PERFORMANCE OF EPOXY-COATED REBARS: A REVIEW OF CRSI RESEARCH STUDIES

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This is a summary of an evaluation of corrosion research sponsored by the Concrete Reinforcing Steel Institute. This research consisted of three studies by Kenneth C. Clear, Inc. (KCC) of the corrosion resistance of epoxy-coated reinforcing bars and a review of these studies by Wiss, Janney, Elstner Associates, Inc. after some additional laboratory work. The most controversial portion of the KCC work was the accelerated corrosion study involving straight and bent epoxy-coated bars from eight different suppliers. A review of the KCC data and testing of remnant materials indicated that the frequency and size of holidays in the bar coatings was the dominant factor governing epoxy-coated bar corrosion resistance. Bars with fewer than 6 holidays per m (1.8/ft) generally performed well in these rigorous tests. Bars with higher holiday counts, thin film regions, bending damage or large areas of defective coating generally did not perform as well after the prolonged period of tap water soaking. These same bars with reduced corrosion protection qualities during the prolonged tap water ponding generally provided very good corrosion protection during the 70 week cyclic testing, i.e., prior to the prolonged tap water ponding. These same factors, defining the performance of some epoxy-coated bars, are essentially the same as those found in the first comprehensive U.S. study of epoxy-coated bars performed by the National Bureau of Standards (NBS) in 1974.

This is a summary of corrosion research sponsored by the Concrete Reinforcing Steel Institute (CRSI) from 1982 to 1992. These efforts concentrated upon the performance of epoxy-coated deformed bar reinforcement. The research consisted of three studies performed by Kenneth C. Clear, Inc. (KCC), and a review of these KCC studies and subsequent laboratory work by Wiss, Janney, Elstner Associates, Inc. (WJE) in 1991 to 1992. The reader may refer to References 1 and 5 for detailed discussion of these efforts.

HISTORY OF CRSI FUNDED CORROSION STUDIES

Long-Term Outdoor Exposure Evaluation

The initial study, funded by CRSI and performed by KCC (*1*), started in 1982. It was a long-term evaluation of small reinforced concrete slabs stored outside. Research variables were epoxy-coated, galvanized and black bars in both upper and lower reinforcing mats, and epoxy-coated and galvanized bars in the top mat with black bars in the bottom mat. The as-produced epoxy-coated bars had holiday and cut area counts averaging 10 to 13/m (3 to 4/ft), with a maximum of 23 /m (7/ft). Three percent NaCl solution was ponded three days a week on the tops of the slabs and then removed for four days a week for a total test period of about 3 years. Cyclic saltwater ponding was discontinued when chloride contents at the top mat bars exceeded 5.9 kg/m^3 (10 lbs/yd^3) of concrete.

After approximately 3 years of cyclic saltwater ponding and air drying, and an additional 5½ years of outside exposure, KCC found that "the only salted slabs... which did not crack... were the slabs with epoxy-coated reinforcing steel (top mat only and both mats coated) (*1*)." About 6 months later, the same researchers reported "Surveys in the fall of 1991 identified hairline cracking varying from 5 to 30 cm (2 to 12 in) long... on all six salted epoxy-coated rebar slabs" (*2*). These were the same slabs reported on previously. No reasons were given for the deterioration of the six slabs during the summer of 1991. One of the slabs was dismantled after 9 years of outdoor exposure and it was reported that the epoxy-coated bar beneath the crack had "significant corrosion" with "blistered and cracked areas" of epoxy coating.

Evaluation of Bent and Straight Epoxy-Coated Rebars from Eight Suppliers

In 1988 eight suppliers of epoxy-coated reinforcement furnished bars for the 3 year CRSI research effort at KCC (*1*) that involved 40 slabs cycled indoors according to the *NCHRP Report 244* Southern Exposure (SE) test method (*3*). This involved weekly soaking of the top

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of the slab with 15% sodium chloride solution for 4 days, followed by 3 days of drying at 38°C (100°F) and exposure to ultraviolet light. Each slab had two mats of reinforcement. One top mat segment consisted of two straight bars and the other top mat was a single bent bar. The bottom mat consisted of uncorroding black bars electrically connected to each top mat segment. Cover for the top bars was 25 mm (1 in) of concrete with a water-cement (w/c) ratio of 0.47.

After 70 weekly SE cycles, corrosion and cracking had occurred on the uncoated bars in the companion slabs. Chloride content levels at the top mat averaged 12.7 kg/m^3 (21.4 lbs/yd^3). With regard to the 36 slabs with epoxy-coated bars, the researchers concluded after 70 SE cycles that:

- Overall, 53 of the 72 epoxy-coated specimens exhibited negligible macrocell corrosion.
- Seventeen exhibited very low macrocell corrosion.
- Two exhibited moderate macrocell corrosion.
- Straight bars performed slightly better than bent bars.
- Mat-to-mat AC resistance measurements indicated there was no degradation of the epoxy coatings on either the bent or straight bars.
- Slab demolition and autopsies on 11 slabs with epoxy-coated bars indicated only minor corrosion on the epoxy-coated bent and straight bars.

Following the 70 SE cycles, the 25 remaining slabs with epoxy-coated bars were ponded continuously with tap water for either 4.5 or 10.5 months, and then stored outside for an additional 9.5 months. The researcher's finding on corrosion performance was "During the continuous ponding, a majority of the epoxy-coated bent and straight rebar specimens underwent a significant change. Mat-to-mat resistances were reduced many fold and macrocell corrosion currents increased significantly to levels commonly seen on uncoated rebars. Almost complete failure of the corrosion protective properties of many of the coated rebars was indicated." Two significant conclusions from the study were 1) "The only variable which had a significant effect on performance was SOURCE" and 2) "... the deterioration is probably the result of the continuously wet environment."

Field (Bridge Deck) Performance of Epoxy-Coated Reinforcing Steel

A total of 85 cores were taken through epoxy-coated reinforcement from 13 bridge decks in the eastern U.S. during the third KCC study (*1*) for CRSI. These bridge decks ranged in age from 9 to 16 years. As indicated by the researchers, "Overall, 87 percent of the top-mat epoxy-coated rebars were essentially corrosion free, and all of the 13 percent exhibiting significant corrosion were from cores with cracks to the rebar level." A cautionary note based on a small sampling of chloride contents indicated that half the cores, particularly those in uncracked areas, contained reinforcement in an environment without sufficient chloride to start corrosion. The other half of the decks had water-soluble chloride contents between 0.6 and 4.7 kg/m^3 (1 and 8 lbs/yd^3 at the rebar level.

WJE Review

In August 1991, WJE was requested by CRSI to review the June 1991 draft KCC report (*4*) entitled "Effectiveness of Epoxy-Coated Reinforcing Steel," which discussed the three CRSI-funded corrosion studies. The following documents and reports were reviewed: data gathered by KCC, findings noted in the KCC reports, and reports and documents from the Federal Highway Administration (FHWA), KCC and CRSI that related to corrosion behavior of epoxy-coated bars. A preliminary review was completed and a brief report was issued to CRSI in October 1991. The report concluded that the high mat-to-mat AC resistance of the embedded epoxy-coated bars in concrete slabs was the dominant factor in determining corrosion performance during the 70 cycles of the SE testing and the subsequent tap water ponding.

Based on this preliminary review, further investigation of the various slab specimens from the 9 year outdoor exposure study and the 3 year eight source straight and bent bar study, was proposed. This investigation consisted of a series of tests to determine the factors contributing to the corrosion performance. Eleven corrosion-tested slabs, 11 companion slabs not salted but stored outdoors for 3 years, and 54 untested companion, retained bare and epoxy-coated bars (as received from the 8 coated bar sources) were obtained from KCC for this WJE study. Four of the long-term outdoor study slabs also were obtained for the WJE study.

WJE CORROSION STUDY

Initial Considerations

During this study, the physical properties of epoxy-coated bars that might affect bar corrosion durability had to be addressed. Some of the more important properties of the bar coatings are:

- **Coating holidays.** A definition of a holiday is any opening in the epoxy coating capable of transmitting corrosion current. Manufacturers utilize holiday detectors that will sense electrical resistances of 80,000 Ω (ohms) or less. They must meet AASHTO/ASTM limitations as to number and types of holidays during coating operations. Bare areas, caused by damage during transport and job site conditions, must also be addressed.
- **Bar surface preparation.** Adequate blasting is necessary to remove scale and contaminants, and give the bar a proper surface profile to which the coating will adhere. Bar surfaces must meet cleanliness criteria before the coating operation.
- **Coating thickness.** The final coating thickness must meet AASHTO/ASTM limits.
- **Other plant operations.** Operations which may affect coating performance, but not easily checked by bar examination, are bar temperature at coating, powder application techniques, proper gel time, cure, etc.

Details of bar surface preparation and coating thickness are measured by quality control personnel at the coating plant. Equipment to measure the suitability of the epoxy cure, etc., is specialized and usually available only to the epoxy powder coating manufacturer. Determination of the number of holidays in bars and patching of damaged areas is a routine operation conducted by plant inspectors prior to shipment.

KCC Test Procedure

The significance of the test procedures utilized by KCC to measure the corrosion of reinforcement inside laboratory concrete slabs must be considered properly to evaluate the laboratory data.

Test measurements utilized during the CRSI corrosion research were:

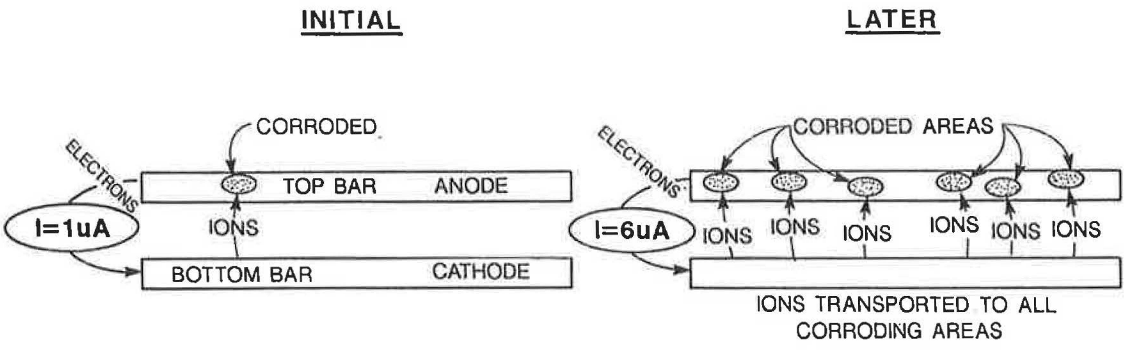
- Half-cell potentials (ASTM C-876).
- Macrocell corrosion currents between top and bottom layers of reinforcement.
- Instant-off potential. The voltage between top and bottom reinforcement layers immediately after this circuit is disconnected.
- Alternating current electrical resistance between top and bottom layers of reinforcement.

Current, voltage and resistance are related by ohms law, that is the current (amperes) equals the potential (volts) divided by resistance (ohms). Corrosion potentials (I/O) are zero with no corrosion and gradually increase to a nominally constant voltage as corrosion becomes pronounced.

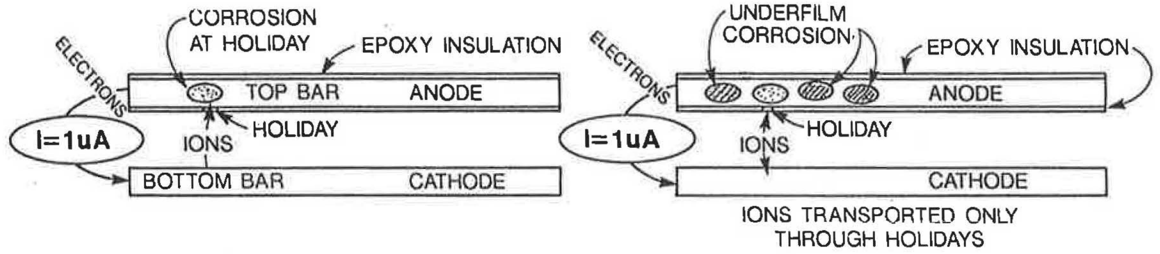
Resistance between bar layers is a function of bare areas of steel (holidays, etc.) in contact with cement paste and of the resistivity of the concrete between the bar layers. Concrete resistivity increases as concrete cures and decreases as electrically-conductive deicing salt permeates concrete pores. Increases in holiday area or ruptures of the epoxy coating during corrosion testing will cause the resistance to decrease.

Figure 1 illustrates the macrocell current relationships between corroding black bars and corroding epoxy-coated bars. Figure 1(a) illustrates that macrocell corrosion currents are a function of the corroding area when black bars are being tested. As shown in Fig. 1(b), this may not be the case with epoxy-coated bars. Epoxy coatings are insulators. Consequently, all macrocell ionic charges are initially funneled to bare steel in contact with cement paste through holiday openings in the coating. Should corrosion occur over significant areas of steel beneath the coating, as in Figure 1(b), measured macrocell currents may not increase significantly until, and if, corrosion pressures break new holes or cracks through the epoxy layer. So long as the area of bare steel at holidays and the I/O potentials at the holidays remain constant, macrocell currents may remain constant also.

In summary, corrosion measurement by electrical testing of slabs containing corroding epoxy-coated bars is not nearly as straightforward as is the testing of slabs with corroding uncoated black bars. Of the three procedures discussed above, the WJE authors believe that the resistance measurements give better information concerning the bar corrosion condition than do I/O potential or corrosion currents. This is because initial resistance measurements give a good indication of the areas of holidays at the start of the test. Changes in resistance are then due either to changes in concrete resistivity or holiday and bare area effects. Since concrete resistivity changes in black-bar companion slabs should be similar to those in slabs with epoxy-coated



(a) BLACK BAR CORROSION



(b) POSSIBLE CORROSION OF EPOXY COATED BAR

Figure 1 Macrocell current "I" may indicate greater corrosion for black bar than for epoxy coated bar.

bars, changes in resistivity of coated bar slabs can be estimated for a test series.

CRSI Long-Term Outdoor Exposure Evaluation

Four of the 9-year old CRSI slabs from the long-term outdoor exposure evaluation were requested by WJE for examination and testing. Two of these slabs (FBCA 48 and 50) had never been salted. Two slabs (FBCA 1 and 5) had been cyclicly ponded with salt water for 3.1 years and then subjected to outdoor exposure for an additional 5½ years; both FBCA 1 and 5 exhibited hairline cracks above some of the bars when received in November 1991. The four slabs were trimmed at each end and then cut in half in a direction transverse to the reinforcement to obtain 20 cm (8 in) long concrete specimens. Electrical connections between bars were reestablished. Then one-half of each original slab was ponded continuously with 15% salt solution, while the other half was ponded with tap water. This conditioning is continuing with most slab sections (October 1992).

The coated bar beneath the hairline crack in the half of slab FBCA 5 that was ponded at WJE with salt solution eventually developed significant rust exudations. After 175 days of continuous salt solution ponding, final electrical measurements were made using the original electrical hookup (with the top reinforcement mat as the anode and the bottom mat as the cathode). Finally, connections were revised so macrocell currents and A.C. resistance could be measured between individual coated bars and the bottom reinforcement mat. After these measurements, the coated bars were removed from the slab, inspected visually and tested for holidays. Attempts were made to pry or peel the coatings loose from the steel substrate with an "X-Acto" knife (No. 11 fine blade). The steel surface condition was categorized as:

- **Intact.** When it was impossible to dislodge the coating without leaving some coating residue adhering to the steel and otherwise disrupting the remaining coating.
- **Poor bond.** When the coating could be pried loose from the steel without leaving residue on the bright-steel surface.
- **Corroded.** When the steel surface was discolored by corrosion products and there was a general loss of bond between the epoxy coating and steel.

Table I shows the information obtained from the FBCA-5 slab. This slab was previously reported (*1*) to contain 31 holidays and cut areas in the four 61 cm (24 in.) long coated bars used in the top mat, i.e., 12.8/m (3.9/ft) -- about average for the other five corrosion tested FBCA slabs.

Bar B was beneath the longitudinal hairline crack. This bar segment had a high macrocell corrosion current and a low resistance of 210 Ω. When this bar was removed from the concrete, about half the coating area was intact while the remainder was blistered and cracked, making it impossible to do a meaningful holiday survey. All the coating on this corroded bar could be dislodged from corrosion stained substrate steel.

Bar A was adjacent to a surface crack. This bar had a high macrocell corrosion current and low AC resistance at 810 Ω. Ten large "areas" located over corroded steel responded to the holiday detector. Approximately two-thirds of the coating overlaid a steel surface discolored by corrosion. One-third of the coating area was bonded to substrate steel. A minor area (4% estimate) of coating was poorly bonded to bright substrate steel.

Bars C and D were cathodic to the lower steel bar mat and had high resistances of 5,300 and 39,000 Ω, respectively. Eight and five holidays, respectively, were detected for the 20 cm (8 in) long segments C and D. As shown in Table I, areas of corroded steel surface were found on these segments, with the largest areas of corrosion in regions where holidays were close together. Minor areas of disbonded coating over bright steel occurred near a few holidays. Those bars maintaining high resistance provided the best corrosion performance. Testing of the remaining slabs is continuing at WJE (October 1992).

CRSI Evaluation of Bent and Straight Epoxy-Coated Rebars from Eight Suppliers

Eleven corrosion-tested slabs, 11 companion slabs not salted but stored outdoors for 3 years, and 54 untested bare and epoxy-coated bars (as received from the 8 sources) were obtained from KCC. The 11 corrosion-tested slabs had two straight bars (one condition) and one bent bar (another condition). Six conditions had essentially no macrocell corrosion current, two had low current, four had moderate current, and 10 had high corrosion currents when received in November 1991. Numerous tests were performed on these 22 reinforced concrete slab test conditions and their companion, untested epoxy-coated and bare bars.

The details of the extensive WJE study are discussed in the June 1992 report (*5*). The observations and conclusions from this investigation are described below.

The corrosion studies conducted at FHWA and WJE during the past 12 years and those conducted at KCC each used a different corrosion test method. The severity of these test methods, as judged by the corrosion current density measured on the black bar samples, varied widely. At the conclusion of the 70 SE weekly cycles (prior to tap water ponding), the average black bar currents were 2.10 μA/cm^2 (1.95 mA/ft^2). After the subsequent three to 10.5 months of tap water ponding, the average black bar currents were 3.79 μA/cm^2 (3.52 mA/ft^2). These values are much higher than the 1.6 μA/cm^2 (1.50 mA/ft^2) found at the conclusion of the 1-year FHWA "non-specification" study (*6*), the 1.57 μA/cm^2 (1.46 mA/ft^2) at the conclusion of the 3.1 year ponding period in the 9-year long-term study (*7*), and the 0.96 μA/cm^2 (0.89 mA/ft^2) at the conclusion of a 48-week SE cycle study (*8*). Therefore, the 70-week SE cycles and tap water ponding conditions were more severe than previous accelerated corrosion studies undertaken on epoxy-coated bars.

Even with such severe test conditions and the fact that numerous coated bars had excessive holidays, the 36 corrosion-tested slabs (with 72 coated bar test conditions) exhibited the following corrosion current density distributions at the completion of the 70 SE cycles:

Corrosion current density less than	% of 72 test conditions
2.10 μA/cm^{2,*} (1.95 mA/ft^{2,*})	100
1.08 μA/cm^2 (1.00 mA/ft^2)	100
0.108 μA/cm^2 (0.10 mA/ft^2)	96
0.0108 μA/cm^2 (0.01 mA/ft^2)	74
0.00108 μA/cm^2 (0.001 mA/ft^2)	44

* Average of black bar companion slabs

These data show that the coated bent and straight bars exhibited low corrosion current densities when compared to the average of 2.10 μA/cm^2 (1.95 mA/ft^2) for the

Table I PROPERTIES OF EPOXY-COATED BARS FROM FBCA-5 CRSI SLAB AFTER TESTING AND AUTOPSY IN JUNE 1992

Bar Segment	Macrocell Current (μA)	A.C. Resistance (Ω)	Coating-Steel Interface (%)			Holidays Detected per 20 cm (8 in) bar
			Intact	Poor Bond	Corroded	
A	-63	810	30	4	66	10
B	-430	210	--	-	100	Too many to determine
C	+4	5,300	91	3	8	8
D	+1	39,000	89	5	6	5

black bar companion specimens at the end of the 70 SE cycles. These data indicate that 96 percent of the test conditions experienced 20 times less macrocell corrosion than the black bar, 74 percent experienced 200 times less, and 44 percent experienced at least 2000 times less. These 72 test conditions did not exhibit a rust stain or crack at the end of the 70 SE cycles. The four uncoated black bar slabs were rust stained and cracked at this age.

The 72 test conditions exhibited the following corrosion current density distributions after the completion of the subsequent tap water ponding:

Corrosion current density less than	% of 72 test conditions
3.79 $\mu A/cm^{2,*}$ (3.52 $mA/ft^{2,*}$)	99
1.08 $\mu A/cm^2$ (1.00 mA/ft^2)	85
0.108 $\mu A/cm^2$ (0.10 mA/ft^2)	49
0.0108 $\mu A/cm^2$ (0.01 mA/ft^2)	26
0.00108 $\mu A/cm^2$ (0.001 mA/ft^2)	18

* Average of black bar companion slabs

These data show that after tap water ponding, the average macrocell corrosion currents in the straight and bent black bar companions increased by 80 percent, from 2.10 to 3.79 $\mu A/cm^2$ (1.95 to 3.52 mA/ft^2). The data show also that the tap water ponding increased the corrosion currents in some of the epoxy-coated bars. These data indicate that 49 percent of the test conditions experience at least 35 times less macrocell corrosion than the black bar, 26 percent experience at least 350 times less, and 18 percent experience at least 3500 times less.

As discussed previously, direct comparisons of macrocell currents between black bar companion slabs and slabs reinforced with bars coated with an electrical insulator might misrepresent the magnitude of corrosion occurring within the two systems. The relationship between maccocell currents and general corrosion conditions in two slabs is comparable if both slabs have epoxy-coated reinforcement. However, because of this consideration, the most significant information in the preceding tables is that there was about three orders of magnitude difference between the macrocell corrosion currents of epoxy-coated bars after 70 SE cycles and about four orders of magnitude between the currents in the same slabs after ponding with tap water. In addition, those slabs with the lowest macrocell corrosion currents were found to contain essentially corrosion-free epoxy-coated bars.

The KCC data (*1*) show that only 16 of these 72 test conditions developed cracks during the tap water ponding. These 16 conditions did not sustain a high electrical resistance during the tap water ponding period. They ended up with low "final resistance ratios" compared to black bar specimens (*5*). This KCC study contained three series. Series I slabs had three months of continuous tap water ponding, Series II had 10½ months and Series III had 4½ months. The 56 uncracked specimens following the Series I, II and III ponding tests had "final resistance ratios" averaging 62, 150, and 205 for straight bars, respectively, and 33, 105 and 11 for bent bars (*5*). The 56 uncracked coating conditions were supplied from all eight sources. The 16 cracked coating conditions were from sources 1, 2, 3, and 7.

The corrosion performance is related to the holiday count (that is, any hole or defect in the coating that permits current to pass between the bare steel and liquids) and electrical resistance qualities, and not based on the bar source as reported in reference (*1*). High, sustained electrical resistance properties depend upon proper film thickness, good surface preparation and low holiday counts. These same factors were identified for FHWA by NBS in 1974 (*9*). A total of 20 of the 72 epoxy-coated bar test conditions provided these properties in the KCC study following tap water ponding. Seven of the bent bar configurations (4 with patches) and 13 of the straight bar configurations had final corrosion current densities less than about 0.011 $\mu A/cm^2$ (0.01 mA/ft^2), averaging 0.0027 $\mu A/cm^2$ (0.0025 mA/ft^2). These test configurations were supplied by sources 1, 3, 4, 5 and 6. The 13 straight bar specimens maintained an average resistance of about 327,000 Ω and the 7 bent bar specimens maintained an average resistance of about 14,000 Ω following the tap water ponding. The following observations can be made based on the KCC data and studies at WJE.

- **Holidays were the dominant factor in determining the corrosion performance of the tested specimens.** After the 70 weeks of SE cycling, 30 of the 38 retained coated bars with less than 98 holidays/m (30/ft) had companion corrosion tested slabs with current densities less than 0.011 $\mu A/cm^2$ (0.01 mA/ft^2). However, after tap water ponding, slabs with companion bars with 7 to 98 holidays/m (2 to 30/ft) exhibited poorer corrosion performance. Retained bars with 98 holidays/m (30/ft) had companion slabs that provided poor performance during both test phases. Eight retained bars had 3 to 7 holidays/m (1 to 2/ft). Their companion tested slabs performed well in the 70 weeks of SE exposure but had performance varying from excellent to poor when subjected to tap water ponding. Eight retained bars of the 38 with less than 2 holidays/m (1/ft) had companion slabs that exhibited excellent corrosion performance at the conclusion of the 70 weeks of SE cycling and the tap water ponding.
- **Coating films are consistently thinner at the edge of deformations than in the areas between the deformations.** This difference averaged about 0.9 mils with straight bars and about 2.2 mils with bent bars. The edge of the deformation was often times found to be a point of corrosion weakness. Microscopic measurements of coating thicknesses suggest thin films influence holiday formation and can contribute to poor corrosion performance. Microscopic examination found numerous corrosion spots that relate to thin film (2 mils) at regions that contained or developed holidays and corrosion. Undesirable thin films can be identified by laboratory microscopic measurements of bar cross-sections that would not be detected by currently specified testing techniques (that is, magnetic gage measurements taken in the flat areas between the deformation).
- **Electrical resistance, particularly at the start of testing, is a good measure of holidays and the potential corrosion protection qualities of epoxy-coated rebar.** There appears to be a good relationship between the percentage of metal exposed and the electrical resistance properties of a coated bar. The KCC researchers in the 70 week SE cycle study (*1*) measured a wide range in the initial mat-to-mat electrical resistance of the coated bar slabs. These differences correlated with numbers of holidays and electrical resistance properties measured in the follow-up study on companion retained bars (*5*). The follow-up study tested 15 retained coated bars. Resistance ranged from 8 Ω to 450,000 Ω. The 8 Ω coated bar had several large, uncoated areas. Other coated bars having low resistances (30 to 100 Ω) had 33 to 105 holidays/m (10 to 32/ft). Resistance tests on retained coated bars and review of the initial mat-to-mat resistance of the test slabs show that bars with high holiday counts or large bare areas were used in the bent and straight bar study. The resistance test is a good laboratory procedure to determine holiday and potential corrosion protection qualities based on the good correlation between the initial resistance and final corrosion current test results.
- **The 1974 NBS feasibility study (*9*) and the 1980 to 1983 FHWA non-specification bar study (*6*) showed the same type of correlation of initial resistance to corrosion performance.** Review of the straight bar initial mat-to-mat resistance data from KCC showed that the corrosion performance can be estimated based on this initial resistance.
- **Corrosion by-products are indicative of filiform corrosion.** Filiform corrosion results in hair-like corrosion tracks that occur beneath coatings of steel or other metals when exposed to a humid environment. The corrosion originates at a break in the coating. The filiform track is composed of a head and a tail. Corrosion takes place at the anodic head with the tail section being primarily cathodic. The separation between the anodic head and cathodic tail areas allows the cell to move beneath the coating in one direction. Anions

migrate to the head, due to the solution potential difference and the polarity difference between the head and tail. Oxygen and water are supplied to the head through the break in the coating and through the porous tail. Oxygen and water are required for filiform corrosion to propagate. Generally, the higher the humidity, the more rapid growth of this corrosion. When a low relative humidity is reached, the saturated solution cannot be maintained in the head, and the corrosion cell will dry out and stop. The lower relative humidity limit for filiform corrosion on steel is approximately 60 percent (*10*). Filiform corrosion is relatively insensitive to the type of coating and does not correlate to the permeability of the coating. This aspect of the corrosion process of epoxy-coated bars needs further study.

- **Limited scanning electron microscopic (SEM) studies on the cross-section of epoxy chips removed from bars after corrosion slab testing indicated that chloride did not penetrate through the epoxy coating.** Chloride ions were present along the exterior surface and along the steel interface in areas of corrosion beneath the coating, but not within the epoxy coating. This suggests that the chloride did not penetrate the coating, but entered through a break in the coating and traveled along the steel surface.
- **While most bent bars exhibited poorer performance than their companion straight bars, the use of 100 percent patching of bending-induced holidays produced corrosion-free conditions with two bent bar test conditions.** This illustrates the positive effect that patches can have on corrosion performance.
- **The role that osmotic pressure played during the tap water ponding in creating corrosion is still unknown.**

The following are items in the eight-bar source report (*1*) where additional information was needed to effectively evaluate the corrosion performance of coated bars:

- The as-received epoxy film thicknesses and thickness distributions for the 72 test conditions.
- The as-received holiday and bare area counts per meter for these 72 test conditions.
- The as-received backside contamination characteristics of the epoxy films.

Testing by the authors provided data which resulted in the following observations:

- Essentially none of the tested bars achieved the investigation's targeted film thicknesses of 6, 9 and 12 mils.
- Review of the film thicknesses found that seven of the 22 slabs contained bars having film thicknesses less than 5 mils. All of these slabs developed corrosion activity, except for CR9-SE1 where 26 patches were applied to the bent bar holidays.
- The holiday counts performed on 48 coated retained, untested bars were found to be higher than the KCC count data on companion bars.
- The holiday counts on 48 retained, untested coated bars varied from less than 3 to 115 holidays per m (1 to 35/ft). Therefore, numerous as-received coated bars were of "non-specification" quality.
- No correlation was observed using the SEM techniques between the performance of companion specimens in the slab corrosion tests and the presence of contaminates on the backside of the chips removed from retained bars. Contamination of chloride ions was not found in large quantities on the backside of the chips removed from the retained bars.

Factors that did not have a significant influence on the variability of test results were: differences of clear cover over the bars, concrete water absorption, epoxy water absorption, surface roughness of blasted bars prior to coating, backside contamination on the epoxy film, and curing of the epoxy coatings.

Other factors which need to be considered in testing and long-term structure durability are:

- The corrosion research studies during the period 1975 to 1990 (*1,6,7,8,11,12,13,14*) on unprotected black rebar and epoxy-coated rebar have utilized clear cover of 19 to 25 mm (¾ to 1 in) and w/c ratios between 0.47 and 0.53. These test conditions were selected by the researchers to produce "worst case experiments" as noted in the 1983 report (*6*). These conditions result in early initiation of corrosion of unprotected, black rebar and early cracking of concrete over these black bars with minimal cover. The 3-year FHWA-sponsored corrosion study (*8*) with 0.50 w/c ratio concrete showed that the time-to-corrosion for black bar with 25 mm (1 in) cover occurred after six weeks of SE cyclic testing. With 50 and 76 mm (2 and 3 in) clear cover, there was no corrosion with the same black bar and a 0.50 w/c ratio concrete after 48 weeks of SE cyclic testing. The time-to-corrosion for black bar was eight times longer when 50 or 76 mm (2 or 3 in) clear cover was used when compared to 25 mm (1 in).
- Another significant consideration is the time prior to cracking. Concrete test specimens with 19 to 25 mm (¾ to 1 in) clear cover will crack earlier and with less corrosion-induced pressure than specimens with

corroding bars with 50 or 76 mm (2 or 3 in) of cover. AASHTO clear cover specification requirements for the top mat were changed from 25 mm (1 in) to 50 mm (2 in) in 1974 and the AASHTO w/c ratio was changed in 1974 to a maximum of 0.44. Thus, bridge decks constructed in the last 18 years have 50 to 76 mm (2 to 3 in) of cover and higher strength concrete. Projections of serviceability life for black or epoxy-coated rebars, based upon corrosion research utilizing 19 or 25 mm (¾ or 1 in.) clear cover and high w/c ratios, will not reflect the actual serviceability conditions of black or epoxy-coated rebars embedded deeper in more crack resistant concrete.

SUMMARY

To summarize, excellent corrosion protection was achieved under the severe eight-bar source corrosion study when slabs reinforced with straight and bent bars with original retained coated bars having less that 3 to 7 holidays per m (1 to 2/ft) were tested. Properly patched bent bars with bending-induced damage and bent bars that were not patched, and which had the same low holiday counts, were essentially corrosion free. Detained coated bars with 7 to 115 holidays per m (2 to 35/ft), very thin film regions, or large areas of defective coating were associated with slabs which provided less corrosion protection and became corroded during the prolonged tap water ponding. This reduction in corrosion protection should be anticipated since every "holiday" can pass corrosion current when subjected to rigorous corrosive environments, such as were imposed upon the 8-bar source specimens. These same bars with reduced corrosion protection qualities during the prolonged tap water ponding generally provided very good corrosion protection during the 70 SE cycles, i.e., prior to the prolonged tap water ponding. Field cores by KCC (*1*) from 13 bridge decks ranging in age from 9 to 16 years showed that 87 percent of the top-mat epoxy-coated bars were essentially corrosion-free.

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