x3-in. (75x75-mm) prisms are used. In both cases, the prisms are approximately 11.25 in. (285 mm) long. The test method requires an average of three prisms for each test condition.

The specimens are removed from the molds at 23.5 ± 0.5 hours after casting and are placed in lime-saturated water maintained at 73.4 ± 1.0°F (23.0 ± 0.5°C) for a minimum of 30 minutes before the initial length measurement. The initial comparator reading is taken 24.0 ± 0.5 hours after the addition of water to the mix. Then, the specimens are stored in lime-saturated water at 73.4 ± 3.0°F (23.0 ± 1.7°C) for an additional 27 days. The specimen's age is then 28 days. At that time, a second comparator reading is taken. Thereafter, the specimens are stored either in air or in water (water storage must be specified prior to testing). Water storage requires the specimens to be immersed in lime-saturated water. Air storage requires the air in the room to be maintained at a temperature of 73.4 ± 3.0°F (23.0 ± 1.7°C) with a relative humidity of 50 ± 4%. Other storage conditions may be used as long as they are appropriately documented in the report. During storage, length change measurements are taken at 4 days and 1, 2, 4, 8, 16, 32, and 64 weeks after initial curing. Results are presented as strain verses time.

Because the initial reading is taken before the specimens are immersed in water, any length change that takes place while the specimens are in the water will be included in the reported strains. For this reason, a modified method is sometimes used, in which the length change is calculated from the reading taken at 28 days.

The length change measured on the prisms under constant environmental conditions does not equal the shrinkage that occurs in a bridge deck. Other factors such as deck thickness, internal restraint from reinforcement, external restraint from beams and diaphragms, variable environmental conditions, and deck curing conditions affect the shrinkage of a real deck. The test, however, does provide a means to compare the unrestrained drying shrinkage of different concretes.

EDITOR'S NOTE

This article is the seventh in a series that describes tests for use with HPC. Previous articles appeared in Issue Nos. 36, 37, 39, 40, 42, and 45.

ERRATA

HPC Bridge Views No. 42, Page 2: The Rigolets Pass Bridge redesign used BT-78 girders spaced at 12.6 ft (3.83 m).

FUTURE ISSUES

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