ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 103-M52

Effect of Cracking on Chloride Content in Concrete Bridge Decks

by Will D. Lindquist, David Darwin, JoAnn Browning, and Gerald G. Miller

Field surveys to measure bridge deck cracking and chloride contents of uncracked as well as cracked concrete were performed as a part of a larger research program evaluating bridge deck performance. Three deck types were studied: monolithic decks, decks with a conventional high density concrete overlay, and decks with a high density concrete overlay containing either a 5 or 7% replacement of cement by silica fume.

The results of the field surveys indicate that bridge deck type does not have a major effect on chloride content. For samples taken away from cracks, the average chloride concentration at the top of transverse reinforcement rarely exceeded even the most conservative estimates of the corrosion threshold for conventional reinforcement. Chloride concentrations taken at crack locations, however, often exceeded the corrosion threshold of conventional reinforcement in less than 1 year.

Keywords: bridge deck; chlorides; cracking; overlay; permeability.

INTRODUCTION

The annual direct cost of corrosion in highway bridges exceeds \$8 billion, and indirect costs to users due to traffic delays and lost productivity has been estimated to be 10 times as much.[1] A significant portion of the corrosion damage is due to the corrosion of reinforcing steel in bridge decks.[2]

Reinforcing bars in concrete will not corrode unless the pH of the concrete drops due to carbonation or the chloride content of the concrete reaches the corrosion threshold of the reinforcement. The chloride threshold of conventional reinforcing steel ranges between 0.6 and 1.2 kg/m^3 (1 and 2 lb/yd^3).[3] As will be demonstrated in this paper, at a depth of 76 mm (3 in.), chloride contents in uncracked regions of bridge decks remain well below this threshold range for many years. In contrast, at cracks, this value can be exceeded by the end of the first winter, necessitating the use of corrosion protection systems for reinforcing steel over a wide portion of the U.S. and Canada. This paper describes a study designed to determine the effect of cracking on the chloride content in reinforced concrete bridge decks using chloride concentrations measured in the field. The study is part of a larger research program aimed at determining the effects of construction practices, material properties, and structural design on bridge deck performance and includes data on the chloride content of uncracked as well as cracked concrete. Full details of the study are presented by Miller and Darwin[4] and Lindquist et al.[5]

RESEARCH SIGNIFICANCE

The corrosion of reinforcing steel in bridge decks is a significant financial problem that is exacerbated by bridge deck cracking and deicing chemicals. Cracks in bridge decks provide the principal path for deicing salts to reach reinforcing steel and may extend through the deck and accelerate corrosion of the supporting girders. The results of this study demonstrate the importance of limiting bridge deck cracking and provide information that can be used to estimate chloride concentrations in both cracked and uncracked regions of reinforced concrete bridge decks.

CRACKING IN BRIDGE DECKS

Cracks occur in bridge decks due to a number of causes, including plastic shrinkage, settlement, drying shrinkage, thermal changes, and loading. Whereas they all appear to play a role, drying shrinkage and settlement cracking appear to dominate. Figure 1 shows the cracking map for one of the bridges evaluated in this study. As a general rule, cracking increases over time,[5,6] but the greatest contribution to crack density appears to occur early in the life of the structure, as shown in Fig. 2, where data points connected by lines represent crack densities measured on the same bridge decks at different times. The generally low slope of these lines

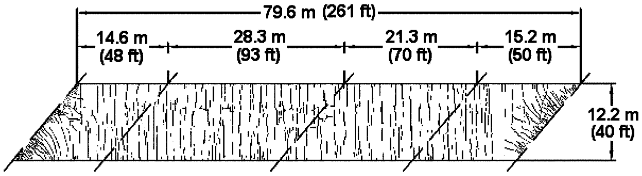

Fig. 1—Sample bridge deck crack map.[5]

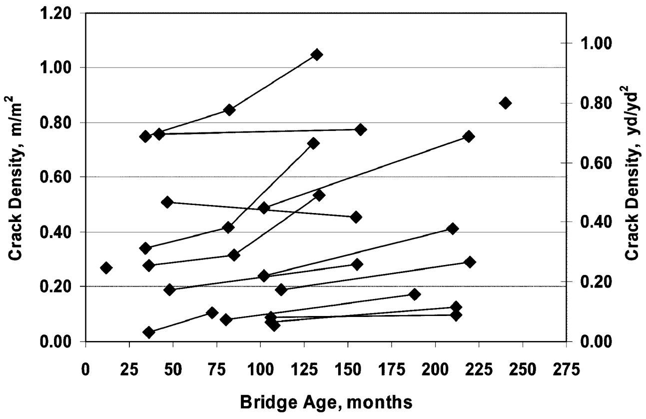

Fig. 2—Crack density of monolithic bridge decks versus bridge age. Observations connected by lines indicate the same bridge surveyed multiple times.

ACI Materials Journal, V. 103, No. 6, November-December 2006.

MS No. 06-004 received January 3, 2006, and reviewed under Institute publication policies. Pertinent discussion including authors' closure, if any, will be published in the September-October 2007 *ACI Materials Journal* if the discussion is received by June 1, 2007.

ACI member **Will D. Lindquist** *is a PhD student at the University of Kansas, Lawrence, Kans., where he received his BS and MS in civil engineering.*

David Darwin, *FACI, is the Deane E. Ackers Distinguished Professor of Civil, Environmental and Architectural Engineering and Director of the Structural Engineering and Materials Laboratory at the University of Kansas. He is a Vice President of ACI and serves on a number of ACI committees, including Committees 222, Corrosion of Metals in Concrete, and 224, Cracking.*

ACI member **JoAnn Browning** *is an Associate Professor of Civil, Environmental and Architectural Engineering at the University of Kansas. She is a member of ACI Committees 341, Earthquake-Resistant Concrete Bridges; 374, Performance-Based Seismic Design of Concrete Buildings; 408, Bond and Development of Reinforcement; and ACI Subcommittee 318-D, Flexure and Axial Loads: Beams, Slabs, and Columns.*

Gerald G. Miller *is a Civil Engineer for GE Energy Products Europe. He received his AB degree in math and German from Bowdoin College and his BS and MS in civil engineering from the University of Kansas.*

indicates a gradual increase in cracking over time, so that the initial crack density becomes an important parameter for long-term crack control.

SCOPE

The results presented in this paper summarize the results of crack density and chloride surveys of reinforced concrete bridge decks (principally in northeastern Kansas) performed over periods of 10 and 6 years, respectively. The studies involve composite steel girder bridges, the type normally associated with the highest degree of deck cracking.[7-9] The study covers three deck types: monolithic decks, decks with a conventional high density concrete overlay, and decks with a high density concrete overlay containing silica fume, with either a 5 or 7% mass replacement of cement by silica fume. Table 1(a) contains the range of water and cementitious material contents for the upper surface concrete (deck or overlay) for each deck type examined. Table 1(b) presents the water and cementitious material contents, as represented by the mode (most frequent value) of these mixture parameters for the bridges included in this study. Cracks were measured in three studies[4-6,10,11] and involved 76 bridges, 160 individual concrete placements, and 139 surveys. Chloride contents were evaluated in two of the studies[4,5] and involved 57 bridges, 107 individual concrete placements, and 97 surveys. Schematics of bridge deck designs are shown in Fig. 3(a), (b), and (c) for monolithic bridge decks, bridge decks with conventional overlays, and bridge decks with silica fume overlays, respectively.

Table 1(a)—Range of water and cementitious material contents for bridge decks examined

Concrete type	Water content, kg/m^3 (lb/yd^3)	Cement content, kg/m^3 (lb/yd^3)	Silica fume content, kg/m^3 (lb/yd^3)	*w/cm*
Monolithic/ overlay subdeck	143 to 167 (241 to 281)	357 to 413 (602 to 696)	—	0.40 to 0.44
Conventional overlay	133 to 148 (225 to 250)	371 (625)	—	0.36 to 0.40
5% silica fume overlay	133 to 148 (225 to 250)	343 to 353 (578 to 595)	18 to 28 (30 to 47)	0.36 to 0.40
7% silica fume overlay	137 to 138 (231 to 233)	345 to 346 (581 to 583)	26 (44)	0.37

Table 1(b)—Mode of water and cementitious material contents for bridge decks examined

Concrete type	Water content, kg/m^3 (lb/yd^3)	Cement content, kg/m^3 (lb/yd^3)	Silica fume content, kg/m^3 (lb/yd^3)	*w/cm*
Monolithic/ overlay subdeck	158 (266)	359 (605)	—	0.44
Conventional overlay	133 (225)	371 (625)	—	0.36
5% silica fume overlay	148 (249)	352 (594)	18 (30)	0.40
7% silica fume overlay	138 (233)	346 (583)	26 (44)	0.37

SURVEY TECHNIQUES

On-site surveys were performed for each of the bridges. The surveys included both a crack survey and chloride sampling. The crack surveys were not designed to identify every crack, but rather to obtain a consistent measure of cracking. Specific guidelines were followed for the crack surveys to minimize differences that might result from changing personnel: three to six inspectors performed the surveys on days that were at least partly sunny with a minimum temperature of 16 °C (60 °F). The entire deck surface was required to be completely dry before beginning the survey. Prior to identifying and marking cracks, a 1.5 x 1.5 m (5 x 5 ft) grid was marked on the deck surface. Inspectors marked cracks that were visible while bending at the waist. Once a crack was identified, the entire crack was marked, including parts of the crack that were not initially visible while bending at the waist. Cracks were marked with lumber crayons and then transferred to a scaled drawing. The use of these guidelines allowed the results from the three studies to be combined with confidence that the results were not biased by the survey technique.

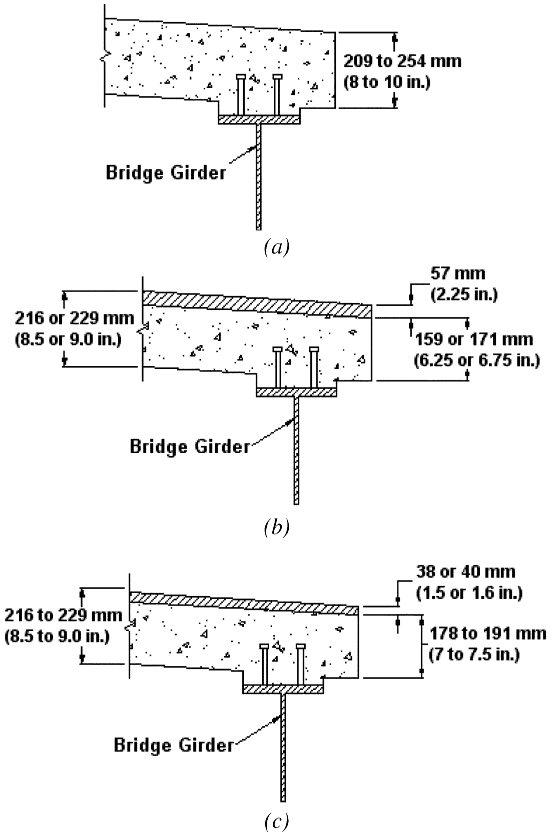

Fig. 3—(a) Schematic of monolithic bridge deck; (b) schematic of conventional overlay bridge deck; and (c) schematic of silica fume overlay bridge deck.

To determine the chloride content, the concrete was sampled at three locations on cracks and three locations away from cracks for each concrete placement. Powdered concrete samples were obtained using a hammer drill fitted with a hollow 19 mm (3/4 in.) bit attached to a vacuum. As shown in Fig. 4, five powdered samples were taken in 19 mm (3/4 in.) increments at depths of 0 to 19 mm (0 to 0.75 in.), 19 to 38 mm (0.75 to 1.5 in.), 38 to 57 mm (1.5 to 2.25 in.), 57 to 76 mm (2.25 to 3 in.), and 76 to 95 mm (3 to 3.75 in.). For decks that were sampled on a second occasion, the new samples were taken within 150 mm (6 in.) of the earlier sampling points. Each powdered sample was tested for water-soluble chloride content using an automatic titrator and a procedure similar to that in ASTM C 1218.[12] The exception to the standard was that rather than adding (1:1) nitric acid and hydrogen peroxide (30% solution) to the filtrated sample and heating the solution rapidly to boiling, only (1:1) nitric acid is added in addition to the filtrated solution and the solution is not boiled again immediately prior to titration.

CRACKING

The crack surveys showed that cracking in bridge decks increases with increasing quantities of cement and water and increasing concrete slump, compressive strength, and maximum air temperature on the day of casting. These factors are discussed at greater length by Lindquist et al.[5] and Darwin et al.[6] Of particular interest herein, however, is a trend, to be described in the following, of increasing crack density for more recently constructed bridges.

To aid in these comparisons and allow bridges to be compared on an equal-age basis, the technique of dummy variables[13] is used to determine an age correction term for each bridge deck type using crack density data obtained for bridges surveyed on more than one occasion as a part of multiple studies.[4-6,10,11] The cracking rates obtained from the dummy variable analyses are used to adjust the raw crack density data to an age of 78 months, the average age at the time of the survey for all bridge deck types. Figures 5 through 7 present both uncorrected and age-corrected crack densities as a function of the date of construction for monolithic, conventional overlay, and silica fume overlay decks, respectively. As shown in Fig. 5 and 6, respectively, the age-corrected crack density in monolithic bridge decks increased from an average of 0.16 m/m^2 (0.15 yd/yd^2) for those built in the middle 1980s to 0.50 m/m^2 (0.46 yd/yd^2) for those built in the early 1990s and in conventional overlay decks from 0.24 m/m^2 (0.22 yd/yd^2) for those built in the middle 1980s to 0.81 m/m^2 (0.74 yd/yd^2) for those built in the middle 1990s. This increase in cracking is attributed to changes in material properties and construction procedures over the past 20 years. The silica fume overlay decks (Fig. 7) exhibit a different trend, with a drop in crack density from 0.87 m/m^2 (0.80 yd/yd^2) for those constructed in the early 1990s to 0.42 m/m^2 (0.38 yd/yd^2) for those constructed in the late 1990s. The trend for crack density then reverses, increasing to 0.48 m/m^2 (0.44 yd/yd^2) for the decks constructed between 2000 and 2002. The drop in crack density for the silica fume decks is associated with additional

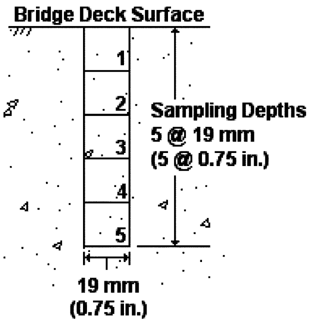

Fig. 4—Chloride sampling depths.

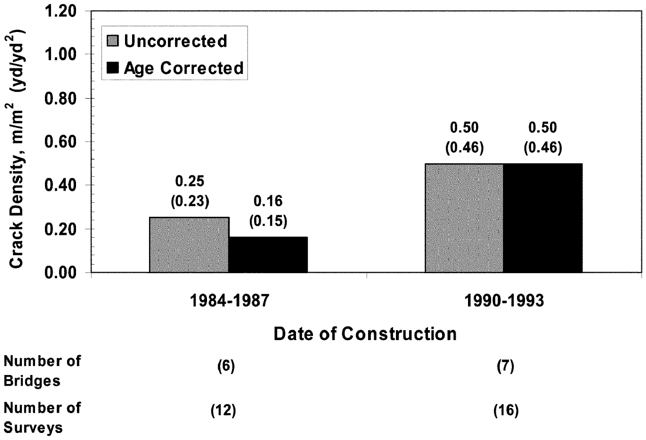

Fig. 5—Mean crack density for monolithic bridge decks versus date of construction.

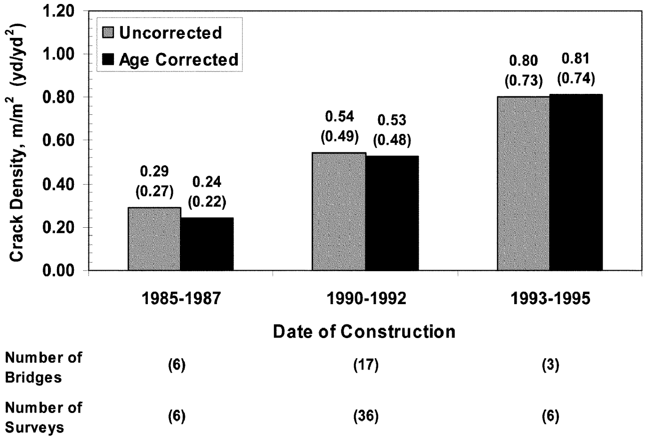

Fig. 6—Mean crack density for conventional overlay bridge decks versus date of construction.

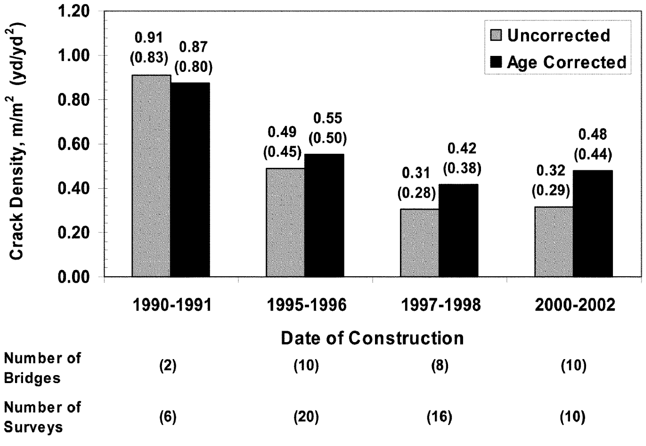

Fig. 7—Mean crack density for silica fume overlay bridge decks versus date of construction.

requirements for early curing, and the increase is associated with a switch from overlays with a 5% silica fume replacement of cement to those with a 7% replacement. The moist curing period for the six oldest 5% silica fume overlay decks examined was 3 days, while the remaining 24 were moist cured for a minimum of 7 days and required immediate treatment with a precure material, fogging after placement, or both. The minimum moist curing period was 3 days for conventional overlays and 7 days for monolithic decks.

SALT EXPOSURE

Typical salt application rates in Kansas range from 28 to 85 kg/km of driving lane (100 to 200 lb per single-lane mile).[5] Ninety percent of the samples included in this study are from Kansas Department of Transportation (KDOT) District 1, which encompasses 17 counties in northeastern Kansas. KDOT District 1 applies rock salt at a rate of 85 kg/lane·km (300 lb/lane·mile). In addition, KDOT applies a salt brine pretreatment consisting of 23% NaCl to bridge decks when frost is expected and the temperature is between –9 and 0 °C (15 and 32 °F). The salt brine pretreatment is applied at a rate of 94 to 118 L/lane·km (40 to 50 gal/lane·mile).

The total centerline length of roads treated in District 1 is 2889 km (1795 mi), and total length of all driving lanes is 7313 km (4544 mi). Rock salt usage, including the salt used for pretreatment in District 1 for the period 1998 to 2004 is presented in Table 2. With an average lane width of 3.7 m (12 ft), the average surface application rate per year over the seven-year period was 1.24 kg/m^2 (2.28 lb/yd^2). This value is below the actual value used on bridge decks, because they are often treated more frequently than other driving surfaces, and bridges subjected to higher traffic are typically treated more often than less traveled structures.

CHLORIDE CONTENT

Uncracked concrete

Figures 8 through 11 show the individual chloride contents obtained at depths of 25, 51, 64, and 76 mm (1, 2, 2.5, and 3 in.) measured from the top of the decks. The values are interpolated

Table 2—Kansas Department of Transportation District 1 salt usage history

	Rock salt totals		Average application rate	
Fiscal year	kg × 1000	Tons	kg/m^2	lb/yd^2
1998	34,443	37,967	1.29	2.38
1999	30,956	34,123	1.16	2.14
2000	28,519	31,437	1.07	1.97
2001	43,906	48,398	1.65	3.04
2002	29,544	32,567	1.10	2.04
2003	23,903	26,348	0.89	1.65
2004	39,639	43,695	1.48	2.73
Average	32,987	36,362	1.24	2.28

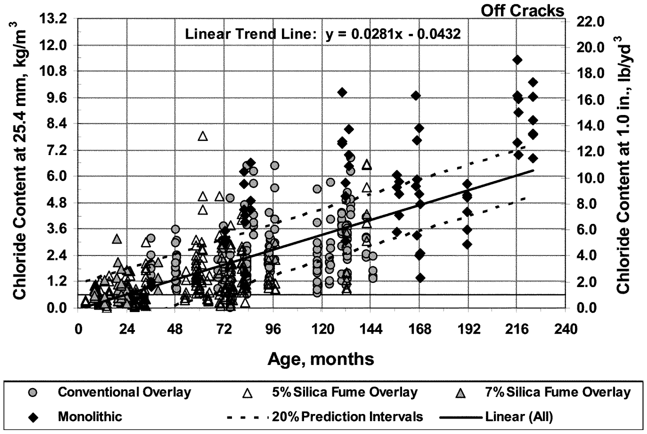

Fig. 8—Chloride content taken away from cracks interpolated at depth of 25.4 mm (1.0 in.) versus placement age.

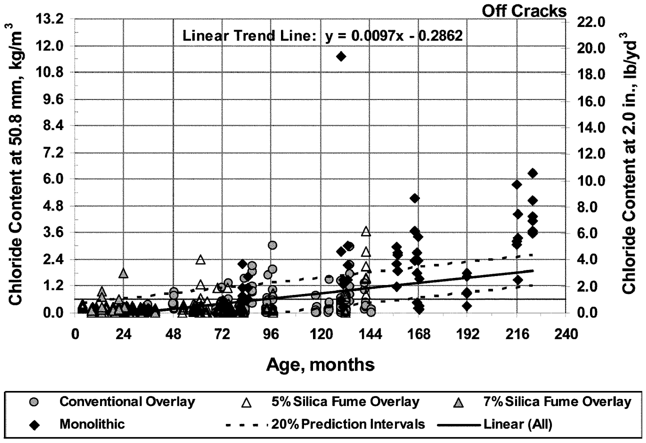

Fig. 9—Chloride content taken away from cracks interpolated at depth of 50.8 mm (2.0 in.) versus placement age.

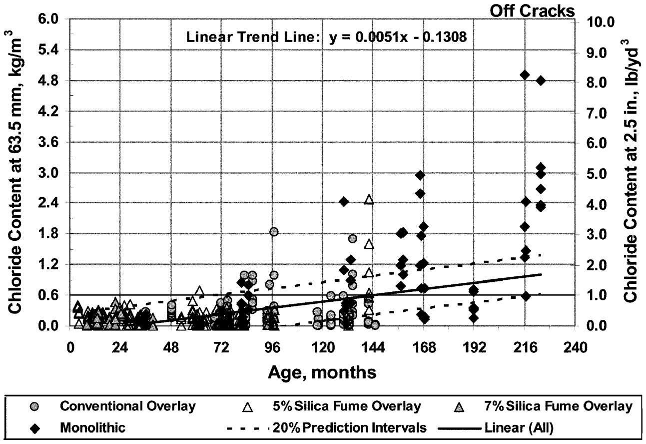

Fig. 10—Chloride content taken away from cracks interpolated at depth of 63.5 mm (2.5 in.) versus placement age.

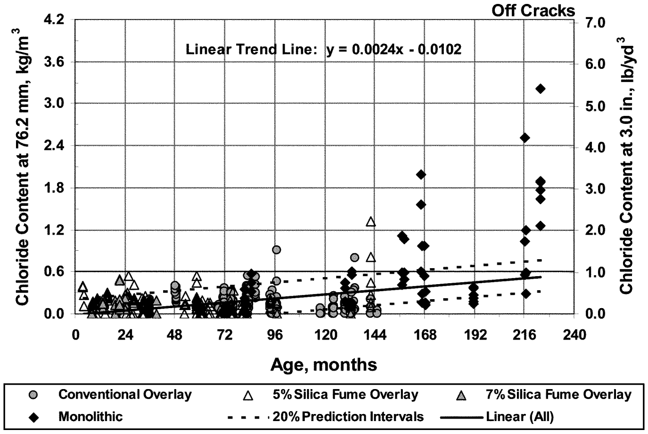

Fig. 11—Chloride content taken away from cracks interpolated at depth of 76.2 mm (3.0 in.) versus placement age.

from the five samples taken at each location, with the value for each sample assigned to the midheight of the sampling region. In addition to the individual chloride values, the figures include the best-fit lines, along with upper and lower prediction intervals corresponding to 20 and 80% probabilities of being exceeded. The lower value for the chloride threshold to initiate corrosion for conventional reinforcing steel is indicated by the heavier line at a concentration of 0.6 kg/m^3 (1.0 lb/ft^3). As expected, the chloride content decreases with increasing cover, but does not substantially differ as a function of bridge deck type. At a depth of 76 mm (3 in.), the value of cover used for bridge decks in Kansas, only four samples out of 514 exceed 0.6 kg/m^3 (1.0 lb/ft^3) for bridges with ages of 12 years or less (Fig. 11). The average trend line does not reach 0.6 kg/m^3 (1.0 lb/ft^3) until slightly over 20 years. In contrast, a reduction in cover of just 12 to 64 mm (0.5 to 2.5 in.), results in a five-fold increase in the number of samples with a chloride content above 0.6 kg/m^3 (1.0 lb/ft^3), with the chloride content reaching the critical chloride threshold in 12 years (Fig. 10). This observation has implications with respect to bridge specifications in the U.S.[14] because the cover requirement is 65 mm (2.5 in.) rather than 76 mm (3 in.).

Diffusion coefficients

The data shown in Fig. 8 to 11 is used to determine an approximate value for the chloride diffusion coefficient for the decks. The value is calculated using Crank's solution to Fick's Second Law[15]

$$C(x, t, C_o, D_{eff}) = C_o \times \left[1 - erf\left(\frac{x}{2 \times \sqrt{t \times D_{eff}}}\right)\right] \qquad (1)$$

where

C = chloride concentration as a function of depth, time, apparent surface concentration, and effective diffusion coefficient, kg/m^3 (lb/yd^3);
C_o = apparent surface concentration, kg/m^3 (lb/yd^3);
D_{eff} = effective diffusion coefficient, mm^2/day (in.^{2}/day);
erf = error function;
t = time, day; and
x = depth, mm (in.).

In this equation, the depth x and time t are known, whereas the apparent surface concentration C_o and effective diffusion coefficient D_{eff} can be estimated using an iterative least-squares fitting technique. Because each sample represents a region with a depth of 19 mm (3/4 in.), the concentration C from Eq. (1) is numerically integrated between the end points of the samples and divided by the total depth of the samples, 19 mm (3/4 in.), to obtain the average chloride concentration for the sample according to Fick's Second Law. This process is performed for each sample (five samples for each location) during each iteration of the minimization process. To begin the calculation, three apparent surface concentrations (one value for each sample location) and one effective diffusion coefficient are assumed as initial values as this process is performed for each placement.

To account for chlorides from sources other than deicing salts, a base level chloride content is estimated for each placement by examining the chloride contents taken from uncracked concrete at all depths and sample locations for that placement. Concentrations that do not differ by more than 0.05 kg/m^3 (0.08 lb/yd^3) from the measured chloride concentration at the deepest level for each sample are considered to be the base level chlorides. The base level is subtracted from the measured level to calculate the effective diffusion coefficient.

The effective diffusion coefficients for the three bridge deck types are shown in Fig. 12 to 14. For monolithic decks (Fig. 12), the diffusion coefficients range from 0.09 mm^2/day (1.40×10^{-4} in.^{2}/day) for the single deck with an age of under

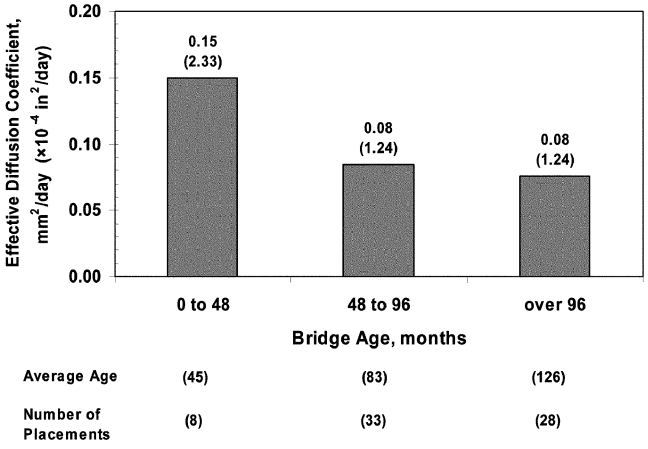

Fig. 13—Mean effective diffusion coefficient D$_{eff}$ *versus placement age for conventional overlay placements.*

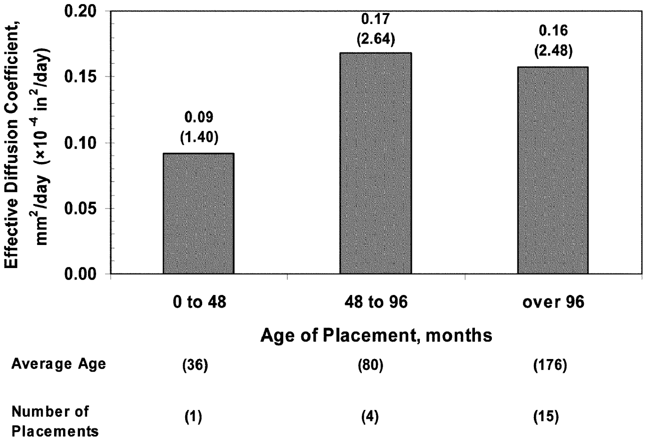

Fig. 12—Mean effective diffusion coefficient D$_{eff}$ *versus placement age for monolithic placements.*

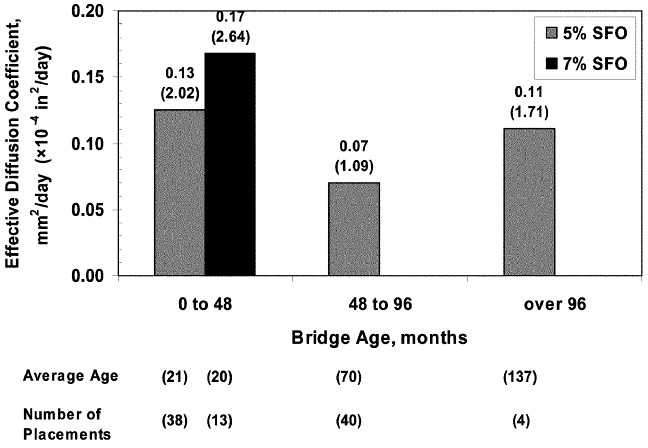

Fig. 14—Mean effective diffusion coefficient D$_{eff}$ *versus placement age for silica fume overlay placements.*

48 months to 0.17 mm^2/day (2.64 × 10^{-4} in.^{2}/day) for decks with ages between 48 and 96 months, dropping slightly to 0.16 mm^2/day (2.48 × 10^{-4} in.^{2}/day) for decks with ages over 96 months. For decks with conventional overlays (Fig. 13), the respective values are 0.15, 0.08, and 0.08 mm^2/day (2.33 × 10^{-4}, 1.24 × 10^{-4}, and 1.24 × 10^{-4} in.^{2}/day). For the decks with silica fume overlays (Fig. 14) with ages up to 48 months, the decks with the 7% replacement have an effective diffusion coefficient of 0.17 mm^2/day (2.64 × 10^{-4} in.^{2}/day) compared with the value for the decks with the 5% silica fume content, 0.13 mm^2/day (2.02 × 10^{-4} in.^{2}/day). Considering that a reduction in permeability is expected with a higher silica fume content, these results may be explained by an increase in difficultly encountered to adequately place the higher silica fume content overlays. For ages between 48 and 96 months, the average value of the effective diffusion coefficient for the 5% silica fume overlay decks (there are no 7% silica fume decks older than 48 months) is 0.07 mm^2/day (1.09 × 10^{-4} in.^{2}/day), which is very close to the value for conventional overlay decks in the same age range, 0.08 mm^2/day (1.24 × 10^{-4} in.^{2}/day). The four silica fume overlay decks over 96 months old exhibit a D_{eff} of 0.11 mm^2/day (1.71 × 10^{-4} in.^{2}/day).

As shown in Fig. 12 to 14, deck type and concrete properties can affect the diffusion coefficient, but overall, as shown in Fig. 11, intact concrete performs very well if adequate cover is provided over the top reinforcement.

Cracked concrete

The previous observations change significantly when chloride contents at crack locations are evaluated. Figures 15 through 18 show the chloride contents at depths of 25, 51, 64, and 76 mm (1, 2, 2.5, and 3 in.) for samples taken at cracks, along with the best-fit lines and the upper and lower prediction intervals. At a depth of 76 mm (3 in.) (Fig. 18), by the end of the first year, the chloride content exceeds the lower value for critical chloride threshold, 0.6 kg/m^3 (1 lb/yd^3), in a number of cases, and by the end of the second year, in over half of the samples obtained. The chloride contents are even greater for bridges in the study that are subjected to higher traffic counts, and presumably higher salt treatments. This point is demonstrated by the progressively higher chloride contents with age shown in Fig. 19 and 20 for bridges in the study with annual average daily traffic (AADT) greater than 5000 and 7500, respectively. In the latter case, the chloride content represented by the trend line reaches 3 kg/m^3 (5 lb/yd^3) in under 12 years.

The results shown in Fig. 18 to 20, which represent chloride contents at a depth of 76 mm (3 in.), demonstrate not only that corrosion protection systems are needed in bridge decks, but that this protection is needed early in the life of the deck. As shown in Fig. 20, corrosion protection systems that rely on an increased chloride corrosion threshold are likely to require threshold values in excess of 3 kg/m^3 (5 lb/yd^3) to prevent the average deck from corroding prior to an age of 12 years.

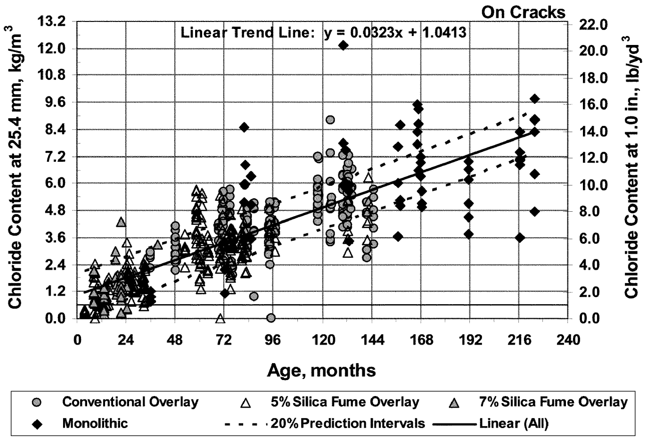

Fig. 15—Chloride content taken on cracks interpolated at depth of 25.4 mm (1.0 in.) versus placement age.

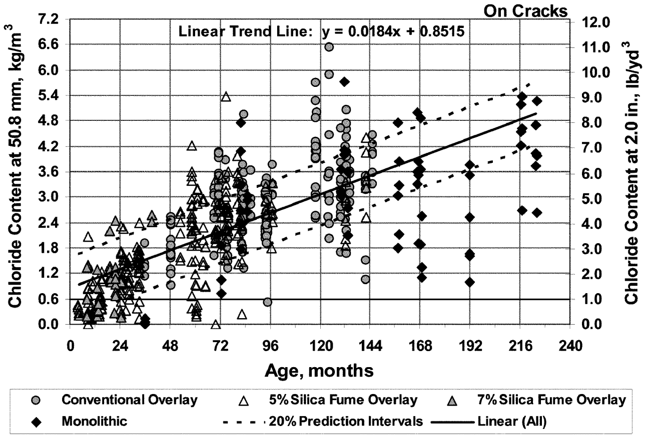

Fig. 16—Chloride content taken on cracks interpolated at depth of 50.8 mm (2.0 in.) versus placement age.

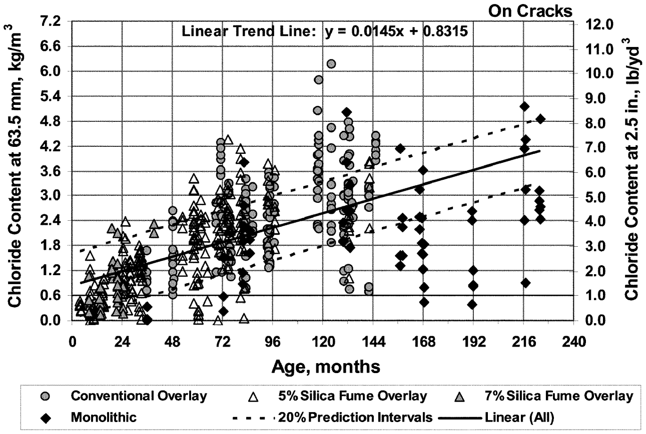

Fig. 17—Chloride content taken on cracks interpolated at depth of 63.5 mm (2.5 in.) versus placement age.

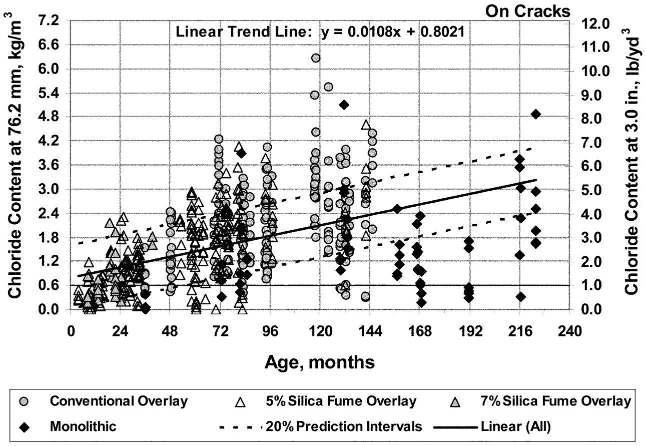

Fig. 18—Chloride content taken on cracks interpolated at depth of 76.2 mm (3.0 in.) versus placement age.

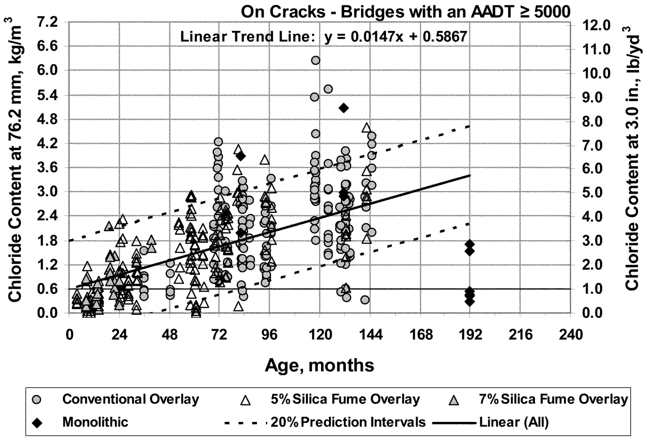

Fig. 19—Chloride content taken on cracks interpolated at depth of 76.2 mm (3.0 in.) versus placement age for bridge decks with average annual daily traffic (AADT) ≥ 5000.

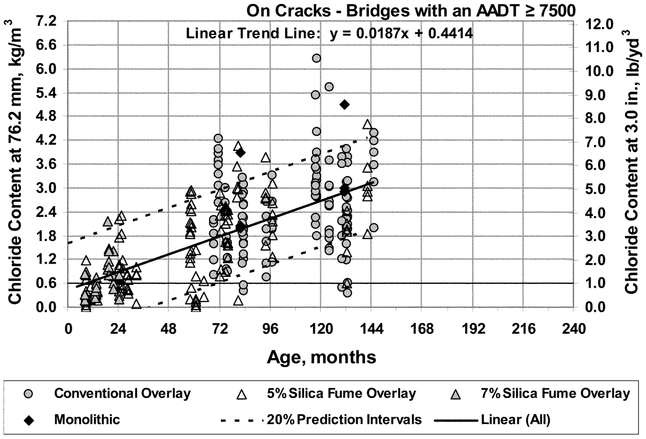

Fig. 20—Chloride content taken on cracks interpolated at depth of 76.2 mm (3.0 in.) versus placement age for bridge decks with average annual daily traffic (AADT) ≥ 7500.

SUMMARY AND CONCLUSIONS

The purpose of this study is to determine the effect of cracking on chloride contents and to characterize the diffusion properties of reinforced concrete bridge decks based on measured chloride contents. This paper includes results from field surveys performed as a part of a larger research program evaluating the performance of bridge decks located primarily in northeastern Kansas.[4-6,10,11] Three deck types are included in the study: monolithic decks, decks with a conventional high density concrete overlay, and decks with a high density concrete overlay containing silica fume, with either a 5 or 7% replacement of cement by silica fume. Full details of the study are presented by Miller and Darwin[4] and Lindquist et al.[5]

The following conclusions are based on the data and analysis presented in this paper:

1. Chloride content increases with the age of the bridge deck;

2. At the same age, the three deck types in this study contain similar quantities of chloride;

3. At a depth of 76 mm (3.0 in.), the chloride contents in uncracked concrete for monolithic, silica fume overlay, and conventional overlay bridge decks with ages of 12 years or less are below even the most conservative estimates of the corrosion threshold for conventional reinforcement (0.6 kg/m^3 [1.0 lb/yd^3]);

4. At cracks, the average chloride concentration at a depth of 76 mm (3.0 in.) can exceed the corrosion threshold of conventional reinforcement within the first year, regardless of deck type. By 2 years, the chloride content at cracks exceeds 0.6 kg/m^3 (1.0 lb/yd^3) in the majority of the decks surveyed; and

5. The use of overlays in Kansas does not provide measurable protection for reinforcing steel from chlorides.

ACKNOWLEDGMENTS

The work reported in this paper was supported by the Kansas Department of Transportation under K-TRAN Projects KU-94-1, KU-98-4, and KU-01-09.

REFERENCES

1. Yunovich, M.; Thompson, N. G.; Balvanyos, T.; and Lave, L., "Highway Bridges," Appendix D, *Corrosion Cost and Preventive Strategies in the United States*, by G. H. Koch, M. Po, H. Broongers, N. G. Thompson, Y. P. Virmani, and J. H. Payer, *Report* No. FHWA-RD-01-156, Federal Highway Administration, McLean, Va., 2002, 773 pp.

2. Virmani, Y. P., and Clemeña, G. G., "Corrosion Protection—Concrete Bridges," *Report* No. FHWA-RD-98-088, Federal Highway Administration, McLean, Va., 1998, 80 pp.

3. Ji, J.; Darwin, D.; and Browning, J., "Corrosion Resistance of Duplex Stainless Steels and MMFX Microcomposite Steel for Reinforced Concrete Bridge Decks," *SM Report* No. 80, University of Kansas Center for Research, Inc., Lawrence, Kans., Dec. 2005, 423 pp.

4. Miller, G. G., and Darwin, D., "Performance and Constructability of Silica Fume Bridge Deck Overlays," *SM Report* No. 57, University of Kansas Center for Research, Inc., Lawrence, Kans., Jan. 2000, 423 pp.

5. Lindquist, W. D.; Darwin, D.; and Browning, J., "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Inc., Lawrence, Kans., Feb. 2005, 453 pp.

6. Darwin, D.; Browning, J.; and Lindquist, W. D., "Control of Cracking in Bridge Decks: Observations from the Field," *Cement, Concrete, and Aggregates*, ASTM International, West Conshohocken, Pa., V. 26, No. 2, Dec. 2004, pp. 148-154.

7. Cheng, T. T.-H., and Johnston, D. W., "Incidence Assessment of Transverse Cracking in Concrete Bridge Decks: Construction and Material Considerations," *Report* No. FHWA/NC/85-002 V. 1, North Carolina State University, Department of Civil Engineering, Raleigh, N.C., 1985, 232 pp.

8. Krauss, P. D., and Rogalla, E. A., "Transverse Cracking in Newly Constructed Bridge Decks," *National Cooperative Highway Research Program Report 380*, Transportation Research Board, Washington, D.C., 126 pp.

9. French, C.; Eppers, L.; Le, Q.; and Hajjar, J. F., "Transverse Cracking in Concrete Bridge Decks," *Transportation Research Record* 1688, National Research Council, Washington, D.C., 1999, pp. 21-29.

10. Schmitt, T. R., and Darwin, D., "Cracking in Concrete Bridge Decks," *SM Report* No. 39, The University Center for Research, Inc., Lawrence, Kans., Apr. 1995, 151 pp.

11. Schmitt, T. R., and Darwin, D., "Effect of Material Properties on Cracking in Bridge Decks," *Journal of Bridge Engineering*, ASCE, V. 4, No. 1, pp. 8-13.

12. ASTM C 1218/C 1218M-99, "Standard Test Method for Water-Soluble Chloride in Mortar and Concrete," ASTM International, West Conshohocken, Pa., 3 pp.

13. Draper, N. R., and Smith, H., *Applied Regression Analysis*, 2nd Edition, John Wiley & Sons, Inc., New York, 1981, pp. 241-249.

14. American Association of State Highway and Transportation Officials, *AASHTO LRFD Bridge Design Specifications*, 3rd Edition, Washington, D.C., 2004.

15. Collepardi, M.; Marcialis, A.; and Turrizani, R., "Penetration of Chloride Ions into Cement Pastes and Concretes," *Journal of American Ceramic Research Society*, V. 55, No. 10, 1972, pp. 534-535.