Low-Cracking, High-Performance Concrete Bridge Decks

Case Studies over First 6 Years

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Cracks in concrete bridge decks provide easy access for water and deicing chemicals that shorten the life of the deck, and field surveys show that the problem has become progressively more severe since at least the 1980s. A two-phase, 10-year Pooled Fund study to minimize cracking in bridge decks is now under way. Twenty bridge decks have been constructed in the program to date. Comparison with conventional decks shows that the techniques embodied in low-cracking, high-performance concrete (LC-HPC) bridge deck specifications have been highly successful in reducing cracking in bridge decks. The results also show that high-slump high-strength concretes result in greater cracking in bridge decks than low-slump, moderate-strength concretes and that concrete temperature control and early application of curing counteract the negative effects of casting concrete under high-temperature conditions. Early owner and contractor buy-in is needed for successful LC-HPC bridge deck construction, and top performance requires the adherence to all aspects of the specifications.

Bridge deck cracking has been widely recognized as a problem since at least 1970 (*1*), and field surveys now show conclusively that because of changes in materials and construction practices, the problem has become progressively more severe since at least the early 1980s (*2–6*). Cracks are not only unsightly but can severely compromise the durability of the decks. In freeze–thaw climates, they provide access for water, increasing the potential damage to the concrete, and in the presence of deicing chemicals, they severely compromise the corrosion protection provided by the concrete to the reinforcing steel (*7*). Recent research demonstrates that even epoxy-coated bars are affected, with bars located at cracks exhibiting significantly more disbondment between the epoxy coating and the reinforcement than bars located in uncracked concrete (*8*).

Research performed at the University of Kansas beginning in 1991 on bridges constructed from the middle 1980s to the present provides strong guidance on how to reduce cracking. The results of that research provided impetus for initiating a two-phase, 10-year Pooled Fund study joining 19 state departments of transportation, the Federal Highway Administration, and industry (*9, 10*). The study involves a combination of laboratory and field research to develop materials, construction, and structural specifications and to construct low-cracking, high-performance concrete (LC-HPC) bridge decks. To date, 20 bridge decks have been built, 14 in Kansas and six in partner states, using a full complement of best practices. All but one of the bridges has a companion control bridge for comparison. The majority of the decks have been cast on steel girder bridges, acknowledged as the bridge type exhibiting the greatest degree of cracking (*1*); three decks have been placed on precast girder bridges.

Important lessons have been learned during the construction of the decks, and eight of the LC-HPC decks are now old enough to allow the success of the methods to be evaluated based on reductions in deck cracking. This paper summarizes the background for the study and the specifications for the decks and describes the principal lessons learned. The results demonstrate that the methods have been highly successful in reducing cracking in bridge decks.

BACKGROUND

The groundwork for the current effort was laid during three bridge deck cracking studies of composite steel girder bridges performed in Kansas over an 11-year period starting in 1991 (*2, 4, 6*). The studies included crack surveys of 76 bridges, involving 160 individual concrete placements, and a total of 139 surveys, so that most decks were evaluated more than once. Three deck types, decks placed monolithically and decks with conventional high-density and silica fume overlays, were evaluated. The results of the surveys were correlated with the structural designs, materials and construction specifications, information from construction diaries, and data from material test reports. The correlations indicate that the principal factors in bridge deck cracking include age, bridge deck type, material properties, site conditions (principally temperature), curing, and date of construction (*5, 6*).

Age

Bridge deck cracking, expressed in linear meters of crack per square meter of bridge deck, is shown for monolithic decks in Figure 1 (*6*). This unit of measurement was established in the earliest studies when Kansas was still an "SI" state (*2*) but has proven to be a useful and clearly understandable measure of cracking and, therefore, continues to be used. The crack densities range from 0.04 to 1.05 m/m^2. As shown in Figure 1, bridge deck cracking increases slowly with age.

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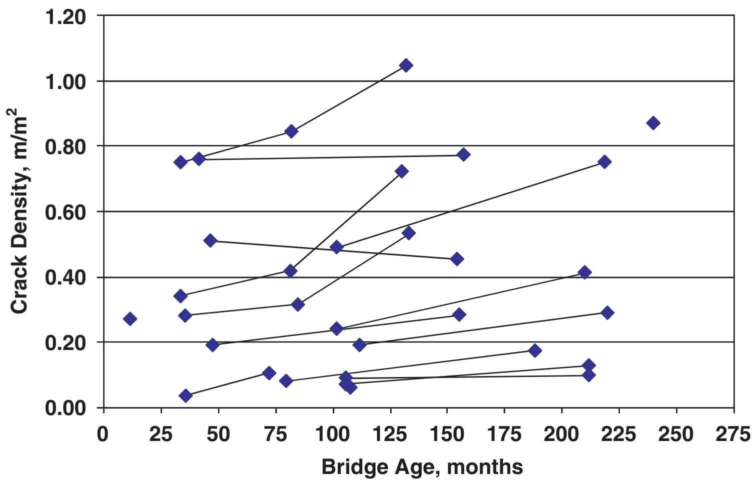

FIGURE 1 Crack density of monolithic bridge decks versus bridge age. Observations connected by lines indicate same bridge was surveyed multiple times (*6*) (1 m/m^2 = 0.305 ft/ft^2).

The figure also shows, however, that cracking within the first 3 years provides a good prediction of long-term cracking, out to 20 years. Thus, controlling early cracking has real potential for controlling long-term cracking.

Bridge Deck Type

In terms of bridge deck type, the older monolithic decks consistently exhibit less cracking than the (presumably) higher-performance, high-density conventional overlay and silica fume overlay decks. Increasing silica fume content from 5% to 7% in the overlay resulted in an increase in cracking (*6*).

Material Properties

An evaluation of material properties shows that an increase in water content, cement content, or the combination of the two (cement paste) results in a significant increase in cracking, especially for cement paste contents in excess of 27% by volume. Higher slump, which has been correlated closely with increase in settlement cracking (*11*), correlates closely with increases in crack density. Cracking also increases with higher concrete compressive strengths, with approximately three times as much cracking occurring for decks with nominal compressive strengths of 6,500 psi than for decks with nominal compressive strengths of 4,500 psi, as represented by laboratory cured cylinders for specimens made at the job site (*5, 6*). Air contents of 6.5% or more result in significantly lower cracking than lower air contents, presumably because increased air content improves workability without adding to shrinkage.

Site Conditions

High maximum air temperatures, which result in an increased potential for both plastic shrinkage and thermal cracking, and an increase in the range of air temperature on the day of construction, which also increases the potential for thermal cracking, correlate with increasing crack densities (*4, 6*).

Date of Construction

One of the most interesting observations involves the date of construction. For both monolithic and conventional high-density overlay bridge decks, newer decks consistently exhibit more cracking than older decks. In fact, bridge decks cast between 1984 and 1987 currently exhibit less total cracking than those constructed in 2002. Only decks with silica fume overlays counter this trend. The downward trend in crack density for the silica fume overlay decks can be tied to the imposition of tighter control of early-age evaporation, limiting the potential for plastic shrinkage cracking, and the institution of improved curing procedures, which can reduce total drying shrinkage.

The causes of the increase in cracking in newer bridge decks are multifold. Cracking can be tied to changes in materials and construction procedures and, in many ways, to an evolving approach to construction that emphasizes ease and lower first cost without always considering longer-term effects. Over the past 25 years, cement has been produced with progressively greater fineness (*12*) [shown to increase shrinkage cracking (*13, 14*)], concrete slump has increased (resulting in increased settlement cracking), concrete placement has changed from the use of buckets and conveyor belts to pumps (the latter requiring increased cement paste contents), and vibrating screeds have given way to roller screeds (the latter in conjunction with the use of higher slump concretes). Figure 2 illustrates the change in slump over time. In 1984, Kansas bridge decks were placed using concrete with slumps ranging from 1½ to 2½ in. (40 to 55 mm). Over the years, the average slump increased to approximately 3 in. (75 mm) by 2002 and then rapidly rose with the introduction of superplasticizers to values as high as 9 in. (230 mm). The increase in slump is of special importance because, as shown in Figure 3, cracks are principally transverse, directly above and parallel to reinforcing steel, suggesting that settlement cracking plays a principal role in bridge deck cracking.

Laboratory Studies

Lab studies indicate not only that low cement and water contents (high aggregate contents) reduce total shrinkage, but that longer

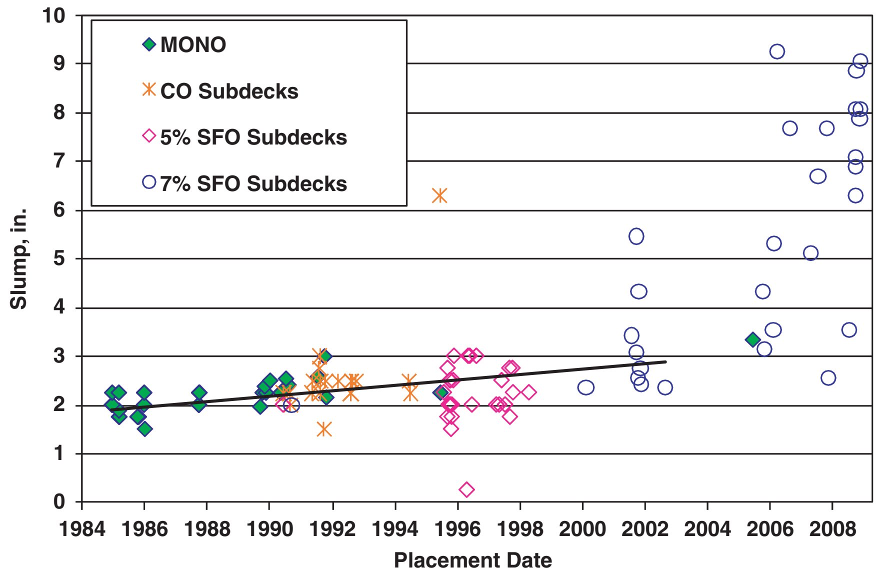

FIGURE 2 Slump versus date of placement for bridge decks in Kansas: MONO = monolithic, CO = conventional overlay, SFO = silica fume overlay (1 in. = 25.4 mm).

curing (for example, increasing the curing period from 7 to 14 days) reduces total shrinkage (*14–16*) and improves concrete durability (*17*).

Overall Approach

Based on these observations and in conjunction with long-term discussions with contractors, designers, material suppliers, and Kansas Department of Transportation engineers, a strategy was developed to minimize cracking through the use of best practices covering design, materials, and construction (*16, 17*). The overall approach includes the use of low-slump concrete with low cement and water contents and moderate rather than high strength; construction procedures that maximize consolidation and minimize the potential for plastic shrinkage cracking; and early initiation of and an increase in the length of curing with the goal of minimizing both early age and long-term cracking.

SPECIFICATIONS

The goal of the specifications for LC-HPC bridge decks is to minimize concrete cracking in both plastic and hardened concrete through the use of best practices. The specifications cover materials and construction and to a small extent design. A key concept in the development of LC-HPC bridge deck specifications is the need to distinguish between best practices that apply to concrete in general and best practices that take into account the aspects that make bridge decks unique.

Materials and Design

Because bridge decks are slabs with horizontal reinforcement and because volume changes are highly restrained by the supporting bridge girders, it is important to minimize the potential for settlement cracking over the reinforcing bars in plastic concrete and drying shrinkage in hardened concrete. High-slump concretes undergo more settlement after initial consolidation than low-slump concretes. Settlement shrinkage cracking can thus be minimized by limiting the slump of the concrete. This point is supported by research evaluating the role of slump in settlement cracking (*9*) and the observed increase in bridge deck cracking as slump increases (*2–6*). For this reason, the designated slump range for LC-HPC is 1½ to 3 in. (40 to 75 mm). In the specifications for the Phase I decks described in this paper, a maximum slump of 4 in. (100 mm) was permitted with the understanding that the mix would be modified to return the slump to the designated range. This provision, however, was interpreted to mean that a slump of 4 in. (100 mm) was allowable in all cases.

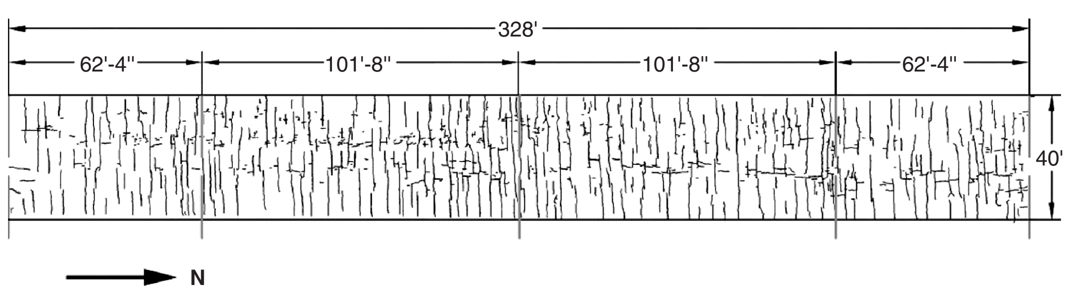

FIGURE 3 Example bridge deck crack map (*6*) (1′ = 1 ft = 0.305 m; 1″ = 1 in. = 25.4 mm).

To tighten control, the specifications for Phase II have reduced the maximum slump to 3½ in. (90 mm).

To limit the potential for shrinkage cracking, a maximum cement content of 540 lb/yd^3 (320 kg/m^3) is specified along with a water–cement ratio range of 0.43 to 0.45 to achieve moderate but not high strength. An air content of 8% ± 1½% is used to aid workability and to produce a hardened concrete with high durability, while helping to limit strength. The limit on strength is important because lower-strength concretes tend to creep more than higher-strength concretes, even at the same ratio of stress to strength, and creep helps relieve tensile stresses and thus minimize the potential for cracking. Aggregate plays an important role in producing workable, placeable concrete with the low slumps and relatively low cement content used for LC-HPC concrete. A 1-in. (25-mm) maximum size aggregate is used to reduce the aggregate surface area, and the aggregate gradation is optimized by ensuring that middle-sized aggregate particles are included in the mixture. Achieving the latter usually requires three or four aggregates. A low-absorption aggregate is also used to improve durability and to limit slump loss when the concrete is pumped.

To limit the potential for thermal cracking, often caused by placing warm concrete on colder girders, the concrete temperature at the time of placement must be in the range of 55°F to 70°F (13°C to 21°C). Limiting the temperature of the concrete also slows the rate of evaporation, thus lowering the potential for plastic shrinkage cracking. Under no conditions may the concrete temperature exceed the air temperature (taken as a measure of girder temperature) by more than 25°F (14°C).

To accommodate the 1-in. (25-mm) maximum size aggregate, the bottom cover of the reinforcing steel is set to a minimum of 1½ in. (40 mm). Concrete testing and acceptance criteria are clearly defined.

Construction

The specifications for LC-HPC bridge deck construction were developed to optimize placing, consolidating, finishing, and curing techniques. The specifications require the contractor to place the concrete using buckets or conveyor belts unless it can be demonstrated, in advance, that the concrete can be pumped. In spite of this requirement, nearly all of the concrete used on LC-HPC bridge decks has been pumped. To limit the loss of entrained air, the specifications limit the drop from a bucket or at the end of the conveyor to 5 ft (1.5 mm) to the deck and require the use of a bladder valve on concrete pumps. To help obtain thorough consolidation, and thereby minimize the potential for settlement cracking, bridge decks are consolidated using vertically mounted internal gang vibrators, a procedure that has been used successfully in Kansas for 30 years. Decks are finished using the minimum effort required and covered within 10 min of strike-off with fully saturated burlap. After the concrete has set, the burlap is maintained in a wet condition by using soaker hoses and covering with plastic. Coupled with the controlled concrete temperature, the early application of the wet burlap has proven highly effective in preventing plastic shrinkage cracking. Wet curing continues for 14 days and is followed by the application of a curing compound, which is used to slow the rate of evaporation. Slower evaporation provides the concrete additional time to creep, thus lowering the potential for early age shrinkage cracking. The hardened decks are grooved to provide skid resistance.

Before construction of the bridge deck, both the concrete and the construction procedures must be qualified, the concrete using a qualification batch and the construction procedures using a qualification slab. The qualification slab is the full width of the bridge deck, 33 ft (10 m) long, and cast on grade with a full complement of reinforcement. Depending on the size of the project and the number of bridges to be constructed, the qualification slab adds between 1.5% and 6% to the cost of deck construction. In constructing the slab, the contractor must demonstrate that the concrete can be placed, consolidated, finished, and cured in accordance with the specifications.

FIELD EXPERIENCE IN ACHIEVING GOALS

Experience during bridge construction has emphasized certain aspects that aid in achieving minimal cracking in bridge decks. Principal among these has been the development of a high-quality concrete and training construction personnel. In both cases it is important not to "practice on the bridge deck," as is often the case in construction when new materials or procedures are used. The production of a qualification batch and the construction of a qualification slab have proven invaluable in successfully completing LC-HPC bridge decks.

As described in the previous section, the concrete specifications are designed to minimize plastic shrinkage and settlement cracking in plastic concrete and drying shrinkage and thermal cracking in hardened concrete. A low-slump mix that is placeable and finishable must be carefully proportioned and evaluated before deck construction. The production of a qualification batch several weeks in advance of deck construction helps ensure that the concrete supplier can produce concrete that meets the specifications. In two cases where a "shortcut" was taken by not requiring that the temperature requirement be satisfied in an early qualification batch, the suppliers later had difficulty producing in-specification concrete for the qualification slabs. In one case in a partner state where the qualification batch was not successfully produced before deck construction, difficulties on the day of construction stopped deck placement. At times, the rather conventional strength of the mix has led suppliers and contractors to believe that special attention to mix proportions is not needed. Thus a key lesson closely tied to the qualification batch is the need to emphasize that special attention is needed to produce LC-HPC, just as it is for other high-performance concretes.

The qualification slab has also demonstrated its importance on multiple occasions. Even when the specifications have not been perfectly executed on the slab, the shortcomings on the part of contractor personnel have been apparent enough so that the problems have been corrected when the deck is constructed. The qualification slab also provides an excellent opportunity to evaluate the placing procedure, whether by pump, conveyor belt, or bucket, all of which have been used on LC-HPC bridge decks. The principal deviation on LC-HPC decks from usual construction procedures in Kansas has been the rapid initiation of curing, that is, the placement of pre-soaked burlap within 10 min of concrete strike-off. Experience now shows that contractor personnel can be trained in a relatively short time to place the burlap and that this training is most effective if completed before actual deck construction.

Another important lesson is the need to clearly define the testing schedule and to communicate how out-of-specification concrete will be handled. The best results involve thorough testing of the first several trucks delivered to the job site, with testing performed on concrete discharged directly from the truck. Later in the placement, testing is performed on the deck itself. On the 14 Kansas bridges, concrete that arrives at the job site with a high slump, air content, or both has in most cases been successfully placed after it has been held at the job site for a period of time to allow the slump and air content to decrease into the ranges permitted by the specification.

When concrete is placed, it is important to select placing equipment and methods to maintain the properties of concrete rather than to modify the properties of concrete based on any weaknesses in placement methods. Along this line, early on in the project it became clear that concrete pumps needed to be fitted with bladder valves or s-hooks to limit loss of air. Both proved quite successful, limiting air loss between the pump and discharge to ½%. The drop of concrete from the end of conveyors must also be limited to minimize air loss, with current requirements limiting the drop at a maximum of 5 ft (1.5 m).

Delays in placing the deck when reaching diaphragms or end walls can be overcome by placing those portions of the bridge in advance of the deck. This may require additional placement equipment and should be addressed before beginning construction of the deck.

High-density consolidation using vertically mounted internal gang vibrators is very effective when the vibrators are operated in accordance with good practice. To obtain a high-quality deck, the rule on finishing has become "less is more." Using minimal finishing effort before placing the burlap minimizes the quantity of the cement paste worked to the surface, as well as the time to burlap placement.

To obtain good curing it is important that the burlap be fully saturated and placed in a timely manner by trained personnel—the same crew and supervisor who placed the qualification slab. After placement, the burlap must be kept continuously wet, initially by a water spray and, after the concrete has set, by soaker hoses. The burlap and soaker hoses are covered with white plastic within 12 h of placement, and the deck is checked every 6 h throughout the 14-day curing period. Best success with spraying the curing compound to slow the rate of evaporation following the curing period has been obtained by using an opaque, rather than clear, curing material, since the former makes it much easier to see if the surface has been completely coated.

LESSONS LEARNED BASED ON DECK PERFORMANCE

The oldest LC-HPC decks at the time of this writing are less than 4 years old with the majority under 2 years old. Eight bridges, along with their companion control bridges, however, are old enough to draw important lessons.

Most important among these lessons is that the techniques for reducing cracking described in this paper are highly effective. Closely tied to this observation is another: It takes at least 2 years for the full extent of cracking to become evident, even for bridges that eventually exhibit very high crack densities.

Crack surveys are performed by marking cracks directly on the bridge deck and transferring those cracks to a crack map that is later scanned and digitized to determine a crack density. The details of the procedures for the surveys are described in Lindquist et al. (*6*).

With reference to Figure 1 showing results of the first three surveys in Kansas, Figures 4 through 7 illustrate the success of the procedures. In each figure, two LC-HPC bridges (with the designation KU) are compared with the companion control bridges, all of which had silica fume overlays. In some cases, the decks were constructed in multiple placements, such as the deck designated as Control 1-2 (Figure 4), which was completed in two placements, p1 and p2, as was bridge KU 1. In this case, the control bridge has performed quite well; LC-HPC bridges KU 1 and KU 2 are performing even better and as well as the very best decks shown in Figure 1. Similar performance is illustrated in Figures 5, 6, and 7 for bridges of each type designated as 3 to 7 and 11. As shown in Figure 6, KU 6 exhibits the highest crack density of any of the LC-HPC decks. The very young Control 6, as well as Control 5, however, exhibit even greater cracking and do so at an age of less than 12 months.

As shown in Figure 2, there has been a general increase in the slump of concrete used on bridge decks over the past 25 years. It is likely that the resulting increase in concrete settlement has been a principal cause for the increase in deck cracking observed over the same period. The LC-HPC decks in this project have not been immune to this trend, with the majority of the decks having average slumps in excess of the 3 in. (75 mm) maximum for the designated slump range. Of particular interest is the observation that crack density increased significantly for decks having 70% or more of the slump tests over 3½ in. (90 mm), as shown for four placements in Figure 8. The crack density in Figure 8 has been age-corrected to 78 months, the mean age of all decks included in Lindquist et al. (*6*), by accounting for the average rate of change in crack density. Because of the gradual change in slump over the past 25 years, most construction crews are not used to working with stiffer concretes. The finishing equipment, previously dominated by vibrating screeds, now consists

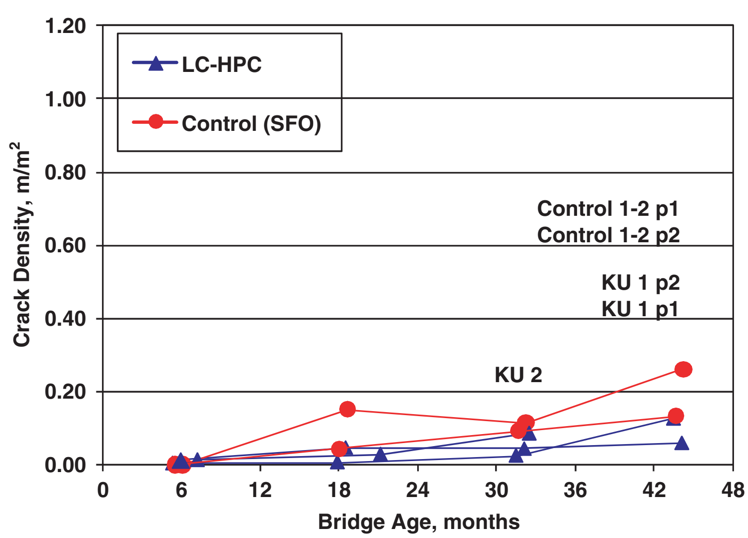

FIGURE 4 Crack density versus age for bridge decks KU 1 and 2 and Control 1-2 (p = placement; 1 m/m^2 = 0.305 ft/ft^2).

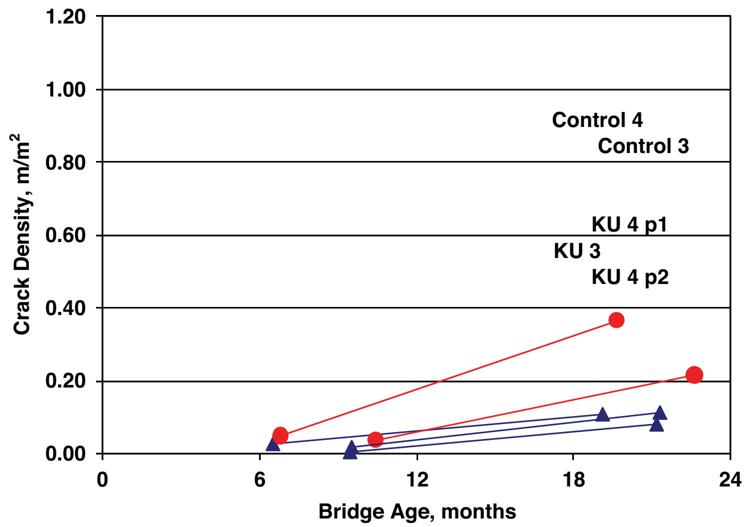

FIGURE 5 Crack density versus age for bridge decks KU 3 and 4 and Control 3 and 4.

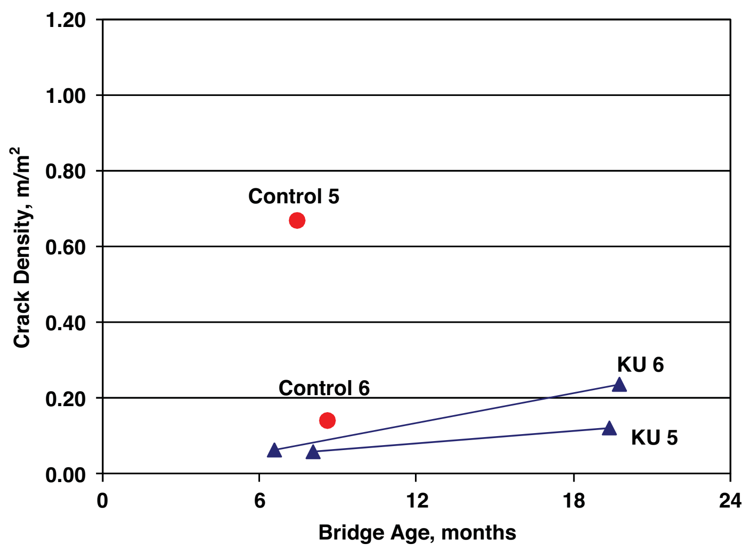

FIGURE 6 Crack density versus age for bridge decks KU 5 and 6 and Control 5 and 6.

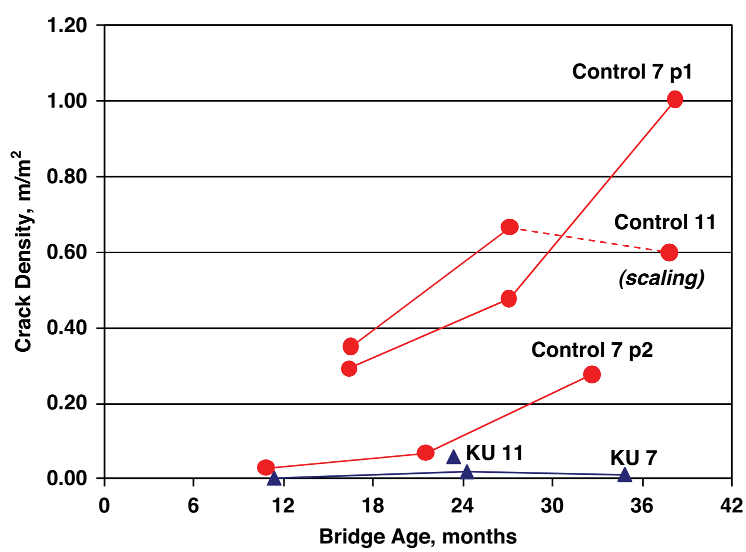

FIGURE 7 Crack density versus age for bridge decks KU 7 and 11 and Control 7 and 11 (p = placement). Reduced crack density on Control 7 resulting from scaling of the surface limited the visibility of some cracks.

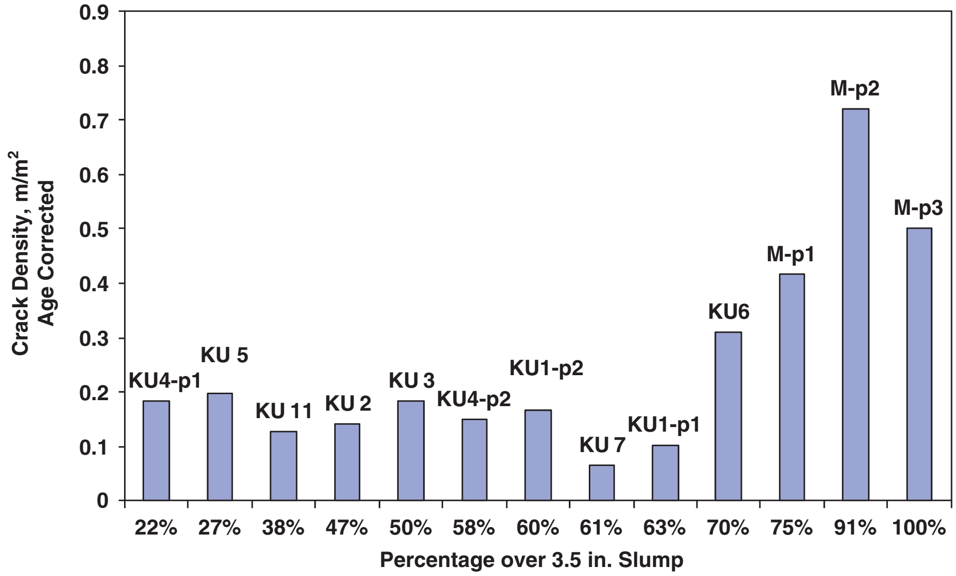

FIGURE 8 Age-corrected crack density versus percentage of slump tests with values greater than 3.5 in. (90 mm).

of roller screeds. These screeds are not the heavy-duty screeds used for pavement construction but rather lower-cost, lighter screeds. Because high-slump concrete results in an increase in settlement cracking, the use of construction techniques tailored for low-slump concrete may have the potential to significantly improve bridge deck performance in the long term.

As observed in the earlier studies, an increase in concrete strength corresponds with an increase in crack density for the eight LC-HPC decks. As shown in Figure 9, an increase in compressive strength from a nominal value of 4,000 psi (28 MPa) to a nominal value of 6,000 psi (41 MPa) results in three times as much cracking. On a positive note, the crack densities illustrated in Figure 9 are consistently below those observed on earlier monolithic bridge decks, as can be seen by comparing Figures 4 through 7 with Figure 1.

As described earlier, a clear trend had been observed between crack density and the high air temperature and the air temperature range on the day of construction. As shown in Figure 10 for LC-HPC decks, the combination of concrete temperature control on the concrete and the early application of curing seems to have removed the effects of air temperature, including the effects of plastic shrinkage and thermal cracking.

For one bridge involving three placements (see M placements in Figure 8), the contractor refused to follow the specifications and was not required to do so by the owner's representatives. The only aspect of the specification that was followed was the use of an LC-HPC concrete mix. The mix, however, was not truly optimized and, as a result, was difficult to place. The contractor consistently placed the concrete with high slumps, used poor consolidation

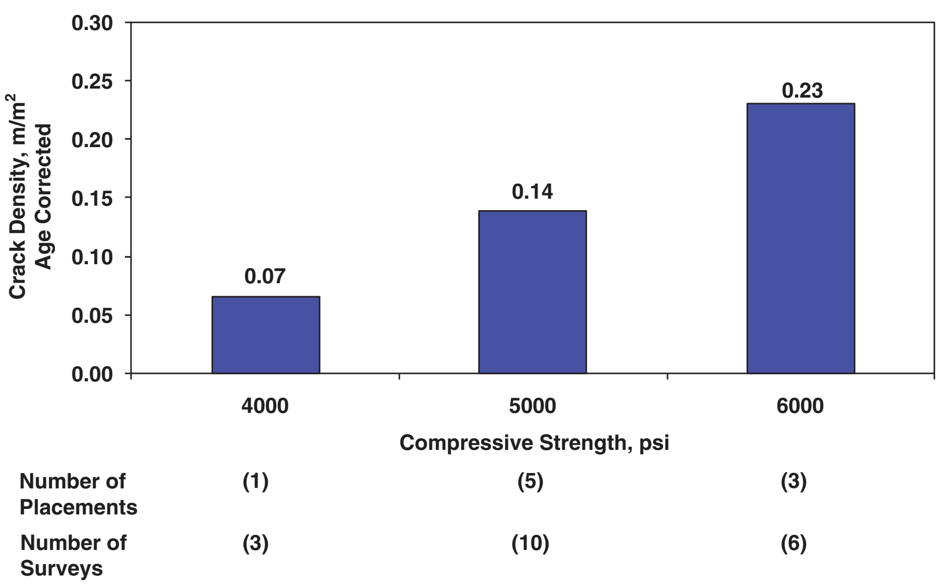

FIGURE 9 Age-corrected crack density versus compressive strength for LC-HPC bridge decks (1 m/m² = 0.305 ft/ft²; 1 psi = 0.00069 MPa).

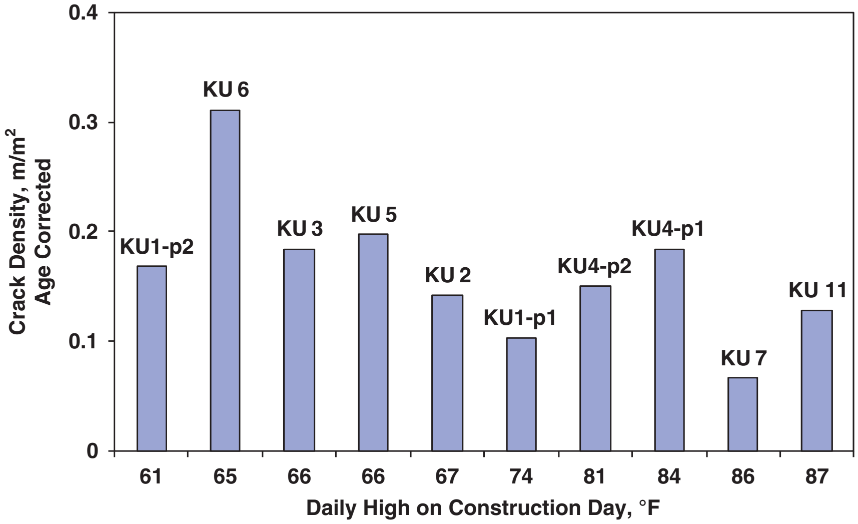

FIGURE 10 Crack density versus daily high temperature on day of construction [temperature in °F = temperature in °C × (5/9) + 32].

techniques, and overfinished the concrete, with the latter resulting in delayed placement of the burlap. All three placements of the deck exhibit very high crack densities. The effect can be seen in Figure 8 for the placements with 75%, 91%, and 100% of the slump tests exceeding 3½ in. (90 mm). Another key lesson for this deck is that buy-in to the specifications by both the owner and the contractor is a necessity for successful construction of low-cracking bridge decks. When the observations are taken together, it becomes clear that best performance requires adherence to all aspects of the specifications.

SUMMARY AND CONCLUSIONS

The University of Kansas, in conjunction with 19 state departments of transportation, the Federal Highway Administration, and industry groups, has embarked on a two-phase, 10-year Pooled Fund study to minimize cracking in bridge decks. Twenty bridge decks have been built to date, with 14 in Kansas and six in partner states. Those decks provide a clear picture of steps that can successfully reduce cracking in bridge decks.

The following conclusions are based on the construction experiences and evaluations of the bridge decks during the first 6 years of the study:

1. The techniques embodied in the low-cracking, high-performance concrete bridge deck specifications are effective in reducing bridge deck cracking.
2. Prior approval of the concrete using a qualification batch and requiring that the contractor demonstrate construction techniques in advance of the bridge deck using the qualification slab are highly effective in ensuring that best practices are followed.
3. High-slump, high-strength concrete will result in greater cracking in bridge decks than low-slump, moderate-strength concrete.
4. Concrete temperature control and early application of curing appear to counteract the negative effects of casting concrete under high-temperature conditions.
5. Early owner and contractor buy-in is essential for successful LC-HPC bridge deck construction.
6. Top performance requires adherence to all aspects of the specifications.

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