RESEARCH SERIES • NO. 10

SUMMARY OF THE IMPACT OF CONCRETE CRACKING ON

Bridge Decks Constructed with Epoxy-Coated Reinforcing Bars

Sponsored by:
Iowa Department of Transportation
and Iowa Highway Research Board

Prepared by:
Center for Transportation Research
and Education (CTRE) *and the*
Civil, Construction, and Environmental
Engineering Department *at*
Iowa State University
Ames, Iowa

Concrete Reinforcing Steel Institute
933 North Plum Grove Road
Schaumburg, IL 60173

www.crsi.org

INTRODUCTION

This CRSI Research Series is based on a study sponsored by the Iowa Department of Transportation (Iowa DOT) and the Iowa Highway Research Board to determine the impact of bridge deck cracking on overall bridge deck durability and to substantiate the methodology used to estimate the remaining functional service life of an existing bridge deck. A secondary objective of the study was to evaluate the performance of epoxy-coated reinforcing bars in Iowa bridge decks.

This study substantiates that epoxy-coated reinforcing bars resist the corrosive damage caused by deicing chemicals and greatly extend the service life of bridge decks—by up to triple—compared to the service life for bridge decks using uncoated reinforcing bars.

CRSI wishes to thank the Iowa Department of Transportation and Dr. Fouad Fanous, Professor of Civil, Construction, and Environmental Engineering at Iowa State University for supplying information and photos for this Research Series. Additional information can be obtained by contacting CRSI directly.

Bridge Deck Deterioration Mechanism

A corrosive condition is created when reinforced concrete is exposed to deicing chemicals, seawater, or other harsh chemicals. Chloride ions penetrate through concrete cracks and pores, and reach the depth of the reinforcing bar mat. In the presence of chlorides, corrosion of reinforcing steel is a natural electrochemical process in which the oxidation process creates iron oxide (rust).

Reinforced concrete bridge decks constructed with uncoated steel reinforcement and exposed to deicing chemicals will suffer premature deterioration caused by corrosion. The steel in the reinforcing bar can expand three to six times its original volume when it corrodes, which often leads to delamination and spalling of the concrete.

Concrete cracking, delamination, and spalling can then cause the rate of corrosion to increase by allowing more chlorides to penetrate or infiltrate the concrete.

Iowa's Practice

Around 1976, in an effort to minimize the damage to bridge decks caused by corrosion of the steel reinforcing bars, the Iowa DOT—and many other transportation agencies—started using epoxy-coated reinforcing bars for the top mat of reinforcement in their bridge decks.

In the mid-1980s, the Iowa DOT started using epoxy-coated reinforcing bars in both the top and bottom reinforcing mats. Fusion-bonded epoxy coating principally protects against corrosion by serving as a barrier that isolates the steel from the oxygen and chloride that causes corrosion.

Although the performance of epoxy-coated reinforcing bars in corrosive environments is superior to uncoated reinforcing bars, the presence of concrete cracks in bridge decks caused some concern regarding the condition of the reinforcement and the effectiveness of epoxy coating in the cracked areas.

Bridges Studied

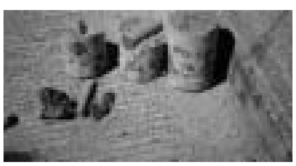
There are 711 bridge decks in Iowa constructed with epoxy-coated reinforcing bars in the top mat only or both the top and bottom mats. These bridges were built between 1978 and 1995.

These bridges have been categorized into various groups to examine the impact of certain characteristics on deck condition ratings. Eighty bridges were selected as a representative sample. Several additional bridges were added to the group of 80 to evaluate the efficacy of concrete surface sealer at resisting the diffusion of chlorides and protecting the reinforcing steel from corrosive conditions.

Field and Laboratory Testing Program

Bridge decks selected for the study were visually inspected for spalling and delamination. Four concrete core samples were then taken from each bridge deck, two taken directly from cracked locations and two from locations on the deck that showed no signs of cracking. One "cracked" and one "uncracked" core was taken from near the gutter line, while the other two cores were taken near the centerline of the deck.

As often as possible, cores were taken at locations where longitudinal and transverse top mat reinforcing bars intersected. The cores were used to measure the cracks within the core and to evaluate the condition of the reinforcing bars and epoxy coating hardness and coating adhesion.



Five concrete powder samples were also collected at each bridge deck: one sample each in the upper 0.5 to 1.5 inches of concrete and the other from a depth of 2.5 to 3.5 inches. The powder samples were used to analyze the chloride content in the concrete. Powder samples were also extracted from each concrete core.

Chloride Content and Diffusion

The chloride content data collected from uncracked cores were used to determine the chloride content of the deck surface and the chloride diffusion constant in Iowa bridges. A typical chloride threshold for uncoated steel, i.e., the chloride content that will initiate corrosion, is 1.2 pounds per cubic yard (lb/yd^3). Corrosion threshold values for epoxy-coated reinforcing bars have not been defined.

The majority of the samples from 0.5 to 1.5 inches deep—and a large number of the deeper samples—had a chloride concentration greater than the typical corrosion threshold for both uncoated and epoxy-coated reinforcing bar. The mean surface chloride concentration, C_o, in Iowa bridges measured for this study was 14 lb/yd^3. Although the newer bridges (constructed from 1990 to 1993) generally had a lower chloride content, the amount of chloride was still significant compared to the threshold value.

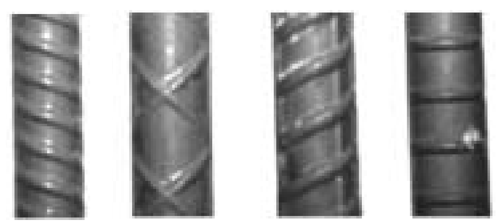
The chloride diffusion constant, D_C, measured in square inches per year (in^2/yr), is the rate at which chloride permeates through concrete. The diffusion constant is a function of the concrete permeability, environmental factors, and the presence of cracks. The time required for chloride to reach the threshold value at the reinforcing bars can be calculated based on the chloride diffusion constant.

Two different analytical methods were used to estimate the average chloride diffusion constant, D_c, for the representative Iowa bridges. In both cases, the chloride diffusion constant was estimated to be 0.05 in^2/yr.

Based on these analytical methods, which were supported by measured data, the chloride concentration in Iowa bridge decks included in this study decreased to almost zero at a depth of approximately four inches.

Performance of Epoxy Coating

Hardness of the epoxy coating was measured on the reinforcing bars from the core samples to evaluate whether there was any relationship between epoxy hardness and reinforcing bar condition (i.e., harder epoxy may be more brittle and subject to damage that would allow chloride to infiltrate) or epoxy hardness and chloride content (i.e., high chloride content may cause the epoxy coating to be harder). No such relationships were observed from the data.



Most, if not all, of the epoxy on the reinforcing bar samples was discolored. Examination under a scanning electron microscope indicated that the severely discolored epoxy coating had a network of micro-cracks on the surface. Not known is the cause of these micro-cracks or their impact on the epoxy coating's ability to protect the reinforcing bar. However, because these micro-cracks appear to be surficial, their significance may be minimal.

Impact of Concrete Cracking

Examination of the representative epoxy-coated reinforcing bar samples from the Iowa bridge decks indicated a range of deterioration. The most corroded reinforcing bar samples were those collected from cracked locations.

The corrosion of the reinforcing bars can be attributed to the presence of high chloride content at the top reinforcing steel layer. The chloride content is higher because the cracks allowed the chloride to permeate the concrete more readily.

Although most of this corrosion was only on the surface of the steel, two samples were observed to have isolated spots where corrosion product had built up slightly underneath the epoxy coating. The largest area of isolated corrosion was approximately 0.3 in^2.

The reinforcing bar samples taken from uncracked areas of the bridge decks were in relatively good condition. Therefore, the data show that the presence of cracks in the deck surface had an impact on the condition of the reinforcing bars below these cracks.

Assigning a reinforcing bar rating r(t), as defined in Table 1, to the reinforcing bar samples enabled a quantitative evaluation of the impact of chloride on the reinforcing bars. The data presented in Table 1 indicate that the epoxy-coated reinforcing bars performed well when no visible cracks were observed in the bridge deck. The data also indicate that in the cracked areas, over 80 percent of the epoxy-coated reinforcing bars were still in good condition (i.e., reinforcing bar rating of 4 or 5) despite the corrosive environment.

Table 1

PERFORMANCE OF EPOXY-COATED REINFORCING BARS

Rating Description r(t)		Percent of Samples taken from **Uncracked** Areas	Percent of Samples taken from **Cracked** Areas
5	No evidence of corrosion	92.9	76.4
4	A number of small, observable corrosion areas	7.1	5.0
3	Corrosion area less than 20% of total surface	0	5.0
2	Corrosion area between 20% and 60% of total surface	0	10.7
1	Corrosion area greater than 60% of total surface	0	2.9

The data from Table 1 are a testimony to the efficacy of epoxy-coated reinforcing bars in resisting corrosion in concrete bridge decks.

Bridge Deck Age Extrapolations

The relationship between the epoxy-coated reinforcing bar rating and the age of the bridge deck has been developed for both cracked and uncracked conditions. A graphical representation of this relationship is shown in Figure 1, along with the weighted average of data collected from the representative Iowa bridges. These relationships were used to determine the functional service life of the bridge decks reinforced with epoxy-coted reinforcing bars.

Epoxy coating bond adhesion measurements revealed that coating adhesion decreases as time increases, as shown in Figure 2. The data also indicate that the epoxy coating adhesion collected from uncracked locations is better than that from cracked locations.

Figure 1

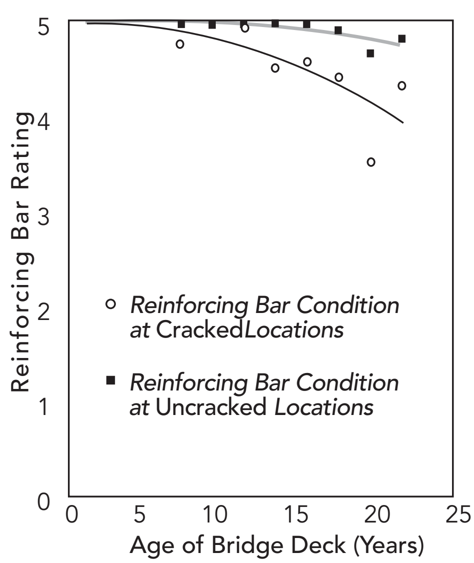
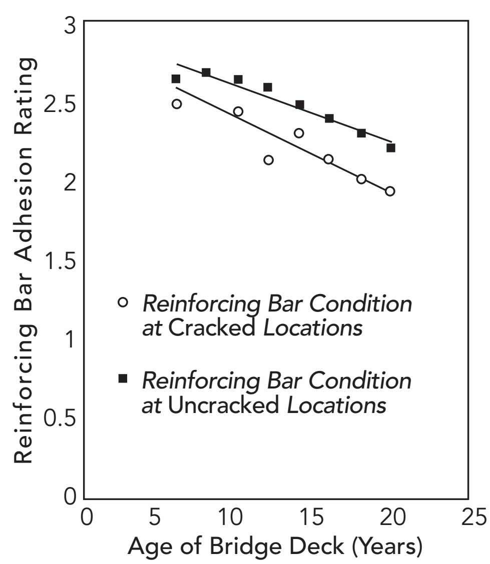


Figure 2



Bridge Deck Service Life

For a bridge deck, the end of the functional service life is reached when severe deterioration occurs. Rehabilitation can range from patching deteriorated areas to overlaying an entire bridge deck with a new riding surface.

There are several methods of estimating the functional service life of a deteriorated bridge deck. The method chosen for this study assumes that major rehabilitation will need to take place only after spalling or delamination has occurred on 9 to 14 percent of a most heavily traveled traffic lane (typically the right or outside lane).

Following this definition, one can estimate the functional service life of a concrete bridge deck based on the depth of concrete cover over the top mat of reinforcing steel, the rate of chloride diffusion, and the surface chloride content at 0.5 inches below the deck surface.

These estimates of functional service life can, in turn, help guide decisions on the time at which preventative maintenance of a bridge deck should be performed.

Basis for Estimation

The basis for estimating a concrete bridge deck's functional service life is Fick's Second Law, which represents the transient diffusion of atoms in a material. A closed-form solution of Fick's Second Law (a second-order differential equation) can be expressed as:

$$C_{(x,t)} = C_o \{1 - erf(y)\} \qquad (1)$$

where

$$y = \frac{x}{2\sqrt{D_c\, t}} \qquad (2)$$

and $C_{(x,t)}$ = measured chloride concentration at the desired depth; for purposes of service life estimates, assumed to equal the chloride threshold,

C_o = constant mean surface chloride concentration measured at 0.5 inches below the deck surface (lb/yd^3)

x = depth of reinforcing bars (inches)

D_c = chloride diffusion constant (in^2/yr)

t = time to reach the corrosive chloride threshold (years)

Method of Estimation

The following steps (A through E) can be used to estimate the total time required for a concrete bridge deck to spall or delaminate over 9 to 14 percent of the worst traffic lanes (i.e., reach the end of its functional service life), if the chloride threshold is known.

(A) Determine a representative cover depth, defined as the clear distance from the surface of the deck to the top of the first layer of reinforcing steel.

$$x = \bar{x} + \alpha \cdot \sigma \qquad (3)$$

where

x = representative concrete cover depth, inches

$\bar{x}$ = mean reinforcing bar cover depths (measured in the field), inches

α = value corresponding to a cumulative percentage of spalling or delamination

σ = standard deviation of the measured cover depths, inches

A cumulative percentage of 11.5 percent (i.e., the average between 9 and 14 percent) is recommended, which represents damage in the worst traffic lane as an indication of the end of a bridge deck functional service life.

Based on a normal cumulative probability with a cumulative percentage of 11.5, $\alpha = -1.20$.

(B) Solve equation (1) for *erf(y)*. Equation (1) can be rewritten as:

$$erf(y) = 1 - \frac{C_{(x,t)}}{C_o} \qquad (4)$$

where:

$C_{(x,t)}$ = chloride threshold

C_o = mean surface chloride concentration

Using the calculated value of *erf(y)*, determine *y* using Table 2.

(C) Solve equation (2) for *t* (the time for the chloride to reach the depth of the reinforcing bars). Equation (2) can be expressed as:

$$t = \frac{x^2}{4\, y^2 D_c} \qquad (5)$$

using:

x = calculated in step (A)

y = calculated in step (B)

D_c = chloride diffusion constant, (in^2/yr)

(D) For epoxy-coated reinforcing bar, the time required to reach a reinforcing bar rating *r(t)*, as defined in Table 1, of one (i.e., the corrosion area is greater than 60 percent of the total surface of the reinforcing bars) can be expressed as:

$$r(t) = \beta_o + \beta_1 t + \beta_2 t^2 \qquad (6)$$

where

$r(t)$ = reinforcing bar rating,

t = time required to reach a given reinforcing bar rating,

β_o, β_1, and β_2 = constants

The constant β_o can be estimated by assuming that when the bridge is new (i.e., $t = 0$), the reinforcing bar rating is highest (i.e., $r(t) = 5$). Therefore, $\beta_o = 5$. The constants β_1 and β_2 were calculated in this study based on whether the bridge deck is cracked or uncracked, as follows:

For locations along bridge decks with cracks in the concrete, $\beta_1 = 0.0038$ and $\beta_2 = -0.00311$. For locations along bridge decks without cracks in the concrete, $\beta_1 = 0.0135$ and $\beta_2 = -0.00134$.

The solution for quadratic equation (6) is as follows: **(7)**

$$t = \frac{-\beta_1 \pm \sqrt{\beta_1{}^2 - 4(\beta_2)(\beta_o - r(t))}}{2\beta_2}$$

Inserting reinforcing bar rating *r(t)* = 1 in equation (7) and solving for *t* gives the additional time needed for the reinforcing bars to reach a rating at which the reinforcing bars are significantly corroded.

(E) The total time required for a bridge deck to spall and delaminate (i.e., reach the end of its functional service life) can be estimated by adding:

four years, which is the approximate average time it takes for reinforcing bar corrosion to build up to spalling—

to the time estimated in steps C or D.

TABLE 2

ERROR FUNCTION VALUES Y FOR THE ARGUMENT OF Y

y	erf(y)	y	erf(y)	y	erf(y)	y	erf(y)	y	erf(y)
0.02	0.022565	0.62	0.619411	1.22	0.915534	1.82	0.989943	2.42	0.999379
0.04	0.045111	0.64	0.634586	1.24	0.920505	1.84	0.990736	2.44	0.999441
0.06	0.067622	0.66	0.649377	1.26	0.925236	1.86	0.991472	2.46	0.999497
0.08	0.090078	0.68	0.663782	1.28	0.929734	1.88	0.992156	2.48	0.999547
0.10	0.112463	0.70	0.677801	1.30	0.934008	1.90	0.992790	2.50	0.999593
0.12	0.134758	0.72	0.691433	1.32	0.938065	1.92	0.993378	2.52	0.999635
0.14	0.156947	0.74	0.704678	1.34	0.941914	1.94	0.993923	2.54	0.999672
0.16	0.179012	0.76	0.717537	1.36	0.945561	1.96	0.994426	2.56	0.999706
0.18	0.200936	0.78	0.730010	1.38	0.949016	1.98	0.994892	2.58	0.999736
0.20	0.222703	0.80	0.742101	1.40	0.952285	2.00	0.995322	2.60	0.999764
0.22	0.244296	0.82	0.753811	1.42	0.955376	2.02	0.995719	2.62	0.999789
0.24	0.265700	0.84	0.765143	1.44	0.958297	2.04	0.996086	2.64	0.999811
0.26	0.286900	0.86	0.776100	1.46	0.961054	2.06	0.996423	2.66	0.999831
0.28	0.307880	0.88	0.786687	1.48	0.963654	2.08	0.996734	2.68	0.999849
0.30	0.328627	0.90	0.796908	1.50	0.966105	2.10	0.997021	2.70	0.999866
0.32	0.349126	0.92	0.806768	1.52	0.968413	2.12	0.997284	2.72	0.999880
0.34	0.369365	0.94	0.816271	1.54	0.970586	2.14	0.997525	2.74	0.999893
0.36	0.389330	0.96	0.825424	1.56	0.972628	2.16	0.997747	2.76	0.999905
0.38	0.409009	0.98	0.834232	1.58	0.974547	2.18	0.997951	2.78	0.999916
0.40	0.428392	1.00	0.842701	1.60	0.976348	2.20	0.998137	2.80	0.999925
0.42	0.447468	1.02	0.850838	1.62	0.978038	2.22	0.998308	2.82	0.999933
0.44	0.466225	1.04	0.858650	1.64	0.979622	2.24	0.998464	2.84	0.999941
0.46	0.484655	1.06	0.866144	1.66	0.981105	2.26	0.998607	2.86	0.999948
0.48	0.502750	1.08	0.873326	1.68	0.982493	2.28	0.998738	2.88	0.999954
0.50	0.520500	1.10	0.880205	1.70	0.983790	2.30	0.998857	2.90	0.999959
0.52	0.537899	1.12	0.886788	1.72	0.985003	2.32	0.998966	2.92	0.999964
0.54	0.554939	1.14	0.893082	1.74	0.986135	2.34	0.999065	2.94	0.999968
0.56	0.571616	1.16	0.899096	1.76	0.987190	2.36	0.999155	2.96	0.999972
0.58	0.587923	1.18	0.904837	1.78	0.988174	2.38	0.999237	2.98	0.999975
0.60	0.603856	1.20	0.910314	1.80	0.989091	2.40	0.999311	3.00	0.999978

Example Service Life Estimate for an Iowa Bridge Deck

Given an Iowa bridge deck constructed with uncoated reinforcing bars with:

C_o = surface chloride concentration = 14.0 lb/yd^3 (as measured in the field),

D_c = chloride diffusion constant = 0.05 (in^2/yr)

End of functional life as defined as 11.5 percent damage in the worst traffic lane,

$\bar{x}$ = 2.74 inches associated with a standard deviation σ = 0.444 inches (as measured in the field), and

$C_{(x,t)}$ = chloride threshold 1.2 lb/yd^3

$$x = \bar{x} + \alpha \cdot \sigma \qquad \textbf{(A)}$$

$$x = 2.74 \text{ inches} + (-1.2)(0.444 \text{ in}) = 2.21 \text{ inches}$$

$$erf(y) = 1 - \frac{C_{(x,t)}}{C_o} \qquad \textbf{(B)}$$

$$erf(y) = 1 - \frac{3.6}{14.0} = 0.914$$

from Table 2, $y = 1.21$

$$t = \frac{x^2}{4\ y^2 D_c} \qquad \textbf{(C)}$$

$$t = \frac{(2.21 \text{ in})^2}{(4)(1.21)^2 (0.05 \text{ in}^2/\text{year})} = 17 \text{ years}$$

The average time between reaching the threshold of uncoated reinforcing bars and initial concrete spalling is approximately 4 years. Therefore, the total functional service of a concrete bridge deck with **uncoated** reinforcing bars = 17 years + 4 years = **21 years**.

Assuming the bridge deck concrete is constructed with epoxy-coated reinforcing bar and the deck is uncracked, the time required for the epoxy-coated reinforcing bars to reach condition 1 can be calculated as follows: **(D)**

$$t = \frac{-\beta_1 \pm \sqrt{\beta_1^2 - 4(\beta_2)(\beta_o - r(t))}}{2\beta_2}$$

t = 60 years

r(t) = 1

Total functional service life of the bridge deck = 60 years + 4 years = **64 years**.

This example illustrates the significant increase in the functional service life (64 years versus 21 years) of a bridge deck constructed with epoxy-coated reinforcing bars, assuming there are no cracks in the concrete deck.

If the bridge deck is cracked, equation D gives a total functional service life of 42 years, still double the estimated life of a bridge deck built with uncoated reinforcing bars.

CONCLUSIONS

Based on this evaluation of representative bridge decks in Iowa, the following conclusions about epoxy-coated reinforcing bars can be drawn:

- ***Most of the corrosion found on epoxy-coated reinforcing bars in this study was on samples from cracked locations on the bridge decks. Conversely, all of the epoxy-coated reinforcing bar samples extracted from uncracked locations showed no evidence of corrosion.***
- ***No delamination or spalling has been found—and no maintenance has yet been performed—on Iowa bridge decks constructed with epoxy-coated reinforcing bars. The oldest bridge deck is over 20 years old.***
- ***Adequate concrete cover depth can significantly prolong the initiation of reinforcing bar corrosion.***
- ***Cracking in a bridge deck has a significant impact on the long-term deck durability.***
- ***There is a threefold increase in the service life of bridges constructed with epoxy-coated reinforcing bars over those constructed with uncoated steel.***