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Summary of Report –

EVALUATION OF MULTIPLE CORROSION PROTECTION SYSTEMS FOR REINFORCED CONCRETE BRIDGE DECKS

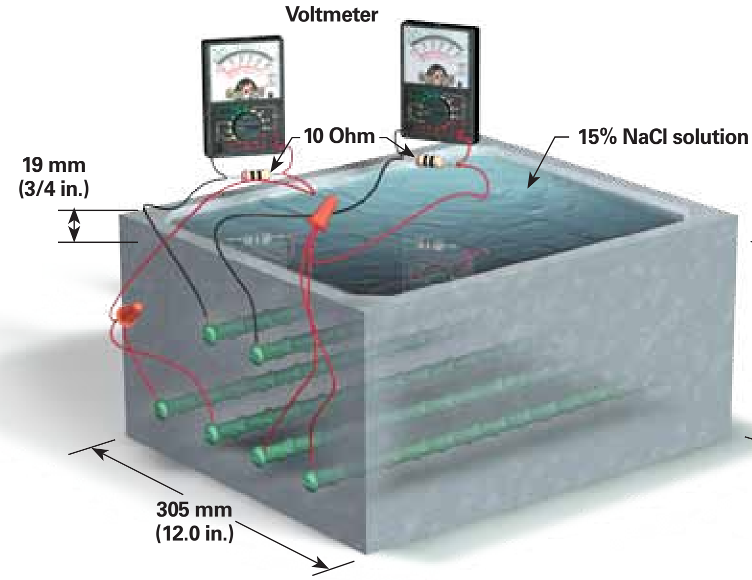
In 2011, the University of Kansas Center for Research published a report titled "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks," based upon a Ph.D. thesis by Matthew O'Reily. Major funding for this work was provided by the Kansas Department of Transportation and the Federal Highway Administration. The 487-page report provides an in-depth evaluation of the performance of corrosion inhibitors, epoxy-coated reinforcing steel and stainless steel. The report includes documentation of extensive laboratory and field research, an evaluation of the amount of corrosion to cause cracking, and an economic analysis. The research supports continued use of epoxy-coated reinforcing steel as corrosion rates were substantially reduced even in cracked concrete and initial and life-cycle costs were lower than the other systems that were evaluated.

INTRODUCTION

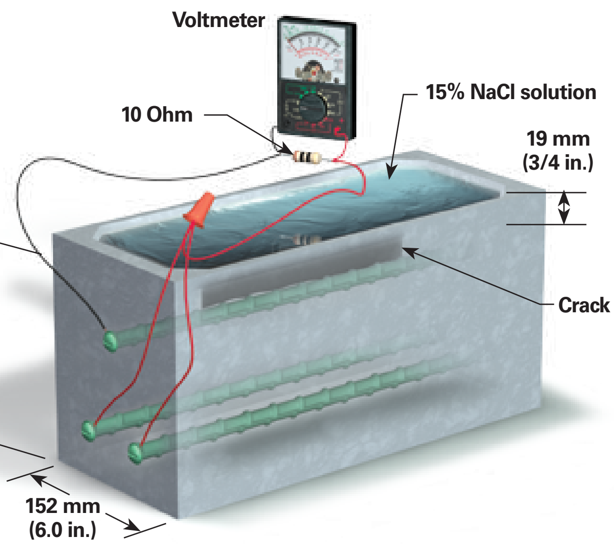
In 2011, a 487-page research report titled "Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks" presenting an evaluation of the performance of several corrosion protection systems for concrete bridge decks was published. These systems included:

- Uncoated reinforcing steel
- Epoxy-coated reinforcing steel (ECR)
- Uncoated steel in concrete containing corrosion inhibitors
- Epoxy-coated steel in concrete containing corrosion inhibitors
- Type 2205 Stainless-steel

Data provided within the report relating to design lives, initial and life-cycle costs of concrete structures are summarized.



Southern Exposure (SE) Specimen



Cracked Beam (CB) Specimen

TEST PROGRAM

Extensive tests were conducted on epoxy-coated and uncoated reinforcing steel in plain concrete and concrete containing corrosion inhibitors. These tests included Southern Exposure, Cracked Beams and Corrosion Initiation specimens as well as Field Exposure slabs.

The concrete for these studies used a Type I/II cement with a crushed limestone coarse aggregate and a Kansas river sand. All concrete was air entrained. Reinforcing steel was obtained from commercial sources. Corrosion inhibitors used were added at the following concentrations:

- calcium nitrite (3 gal/yd^3)
- combined amines and esters (1 gal/yd^3)
- disodium tetrapropentyl succinate (1.54 gal/yd^3)

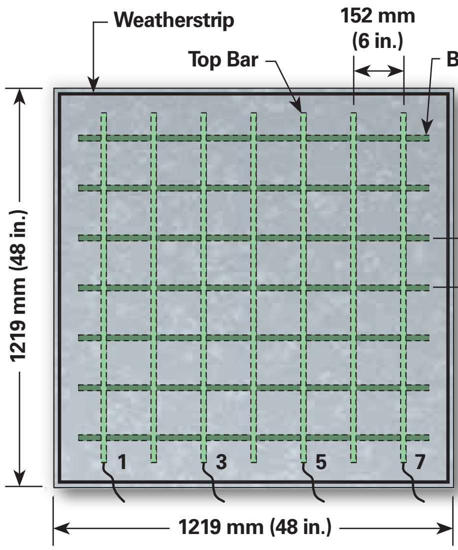
The concrete used for tests used cement contents of 598 lb/yd^3 with a w/c of 0.45, a slump of 3 +/- 0.5 in. and an air content of 6 +/- 1%.

The Southern Exposure tests consisted of slabs measuring 12 x 12 x 7 in. containing two mats of No. 5 ($^5/_8$ in.) bars. The top mat consisted of two bars and the bottom consisted four bars with a clear cover of 1 in. The bars are connected using a 10-ohm resistor to facilitate macrocell measurements. A 0.75 in. dam was integrally cast with the specimen to allow for ponding of these slabs with salt solutions. All epoxy-coated bars were intentionally damaged using a 0.125 inch diameter milling bit. Bars were damaged with either 4 or 10 holes to provide different exposed areas, with half of the holes occurring on each side of the bar.

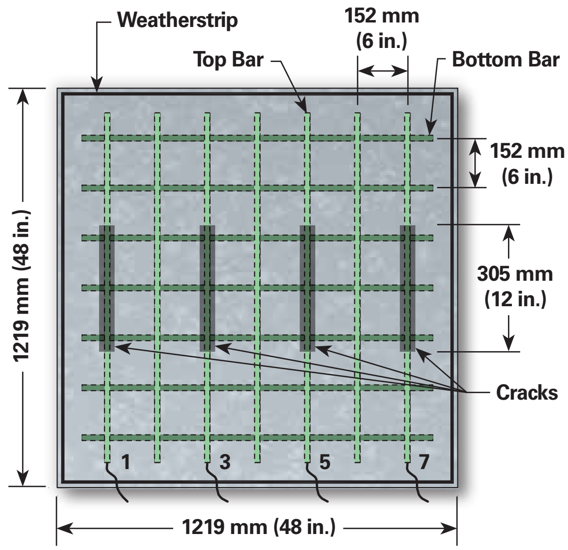
The Cracked Beam specimens were essentially half that of the Southern Exposure test specimens and measured 12 x 6 x 7 in. Prior to casting, a 12-mil (0.012 in.) x 6 in. shim was cast into the concrete mold, creating a 6 in. crack in the concrete exposing the top mat of steel. The Corrosion-Initiation beams were similar in design to the Cracked Beam specimens, except that they did not contain a crack.

The Southern Exposure and Cracked Beam samples were tested over a 96 week period, using two test cycles. The first test cycle involved ponding the samples with a 15 percent sodium chloride salt solution on day 1. On day 4, measurements were conducted and the solution was removed. The samples were then placed under a heat tent at 100 +/-3 °F for three days. This cycle was repeated for 12 weeks. After the 12 weeks of testing, the samples were continuously ponded using a 15 percent NaCl solution. Readings were taken on a weekly basis. After the 12 weeks, the sequence of wet/dry and wetting was repeated for a period of 96 weeks. The Cracked Beam samples followed a similar sequence, except that the testing was terminated following initiation of corrosion.

Epoxy coatings significantly reduce corrosion rates compared to conventional reinforcement.

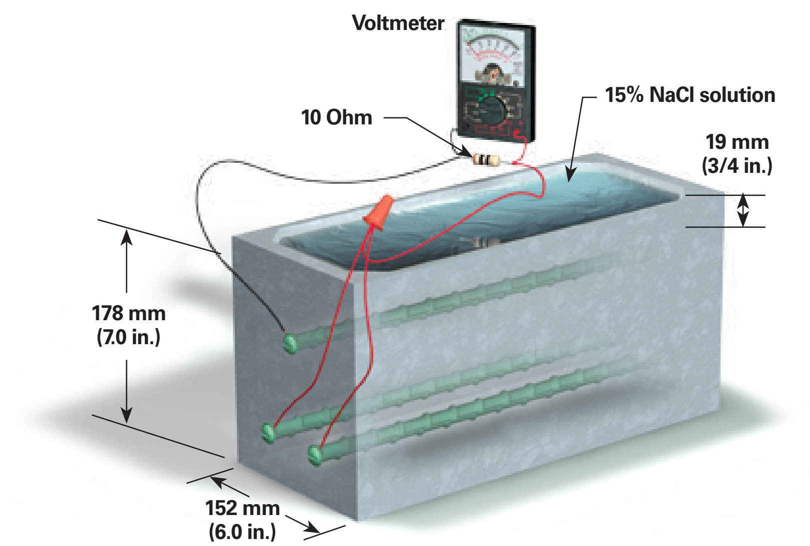


Field Test Specimen Setup — Slab Without Cracks



Field Test Specimen Setup — Slab With Cracks

The Field Test specimens, measuring 48 x 48 x 6.5 in., were cast containing two mats of No. 5 reinforcing steel. Each mat consisted of two layers of seven bars, spaced 6 in. on center. The top mat was run perpendicular to the bottom layer. Specimens were tested in cracked and non-cracked conditions. All epoxy-coated reinforcing steel bars were intentionally damaged using a 0.125 in. drill bit. Each bar was damaged with 16 holes, half on each surface of the bar. The Field Test specimens were stored outside and were ponded with 10 percent rock salt solution, applied every 4 weeks. Test slabs were placed in the field for approximately 4.8 years.



Corrosion-Initiation Beam (CI) Specimen

MEASUREMENTS

Measurement for the Southern Exposure, Corrosion-Initiation and Cracked Beam specimens included macrocell voltage, mat-to-mat resistance, corrosion potential and linear polarization resistance. The amount of chloride in the concrete during the 96 week period was also determined using AASHTO T260-94 at the initiation of corrosion, and after 48 and 96 weeks of testing.

Measurements for the field specimens included macrocell voltage drop, mat-to-mat resistance, and corrosion potential, taken every four weeks for the first 96 weeks and then every 8 weeks. Chloride samples were obtained at the end of the test period.

CORROSION INITIATION

The initiation period is defined as the time at which chloride penetrates in sufficient quantity to initiate corrosion. In order to determine this time, the amount of chloride required to initiate corrosion was required. The onset of corrosion was defined in these tests as occurring when the measured macrocell corrosion rate exceeded 0.3μm/yr or when the corrosion potential became more negative than -0.275V CSE. The average critical chloride threshold values determined using the Southern Exposure tests and Initiation beam tests are shown in Table 1.

INITIATION

Chloride ingress for analysis of the life of bridge decks was based upon work presented by Lindquist et al.(2) An equation was developed to enable prediction of chloride at 3 in. depth in the concrete for bridges with ADDT >7500 (Eqn 1).

Using the threshold values shown in Table 1 and Equation 1 the time to initiation was determined (Table 2).

Table 1:
Critical Chloride Corrosion Thresholds for Corrosion Protection Systems

System	Corrosion Threshold (lb/yd^3)
Uncoated reinforcing steel	1.58
Epoxy-coated reinforcing steel (ECR)	**7.28**
Corrosion inhibitors	0.83 - 3.05
Corrosion inhibitors and epoxy-coated reinforcing	1.69 - 9.85
Type 2205 stainless-steel	26.4

CORROSION RATES

Corrosion rates were generally determined from field test specimens. For uncoated reinforcing with inhibitors, no field tests were cast, so an estimate was made using relationships developed between bench-scale and field tests. Further, in the bench-scale test program for corrosion inhibitors, the uncoated bars in the control concrete exhibited significantly greater corrosion rates than in the test program conducted using the coated bars and thus, additional scaling of the measured corrosion rates was required.

An estimate of the corrosion rate for Type 2205 stainless steel bars was also determined, based upon bench studies, as the field specimens had not exhibit any corrosion during the 4.8 year test program.

The measured corrosion rates assumed that the entire area of the reinforcing steel was corroding; however, the autopsy results showed that for uncoated reinforcing steel, corrosion occurred in localized areas. Thus, the corrosion rates determined from the field results were multiplied by a factor to obtain a localized corrosion rate.

Finally, as both macrocell and microcell corrosion contribute to corrosion losses, the macrocell values were also factored to account for the microcell corrosion.

Table 2:
Time to Initiation, Propogation Period and Time to First Repair

System	Time to Initiation (years)	Progagation Period (years)	Time to first repair (years)
Uncoated reinforcing	2.2	6.8	14
Epoxy-coated reinforcing	**20**	**25**	**50**
Corrosion inhibitor	1 - 4	7 - 27	16 - 33
Corrosion inhibitor & epoxy-coated reinforcing	3 - 24	25 - 46	50 - 63
Type 2205 stainless-steel	68	359	432

**Note: the authors assumed a time to first repair 5 years after cracking.*

Equation 1

$$C(t) = 0.0316.t + 0.746$$

where

t = time (months)

$C(t)$ = chloride content (lb/yd^3)

AMOUNT OF CORROSION TO CAUSE CRACKING

The amount of corrosion to cause cracking was extensively studied by O'Reilly et al. using experimental and finite element analyses. Based upon this work, an equation was developed for the amount of corrosion to cause cracking, based upon the concrete cover, bar diameter, fraction of bar corrosion and fractional area of the corroding bar is shown in Equation 2.

For uncoated and stainless steel reinforcing bars, this critical corrosion value was calculated to be 22 mil. For epoxy-coated reinforcing steel, L_f was calculated to be 0.024 and A_f was calculated to be 0.0023 and the critical corrosion value was calculated to be 96 mil. The value for epoxy-coated reinforcing steel was substantially greater than that for the uncoated bars as corrosion was assumed to only occur at the damage site locations.

Equation 2

$$X_{crit} = 0.53\left(\frac{C^{2-A_f}}{D^{0.38}L_f^{\,0.1}A_f^{\,0.6}} + 0.6\right) X\ 3^{A_f-1}$$

Where

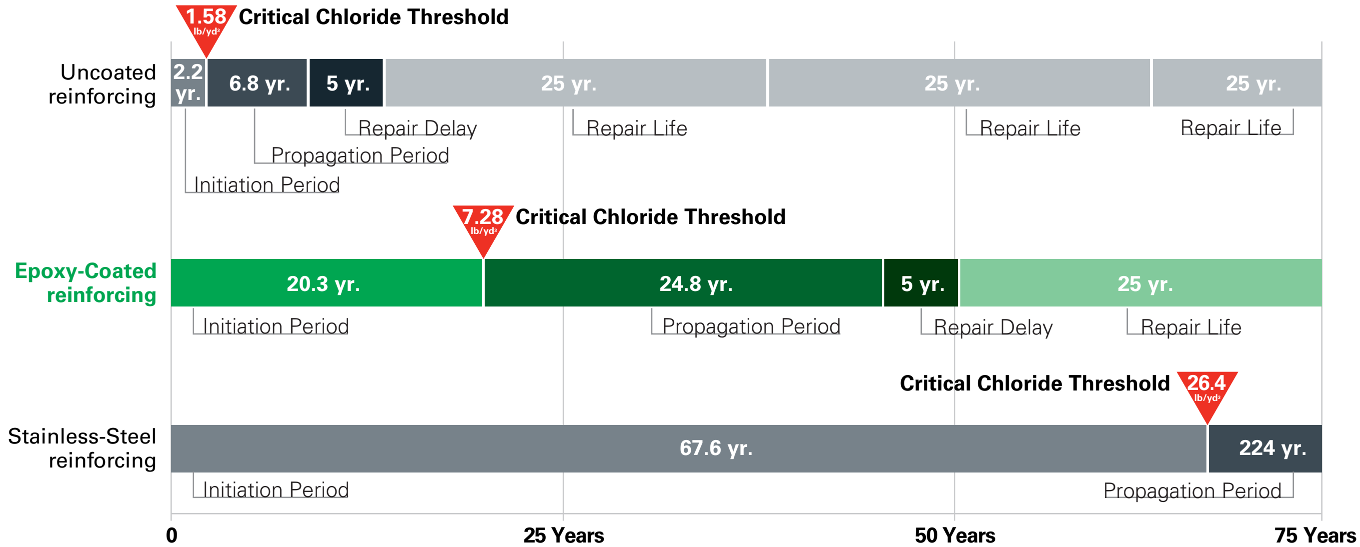
X_{crit} = corrosion loss at crack initiation (mil)

C = cover (in.)

D = bar diameter (in.)

L_f = fractional length of bar corroding, $L_{corroding} / L_{bar}$

A_f = fractional area of bar corroding, $A_{corroding} / A_{bar}$



Initiation, propogation and repair.

PROPAGATION PERIOD

The propagation period was calculated from the corrosion rates measured in the cracked field specimenes and the amount of corrosion required to crack concrete; i.e., 22 mil for uncoated bars and 96 mil for coated bars. The corrosion rates from cracked concrete only were used in the analysis as *"…bridge decks inevitably develop cracks over the reinforcement, the comparisons using the corrosion rates in cracked concrete likely provide the more accurate representation of corrosion in bridge decks."* Calculated values are shown in Table 2.

TIME TO REPAIR

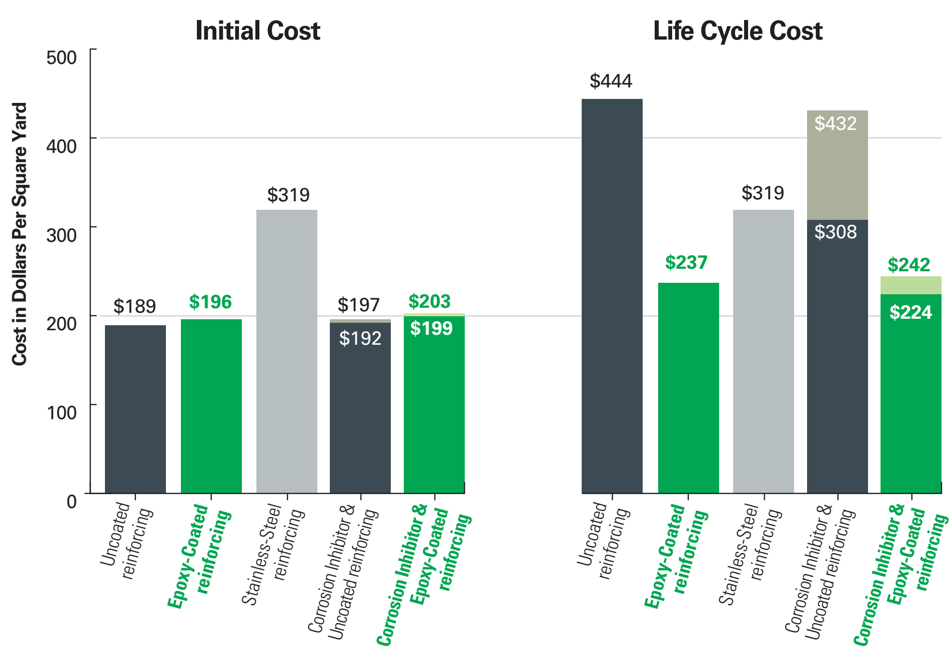
The time to repair is determined by adding the initiation period to the propagation period. An additional five year period was provided to account for time from the first crack to the repair of the deck. The report explains that *"The latter period is based on the observation that a bridge deck is not fully repaired at the development of the first crack. Rather, the bridge typically undergoes a series of short-term temporary repairs. To account for the period of temporary repairs, a five year delay between first cracking and repair is assumed for all corrosion protection systems."* The calculated time until repair is shown in Table 2.

For cracked concrete, the authors indicated that uncoated reinforcing steel would require repair after 14 years. Epoxy-coated reinforcing steel in the cracked concrete would be repaired after 50 years. The reinforcing steel in concrete containing corrosion inhibitors would be repaired after 16 to 33 years and 50 to 63 years for uncoated and epoxy-coated reinforcing steel, respectively. No repairs are used for the stainless reinforcing steel during the 75-year analysis period.

COST EFFECTIVENESS

In economic analysis it is common to use net present value (NPV) to determine the effectiveness of any strategy, shown in equation 3. Calculation of the net present value depends strongly on the discount rate and the timing of maintenance operations.

O'Reilly et al. reported costs of uncoated, epoxy-coated and Type 2205 stainless steel reinforcing as $0.35, $0.45 and $2.35 per lb, respectively. Placement



Initial and 75 Life-cycle Costs using a discount rate of 4 percent.

costs were estimated at $0.52 per lb. Further, they reported that the average amount of steel in a deck was approximately 275 lb/yd^3, based upon an average determined from review of 12 bridges. They also reported that the in-place cost of normal concrete was $562/yd^3 and repair costs were $283/yd^2. It was assumed that these repairs would last 25 years before an additional similar repair would be required.

For uncoated reinforcing steel, the initial deck cost was determined to be $189/yd^2. The use of epoxy-coated reinforcing steel increased the deck costs by only 3.7% to $196/yd^2. When stainless-steel reinforcing was used, deck cost increased by $130/yd^2 or approximately 70% to $319/yd^2.

Life-cycle costs are determined by considering the net present value of all the costs during the life of a structure. Based on using an appropriate discount rate of 4%, the initial and repair costs were considered during a 75-year period. Repairs were assumed to last 25 years before an additional similar repair would be required,and repair costs were assumed to be $283/yd^2.

For uncoated reinforcing steel, the life-cycle cost was estimated to be $444/yd^2, which was approximately 2.3 times the initial deck cost. **The life-cycle cost of a deck using epoxy-coated reinforcing steel was only $237/yd^2, almost half that of the deck containing uncoated reinforcing steel.** When Type 2205 stainless-steel reinforcing was used, the life-cycle cost of the system was $319/yd^2, which was the same as the initial cost, as no repairs were necessary during the 75-year design life, however, this cost was almost $82/yd^2 greater than that of epoxy-coated reinforcing steel.

CONCLUSIONS

Conclusions presented in the report include:

1. Conventional reinforcement exhibits the highest corrosion rates among all systems studied.
2. While corrosion inhibitors reduce the corrosion rates observed for conventional reinforcement, the combination of conventional reinforcement and corrosion inhibitors is not as cost-effective as epoxy-coated reinforcement.
3. **Epoxy coatings significantly reduce corrosion rates compared to conventional reinforcement.**
4. Corrosion inhibitors, in conjunction with both epoxy-coated reinforcing steel and conventional reinforcement, reduce corrosion rates in uncracked concrete; however, corrosion inhibitors are significantly less effective in cracked concrete. Corrosion inhibitors also show relatively less effect when used with epoxy-coated reinforcing steel than when used with conventional reinforcement.
5. For bare conventional steel reinforcing bars, the corrosion losses required to crack concrete are directly proportional to the clear concrete cover. For isolated regions of corrosion, such as occurs at damage sites on epoxy-coated reinforcing steel, the relationship changes to one that is directly proportional to square of the concrete cover as the exposed region on the bar decreases. An equation was developed to predict the corrosion losses required to crack concrete for both bare reinforcement and damaged epoxy-coated reinforcement.
6. For the exposure conditions seen on a typical bridge deck in Kansas, Type 2205 stainless steel reinforcement has a present cost over a 75-year design life that is 10 to 20 percent more expensive than epoxy-coated reinforcement.
7. A bridge deck containing conventional reinforcement has the shortest design life of all corrosion protection systems tested. The use of corrosion inhibitors in conjunction with conventional reinforcement increases the design life of the bridge deck; however, the design

For the exposure conditions seen on a typical bridge deck in Kansas, stainless steel reinforcement has a present cost over a 75-year design life that is 10 to 20 percent more expensive than epoxy-coated reinforcement.

Equation 3

$$NPV = \sum \frac{R_t}{(1+i)^t}$$

Where

R_t = Net cash flow at time t

i = discount rate

t = time of cash flow

REFERENCES

1. O'Reilly, M.; Darwin, D.; Browning, J.; Carl E. Locke, J. "**Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks"**; The University of Kansas Research Inc., Lawrence, KS, 2011.
2. Lindquist, W.; Darwin, D.; Browning, J.; Miller, G., "**Effect of Cracking on Chloride Content in Concrete Bridge Decks. ACI Materials Journal 2006"**, 103 (6), 467.

EPOXY INTEREST GROUP

933 N Plum Grove Road ■ Schaumburg, IL 60173

Tel: 847.517.1200 ■ email: info@epoxy.crsi.org ■ www.epoxyinterestgroup.org