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Control of Cracking in Bridge Decks: Observations from the Field

ABSTRACT: Crack surveys of bridge decks, performed over a 10-year period in northeast Kansas as part of three studies, provide strong guidance in identifying the parameters that control cracking in these structures. The surveys involve steel girder bridges—bridges that are generally agreed to exhibit the greatest amount of cracking in the concrete decks. The surveys include monolithic decks and decks with silica fume and conventional concrete overlays. The study demonstrates that crack density increases as a function of cement and water content, and concrete strength. In addition, crack density is higher in the end spans of decks that are integral with the abutments than decks with pin-ended supports. Most cracking occurs early in the life of a bridge deck, but continues to increase over time. This is true for bridges cast in both the 1980s and the 1990s. A key observation, however, is that bridge decks cast in the 1980s exhibit less cracking than those in the 1990s, even with the increase in crack density over time. Changes in materials, primarily cement fineness, and construction procedures over the past 20 years, are discussed in light of these observations. A major bright spot has been the positive effect of efforts to limit early evaporation, suggesting that the early initiation of curing procedures will help reduce cracking in bridge decks.

KEYWORDS: bridge decks, concrete construction, concrete mix design, cracking, shrinkage

Introduction

In 2002, it was estimated that the annual direct cost of corrosion in highway bridges was $8.3 billion, with indirect costs to users due to traffic delays and lost productivity, estimated to be 10 times as much (Yunovich et al., 2002). A significant portion of that cost can be tied directly to replacement costs for bridge decks, which are damaged principally due to corrosion of reinforcing steel caused by deicing chemicals, primarily sodium chloride and calcium chloride.

Cracks in bridge decks provide the principal avenue for deicing chemicals to reach the reinforcing steel. Chloride surveys performed over the past six years in Kansas demonstrate that, regardless of the bridge deck type, intact concrete provides excellent protection for the reinforcing steel from deicing chemicals. At a depth of 3 in., only two out of the 50 bridges sampled (ages to 20 years) had chloride contents equal to or above the chloride corrosion threshold for conventional reinforcing steel. This picture changes markedly when chloride samples are taken at crack locations, where the chloride corrosion threshold is attained in some bridges within 12 months of construction.

To gain a better understanding of the extent of cracking in bridge decks, surveys have been undertaken in Kansas over the past 10 years, as reported by Schmitt and Darwin (1995, 1999), Miller and Darwin (2000), and this paper. The surveys have been limited to steel girder bridges, the bridge type that generally exhibits the greatest amount of deck cracking (*Durability of Concrete Bridge Decks*, 1970; Cheng and Johnston, 1985; Perfetti, Johnston, and Bingham, 1985; Krauss and Rogalla, 1996). The surveys include 16 monolithic and 60 two-layer bridge decks, the latter with conventional high-density concrete (30) and silica fume concrete (30) overlays. The 76 bridges represent 160 individual concrete placements. Of the bridges surveyed, 13 monolithic, 16 conventional overlay, and 20 silica fume overlay bridge decks have been surveyed two or more times.

Concrete can crack before setting (settlement and plastic shrinkage cracking) and can crack for a number of reasons in its hardened state. Cracking is influenced by ambient conditions during construction, concrete mixture proportions and materials, construction procedures, structural design, and loading. The balance of this paper describes the techniques used in the surveys and then addresses the effects on cracking of age, materials, construction practices, and the degree of fixity at the abutments.

Survey Techniques

The procedures for determining the crack density on bridge decks have been developed with the goal of providing consistent measurements that minimize differences due to changes in survey crew personnel. Bridges are surveyed only on clear days in which the temperature is 16°C (60°F) or higher. The weather must be at least partly sunny, and the deck must be totally dry. Surveys are undertaken by crews of three to six individuals. Prior to making the survey, the deck surface is marked at 5 ft intervals in both directions. Cracks must be visible without the inspector viewing the deck any closer than is possible by bending at the waist. Once a crack is identified, it is marked with a lumber crayon; the continuation of a crack may be marked if it is visible to the individual as he or she marks the crack. The information on the deck is then transferred to

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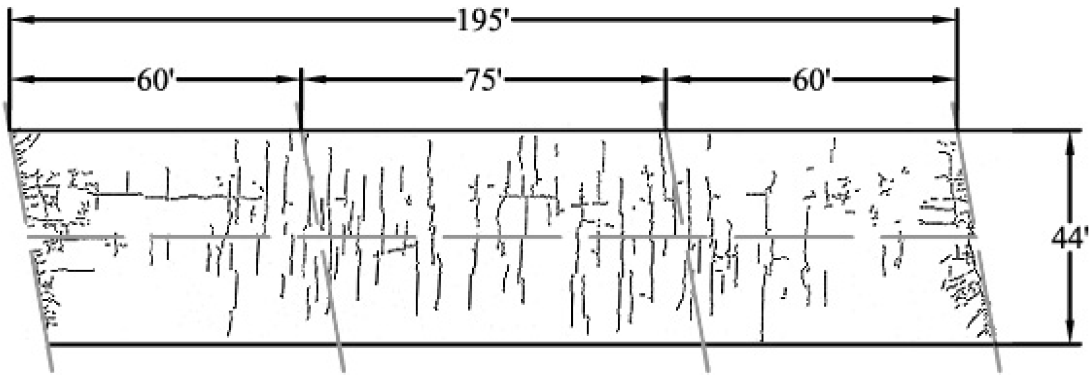


FIG. 1—*Sample bridge deck crack map.*

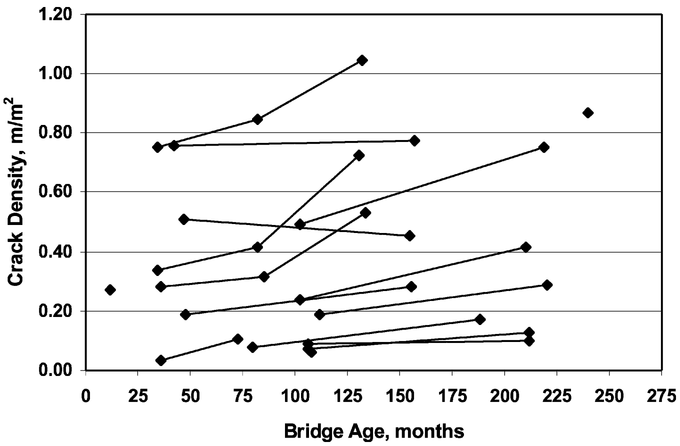


FIG. 2—*Crack density of entire bridge versus bridge age for monolithic bridge decks. Points connected by lines indicate that the same bridge was surveyed multiple times.*

a survey map, such as shown in Fig. 1. For decks that are surveyed on more than one occasion, existing crack maps are not viewed by the new survey team prior to visiting the deck. By using a consistent procedure for crack identification, data from separate studies can be analyzed as a whole with confidence that the results are not biased by the survey technique.

Following the survey, the crack map is scanned and analyzed using a computer program to determine the crack length and orientation. The results are reported as a crack density in meters of crack length per square meter of bridge deck (m/m^2). Approximately 80% of the observed cracking can be categorized as transverse cracks—cracks with orientations between 85 and 95° with respect to the longitudinal axis of the bridge.

Age

Most cracking occurs early in the life of a bridge deck, but continues to increase over time, as shown in Fig. 2 for monolithic bridge decks. In the figure, data points connected by lines indicate that the same bridge has been surveyed on more than one occasion. The technique of dummy variables (Draper and Smith 1981) is used to determine the mean increase in crack density with time based on the assumption that the absolute increase in crack density with time is independent of the initial crack density on a bridge deck. Separate dummy variable analyses are performed for each of the three bridge deck types surveyed: monolithic, conventional overlay, and silica fume overlay. Best-fit lines are then calculated for each bridge.

The comparisons that follow are based on values of crack density obtained from the best fit lines at 78 months ($6\frac{1}{2}$ years), which was the average age at the time of survey for all bridge decks. Results for decks with overlays are presented as a function of the properties of the concrete in the subdeck. As a general rule, trends are clearer for monolithic decks than for bridges with overlays because of additional variables (not addressed in this paper) associated with overlays.

Bridge Deck Type

The three primary types of bridge decks constructed in Kansas over the last 20 years have been monolithic, conventional overlay, and silica fume overlay decks. Construction procedures, specifications, and materials vary between the three bridge deck types. The overall trend in crack densities observed from the bridge surveys of monolithic (Mono), conventional overlay (CO), and silica fume overlay (SFO) bridge decks are shown in Fig. 3. As shown in the figure, bridge decks with overlays tend to have greater crack densities (0.33 m/m^2 for monolithic bridge decks as compared to 0.44 and 0.53 m/m^2 for conventional and silica fume overlay bridge decks, respectively). Thus, when the effect of cracking on corrosion initiation is considered, the use of overlays to improve bridge

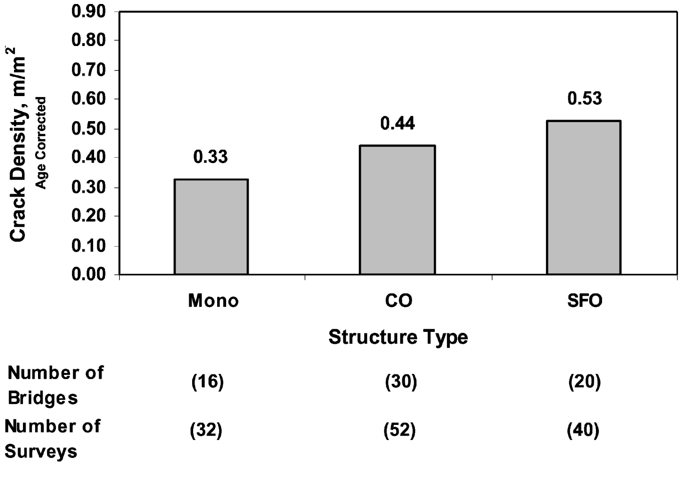


FIG. 3—*Mean crack density of entire bridge corrected to an age of 78 months versus bridge deck type. Deck types are monolithic bridge decks (Mono), conventional overlay (CO), and silica fume overlay (SFO).*

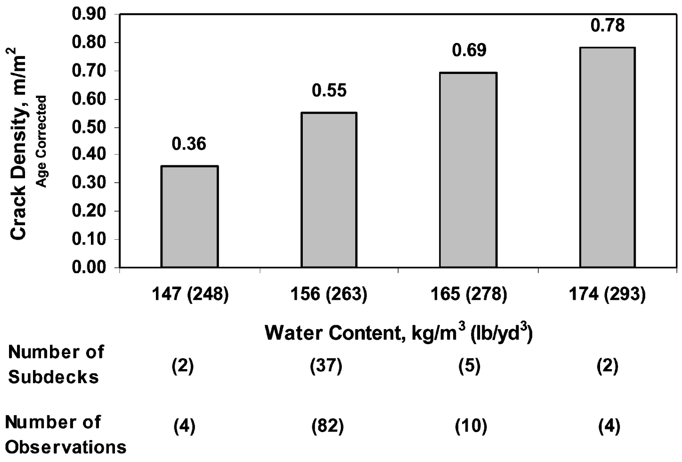


FIG. 4—*Mean crack density for bridge decks corrected to an age of 78 months versus water content for overlay bridge subdecks.*

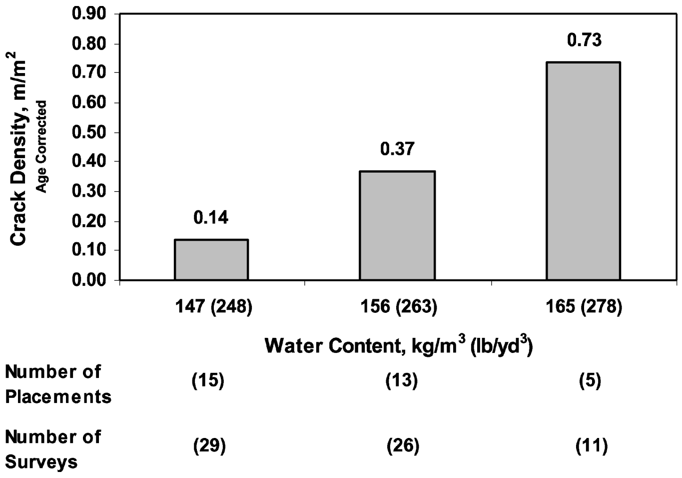


FIG. 5—*Mean crack density for bridge decks corrected to an age of 78 months versus water content for monolithic bridges.*

deck performance is not supported by this data. It should be noted, however, that many individual factors affect trends in bridge deck cracking (as noted in the following sections), including improved construction procedures that have led to decreased cracking in more recently constructed silica fume overlay bridge decks.

Material Effects

As discussed next, concrete mixture proportions, and compressive strength play primary roles in bridge deck cracking.

Concrete Mixture Proportions

Cracking in bridge decks is a function of water content, cement content, and total paste volume.

Water Content—An increase in the water content of the concrete results in an increase in crack density. This is demonstrated in Figs. 4 and 5 for decks with overlays and monolithic decks, respectively. For decks with overlays (Fig. 4), the mean age-corrected (78 months) crack density increases from 0.36–0.78 m/m^2 as the mean water content increases from 147–174 kg/m^3 (248–293 lbs/yd^3). The contrast is even greater for monolithic bridge decks (Fig. 5), where the crack density increases from 0.14–0.73 m/m^2 as the water content increases from 147–165 kg/m^3 (248–278 lb/yd^3).

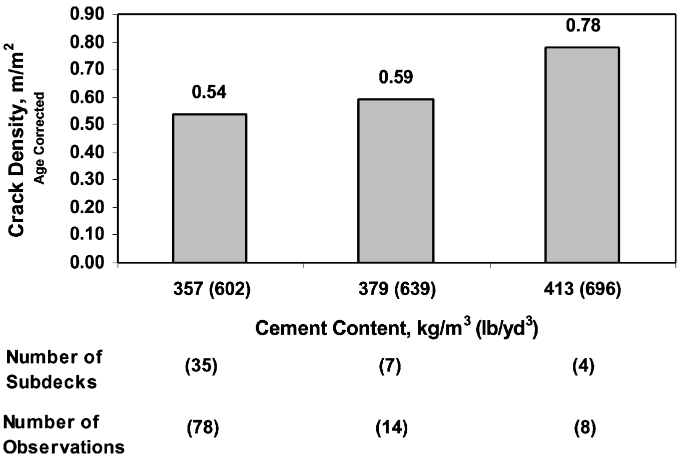


FIG. 6—*Mean crack density for bridge decks corrected to an age of 78 months versus cement content for overlay bridge subdecks.*

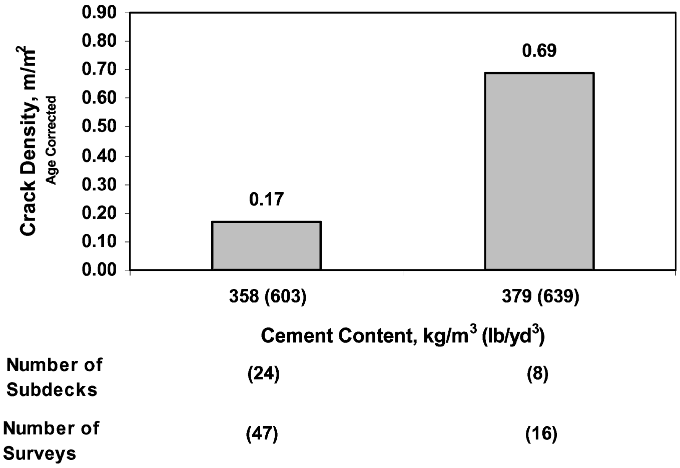


FIG. 7—*Mean crack density for individual placements corrected to an age of 78 months versus cement content for monolithic bridges.*

Cement Content—The effect of cement content on crack density is illustrated in Figs. 6 and 7 for the decks with overlays and monolithic decks, respectively. In both cases, an increase in cement content results in an increase in crack density. For bridges with overlays, the age-corrected crack density increases from 0.54–0.78 m/m^2 as the cement content increases from 357 to 413 kg/m^3 (602 to 696 lb/yd^3). Monolithic bridge decks exhibit a stronger trend, with an increase in crack density from 0.17–0.69 m/m^2 for an increase in cement content from 358–379 kg/m^3 (603–639 lb/yd^3).

Volume of Cement Paste—The cement paste constituent of concrete, equal to the combined volume of water and cement, has a strong influence on crack density, as would be expected based on the trends shown in Figs. 4–7. This observation should be of no surprise since cement paste controls concrete shrinkage. Figures 8 and 9 compare the age-corrected crack densities with the percent of the concrete volume occupied by water and cement for the subdecks of bridges with overlays and for monolithic bridge decks, respectively. For the subdecks, crack density increases from 0.36–0.78 m/m^2 as the paste volume increases from 26–30% (Fig. 8). The results are even more striking for monolithic decks, where mean crack

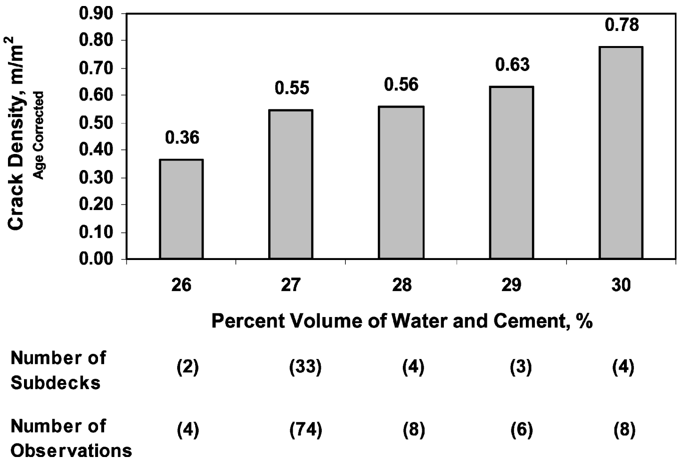


FIG. 8—*Mean crack density for bridge decks corrected to an age of 78 months versus percent volume of water and cement for overlay bridge subdecks.*

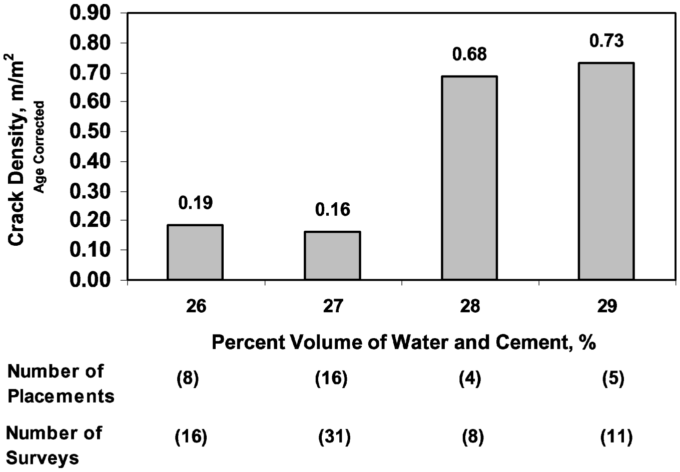


FIG. 9—*Mean crack density for individual placements corrected to an age of 78 months versus percent volume of water and cement for monolithic bridges.*

densities of 0.19 and 0.16 m/m^2 are obtained for paste volumes of 26 and 27%, respectively, but increase to 0.68 and 0.73 m/m^2 for paste volumes of 28 and 29% (Fig. 9). Figures 8 and 9 support limiting the total paste volume to values of 27% or less for all bridge decks and demonstrate the importance of limiting the nonaggregate portion of concrete in controlling bridge deck cracking.

Compressive Strength

Increased compressive strength is usually associated with improved concrete properties. This, however, is not true for cracking in bridge decks. For bridges with overlays, the crack density shows a mild (at best) increase with increasing compressive strength, with values of 0.52 to 0.56 m/m^2 for mean compressive strengths in the range of 31–52 MPa (4500–7500 psi), as shown in Fig. 10. The impact of compressive strength on cracking is, however, very clear when the comparison is made for monolithic bridge decks, with crack densities increasing from 0.16–0.49 m/m^2 as compressive strength increases from 31–45 MPa (4500–6500 psi), as shown in Fig. 11. Analysis of the data suggests that a specified upper-bound on concrete compressive strength (such as 38 MPa or 5500 psi) may lead to decreased crack densities for monolithic concrete bridge decks.

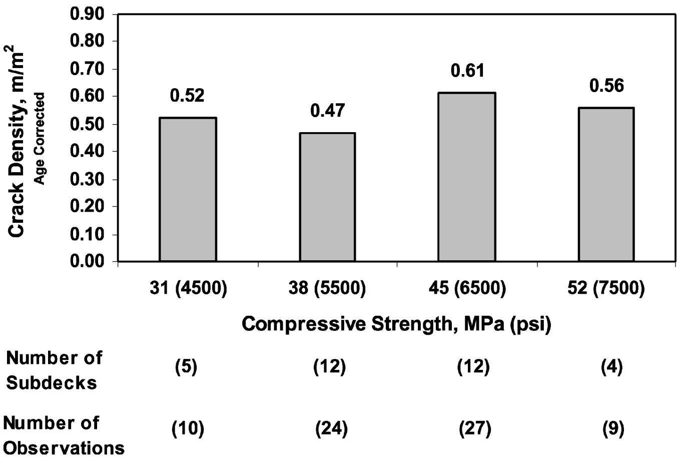


FIG. 10—*Mean crack density for bridge decks corrected to an age of 78 months versus compressive strength for overlay bridge subdecks.*

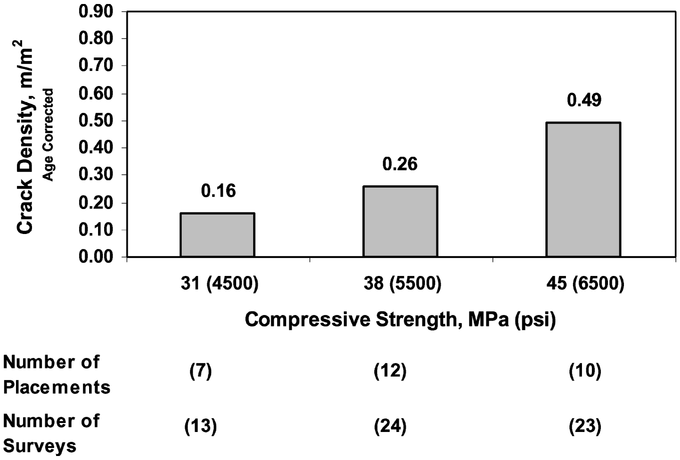


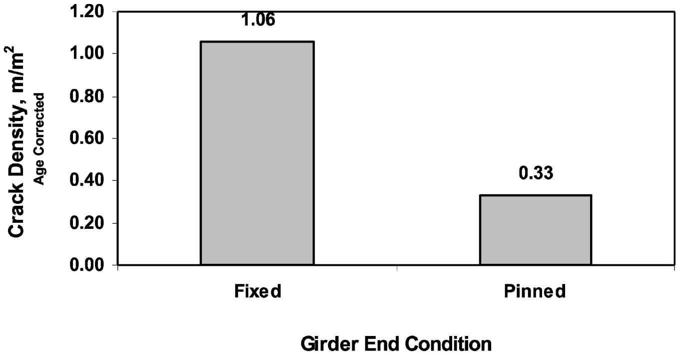
FIG. 11—*Mean crack density for individual placements corrected to an age of 78 months versus compressive strength for monolithic bridges.*

Girder End Condition

As a general rule, highway agencies prefer bridge decks that are integral with the abutment because of difficulties in maintaining connections in pin-ended bridges. The advantages of the fixed end condition, however, must be tempered by potential problems due to increased cracking in end regions (3 m, 10 ft), where the principal cracking is perpendicular to the abutment, rather than transverse, as shown in Fig. 1. The crack density in the end regions of bridge decks with fixed supports (with the resulting increase in restraint) is about three times the value observed for pin-ended decks, as shown in Figs. 12 and 13.

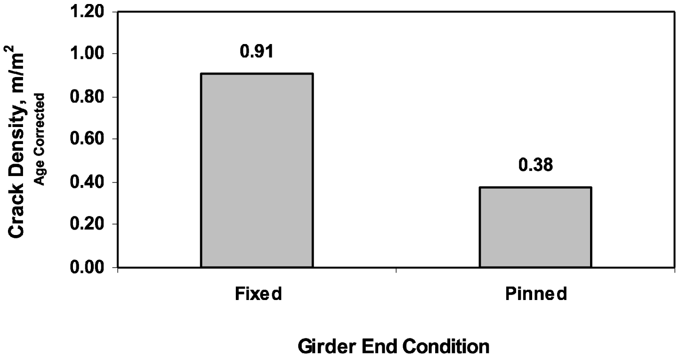
Date of Construction

As a variable, the date of construction (and the associated aspects of construction and materials) has had a measurable impact on cracking in bridge decks. This is illustrated in Figs. 14, 15, and 16. In Fig. 14, monolithic bridge decks are placed in two groups based on casting date, 1984–1987 and 1990–1993. For this deck type,



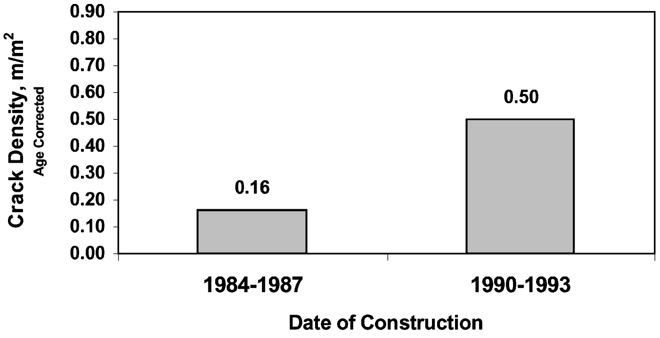
Number of Bridges	(11)	(9)
Number of Surveys	(24)	(18)

FIG. 12—*Mean crack density of end sections corrected to an age of 78 months versus girder end condition for silica fume overlay bridges.*



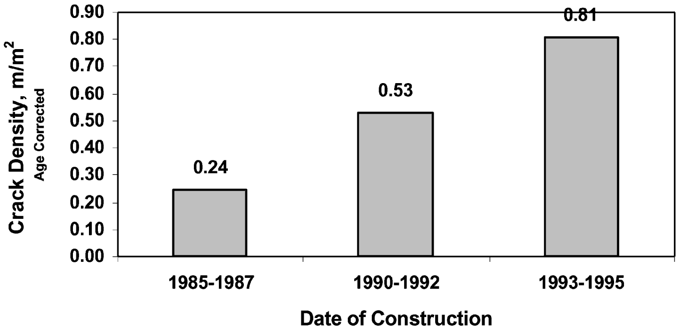
Number of Bridges	(20)	(9)
Number of Surveys	(33)	(18)

FIG. 13—*Mean crack density of end sections corrected to an age of 78 months versus girder end condition for conventional overlay bridges.*



Number of Bridges	(6)	(7)
Number of Surveys	(12)	(16)

FIG. 14—*Mean crack density of entire bridge deck corrected to an age of 78 months versus date of construction for monolithic bridge decks.*



Number of Bridges	(6)	(17)	(3)
Number of Surveys	(6)	(36)	(6)

FIG. 15—*Mean crack density of entire bridge deck corrected to an age of 78 months versus date of construction for conventional overlay bridge decks.*

Number of Bridges	(2)	(10)	(8)
Number of Surveys	(6)	(20)	(16)

FIG. 16—*Mean crack density of entire bridge corrected to an age of 78 months versus date of construction for silica fume overlay bridge decks.*

the mean age-corrected crack density increases from 0.16–0.50 between the earlier and later periods. Similar results are shown for bridges with conventional overlays, which are placed in three groups: 1985–1987, 1990–1992, and 1993–1995. In this case, crack density increases from 0.24–0.81 m/m^2 between the first and last group. In contrast to the results for monolithic and conventional overlay bridges, the crack densities for bridge decks with silica fume overlays decreased with time; for periods 1990–91, 1995–96, and 1997–98, the values dropped from 0.87–0.42 m/m^2 between the early and late period.

A number of changes in concrete materials and construction procedures over the past 20 years may explain the observations found in Figs. 14–16. During this period, cement has become progressively finer, as producers have chosen to develop higher early strength cements. Finer cements lead to greater shrinkage (Chariton and Weiss, 2002).

Concrete placement, which used to involve cranes and buckets, is now almost universally performed by pump. Concretes that are pumped generally require higher paste contents for the efficient use of the equipment than concretes that are not. As shown in Figs. 8 and 9, an increase in paste content can be expected to lead to higher crack densities. Any trend toward the use of higher slump concretes

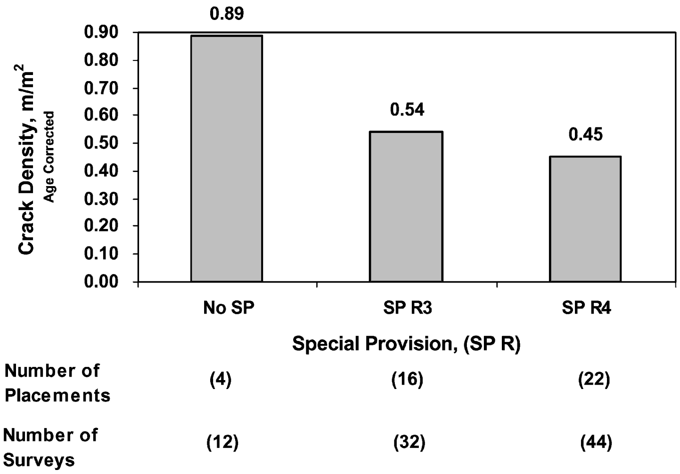


FIG. 17—*Mean crack density of entire bridge corrected to an age of 78 months versus Special Provision revision number for silica fume overlay bridge decks.*

for use with pumping would be expected to increase settlement cracking and, thus, total crack density (Dakhil, Cady, and Carrier 1975).

Finishing machines have also changed during this period. In the early 1980s, bridge decks in Kansas were finished primarily with vibrating screeds. Over the intervening years, the screeds changed, first to single roller drum screeds and, more recently, to double drum roller screeds. Roller screeds move more paste to the surface than vibrating screeds, which tends to increase plastic shrinkage cracking.

The trend in Fig. 16 for bridge decks with silica fume overlays stands in sharp contrast to the trends shown in Figs. 14 and 15 for monolithic concrete decks and decks with conventional high-density overlays. The major change for decks with silica fume overlays has been the effort to limit the evaporation of water during concrete placement and finishing, and prior to the initiation of wet curing. The importance of limiting evaporation is shown even more clearly in Fig. 17, which compares crack density as a function of the special provision used for the decks. Under conditions in which no special provisions were applied to limit early evaporation, the mean age-corrected crack density averages 0.89 m/m^2. Revision 3 to the Kansas Department of Transportation Special Provisions (SP R3) required either fogging or the use of a precure material during and after finishing. The use of *both* fogging and precure material was allowed. With Revision 4 to the Special Provisions (SP R4), both fogging and precure material were required during and after finishing. As a result of these changes, cracking decreased significantly, first after the implementation of SP R3 (0.54 m/m^2) and then, even more, after implementation of SP R4 (0.45 m/m^2). These observations demonstrate the advantages of limiting early evaporation to reduce cracking in bridge decks. It should be noted that the results in Fig. 17 demonstrate only the effects of reduced early evaporation on the overlay. No special requirements were in place for the subdecks.

Summary and Conclusions

An overall description of crack survey techniques and the principal observations obtained in crack surveys for bridge decks, as affected by material properties, bridge deck end fixity, date of construction, and efforts to limit early evaporation have been presented. These observations lead to the following key conclusions:

1. Most cracking occurs early in the life of a bridge deck, but continues to increase over time.
2. Bridge deck crack density increases with increases in water content, cement content, and total cement paste volume in concrete. The total paste volume should be limited to less than 27% for the three bridge deck types evaluated in this study.
3. Increased fixity, such as obtained with bridge decks that are integral with abutments, results in increased crack density near the supports.
4. Over the past 15–20 years, the crack density in monolithic bridge decks and bridge decks with conventional overlays has increased, but has decreased in bridge decks with silica fume overlays. The reduction in crack density observed for bridge decks with silica fume overlays appears to be due to efforts to limit evaporation prior to the initiation of wet curing.

Acknowledgments

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