Long-Term Outdoor Exposure Evaluation of Concrete Slabs Containing Epoxy-Coated Reinforcing Steel

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Corrosion characteristics of straight epoxy-coated reinforcing steel (which met AASHTO and ASTM specifications) in concrete were studied. Specimens were exposed outdoors in a northern environment for more than 6.5 years, including about 3.1 years of salting cycles with a 3 percent sodium chloride solution. Straight epoxy-coated bars were evaluated when they were used in both mats and when they were used in the top mat only. An additional study variable was the use of uncoated bars in both mats. Results indicated that epoxy-coated rebars are many times more resistant to corrosion-induced damage than uncoated bars when embedded in salt-contaminated concrete and coupled to coated or uncoated bars in salt-free concrete. Overall best performance was achieved when the bars in both mats were epoxy coated. An observed softening of the coating in top- and bottom-mat bars after long-term exposure in the highly alkaline environment is also discussed.

For more than a decade, epoxy-coated reinforcing steel has been effective in reducing or preventing chloride-induced corrosion in bridges and other concrete structures. Widespread acceptance of this technology is exemplified by the current use of epoxy-coated bars in most state highway bridges (*1*). An evaluation of 22 Pennsylvania bridge decks with epoxy-coated reinforcing steel and black (uncoated) steel indicated good performance through 10 years of service (*2*). Although 4 of the 11 decks with uncoated bars showed corrosion-induced concrete deterioration, none of the 11 decks constructed with epoxy-coated bars showed any visual signs of corrosion-induced deterioration.

The widespread use of epoxy-coated reinforcing steel and the excellent field performance in deicing-salt environments are not surprising. It is well known that corrosion of reinforcing steel in concrete (excluding that associated with carbonation) requires sufficient chloride ions, oxygen, and moisture at the steel surface. One therefore can prevent or retard corrosion by eliminating one or more of these factors. Early research by the National Bureau of Standards (NBS) and the Federal Highway Administration (FHWA) indicated that reinforcing bars, coated with select powdered epoxies by an electrostatic spray process after bar cleaning, performed well in salt-contaminated concrete (*3,4*). Such coated rebars were resistant to high rates of corrosion and thus early-age deterioration of the surrounding concrete because the pressures generated by expansive corrosion products were minimized. The primary advantage of an epoxy coating is that it acts as a barrier that prevents chloride ions from reacting at the steel surface. Further, by increasing the electrical resistance between neighboring coated steel, an epoxy coating reduces the magnitude of macroscopic corrosion cells responsible for extensive early bridge deck deterioration (*5*).

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Laboratory studies generally concur that epoxy-coated reinforcing steel in concrete contaminated by chloride is superior to bare reinforcing steel in preventing corrosion (*3–6*). It was further determined that epoxy-coated reinforcement was most successful if all the reinforcement was coated as compared with only the upper mat steel and the black lower mat steel (*5,6*). Quality control during the coating application process and subsequent handling of the fabricated bars is of the utmost importance. Strict adherence to ASTM A 775 and AASHTO M 284 specifications is required to effectively use epoxy-coated steel to prevent or reduce the damaging effects of chloride-induced corrosion.

Despite positive laboratory and field performance studies, however, premature corrosion-related deterioration has recently been observed on several bridge substructures incorporating epoxy-coated reinforcement. These structures are located in the Florida Keys and were constructed 6 to 9 years ago (*1,7*). Many field and laboratory investigations are being conducted to determine the cause of the unexpected corrosion (*8,9*).

To address the overall performance of epoxy-coated reinforcing steel in salt-contaminated concrete, the results of a more than 6.5 year, outdoor exposure, comparative study of coated and uncoated reinforcing steel are presented.

EXPERIMENTAL PROCEDURE

Ten 1- × 2-ft concrete slabs, 6-in. thick, were fabricated in September 1982. The slab design is shown in Figure 1. Nine of the slabs were reinforced with four 30-in.-long bars on the top level and six 30-in.-long bars on the bottom level. The remaining slab was unreinforced. Of each bar, 24 in. is embedded in the slabs, with the remainder extending from the two edges. No connections between bars are present inside the concrete. This setup facilitates external connection of the top bars separately from the bottom bars and the subsequent monitoring of the corrosion current flowing between the mats. Earlier FHWA research indicated that such macroscopic corrosion cells, in which a macrocathode on the bottom-mat rebar in salt-free concrete drives corrosion of uncoated top-mat steel in salty concrete, are primarily responsible for rapid corrosion-induced deterioration (*4*).

Reinforcing steel (No. 5, Grade 60) from one production lot was used for all slabs. A portion of the bars was epoxy coated, using Scotchkote 214, in accordance with Maryland Department of Transportation, AASHTO M 284-81, and ASTM D 3963-81 specifications. The bars were plant-coated as part of a normal field production run (i.e., no special coating or handling was used). The coated and uncoated bars were chosen randomly from the production lot for use in each slab. Before being cast in concrete, coated bars were evaluated for coating thickness and number of holidays and cut areas. Coating thickness was measured (using a Mikrotest Model II thumbwell magnetic gauge calibrated according to National Bureau of Standards guidelines) at three locations on each side of each bar along the portion that was to be embedded in concrete. The number of holidays and cut areas was determined using a 67.5-volt Tinker-Rasor Model M-1 holiday detector. The concrete used for all slabs complied with 1982 Virginia Department of Highways specifications for high-quality bridge deck concrete, except that a higher-than-normal air content was used as additional insurance against deicer scaling. Table 1 provides details on this concrete mix design, which exhibited a water-to-cement ratio of 0.42. Clear concrete cover over the top-mat reinforcing steel was 1.0 in. Slab fabrication was accomplished from one 2.5-yd^3 ready-mix batch. The slabs were then cured for 7 days using wet burlap and polyethylene.

Three groups of three slabs each were fabricated with the following variables:

- Epoxy-coated bars in both mats;
- Epoxy-coated bars in the top mat and black steel (uncoated) bars in the bottom mat; and
- Black steel bars in both mats.

An additional unreinforced slab was also included.

After fabrication and curing, reinforcement in each slab was made electrically continuous using external wiring, and the top and bottom mats were connected through a resistor and switch to monitor the macrocell corrosion current [flowing between the top (anode) and bottom (cathode) rebar] and the AC resistance between the rebar mats in the uncoupled mode (see Figure 1). The sides of each slab and all exposed steel were then coated with epoxy and ½-in. diameter holes were drilled to a 3-in. depth in each slab to measure bottom-mat electrical half-cell potential. To introduce chloride at the level of the top steel, dams were placed around the top surface of each slab for salt ponding. The surface around the bottom-mat potential wells was built up using plastic pipe and polymer mortar to prevent salt solution from entering the holes.

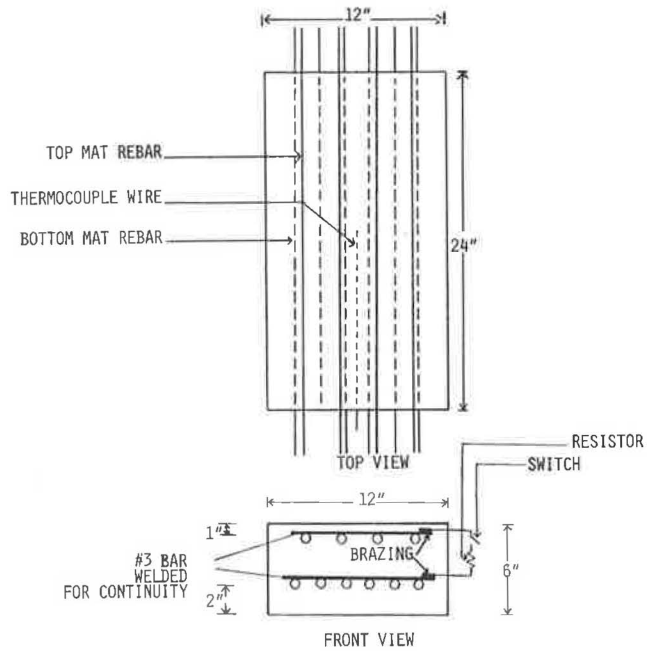

FIGURE 1 Specimen design.

From initial testing in November 1982 through December 1985—3.1 years—all slabs were subjected to weekly exposure cycles of 3 days of ponding with a 3 percent sodium chloride solution followed by 4 days of natural weathering with the solution removed. At select intervals, chloride content versus depth was determined on the unreinforced slab according to AASHTO T-260. Salting was terminated in December 1985 because large quantities (more than 10 lb/yd^3) of chloride were present at the top rebar level. The dams on the slab surfaces were then removed and subsequent exposure was to natural weathering only. A bar graph showing rebar level chlorides defined at various times during the salting cycles is presented in Figure 2.

The results represent an exposure period of more than 6.5 years. The corrosion characteristics of the slabs were periodically monitored using macrocell corrosion current measurements, AC electrical resistance measurements (between the rebar mats when uncoupled), and top- and bottom-mat electrical half-cell potentials. In addition, concrete temperature was recorded with each data set. The macrocell corrosion current for each slab was measured as the voltage drop across the resistor installed between the rebar mats.

Throughout the test period the slabs were exposed above ground at the Kenneth C. Clear, Inc. outdoor exposure facility located in Herndon, Virginia, a suburb of Washington, D.C. Following the exposure period, a full-depth core was obtained from one slab representing each variable. Each core contained a portion of the top and bottom steel. The cores were saw cut and split open to expose the bars. Visual examinations were then conducted to determine relative corrosion activity and to investigate any physical changes in the epoxy coating.

TABLE 1 CONCRETE MIX DESIGN

Cement (Portland Type I, ASTM C150)	635 lbs/cu yd
Coarse aggregate (Crushed limestone)	1928 lbs/cu yd
Fine aggregate (silica sand)	1146 lbs/cu yd
Water reducing/retarding agent (Daratard 17, ASTM C494)	13.5 oz/cu yd
Water	268.5 lbs/cu yd
Slump	4 inches
Air content (Admixture Daravair, ASTM C494)	9.5%
Water/cement ratio	0.42

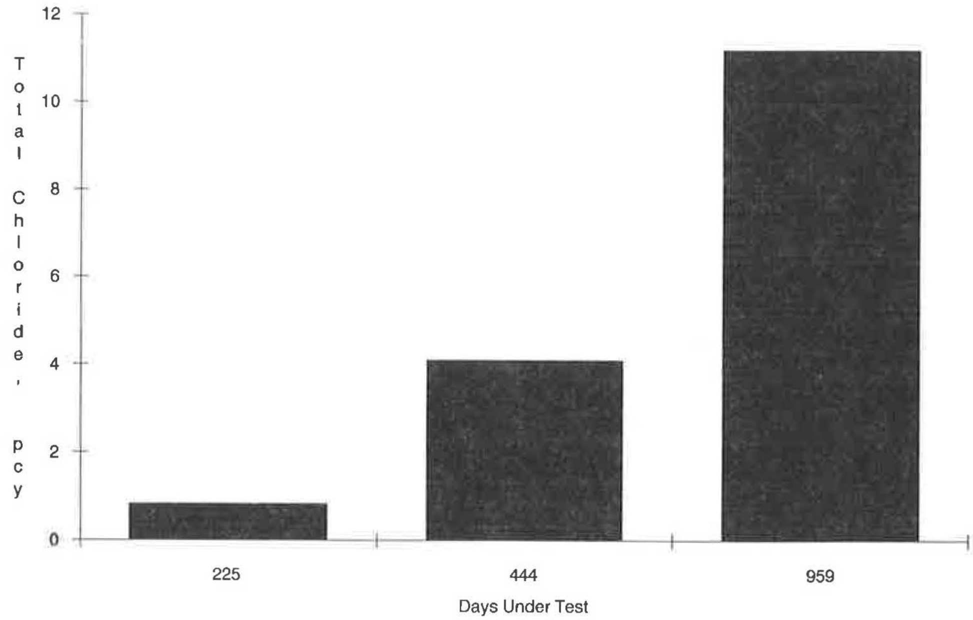

FIGURE 2 Rebar level chloride versus time.

RESULTS AND DISCUSSION

Coating thickness measurements, obtained before casting at three locations on each side of each bar along the portion that would be embedded in concrete (i.e., 24 measurements for each top mat and 36 measurements for each bottom mat), are summarized in Table 2. The average coating thickness was 9.9 mils with a range of 4.1 to 21.5 mils.

Table 3 presents the total number of holidays and cut areas on each mat of coated rebar. There are four bars in each top mat (8 lineal ft) and six bars in the bottom mat (12 lineal ft). The top mat average was 3.5 holidays and cut areas per lineal ft of bar and the bottom mat average was 2.7, for an overall average of 3.3. Most were, of course, not visible to the unaided eye.

The macrocell corrosion current parameter is a direct measure of the electrons released by the macrocell corrosion process and therefore provides a direct measure of macrocell corrosion activity. Microcell corrosion (i.e., anodes and cathodes are present on the same bar with corrosion activity but no current flows between the mats) probably occurs also, but macrocell corrosion has been reported as the main cause of rapid corrosion-induced deterioration. Also, corrosion current is dependent on concrete temperature, primarily because of the effect of temperature on resistance. Therefore, all macrocell corrosion current and mat-to-mat resistance data were adjusted to 70°F equivalents using the known resistance of the current shunt, concrete temperature at measurement, and formulas provided by Clear (*10*).

Figures 3 and 4 present the average adjusted (i.e., 70°F) macrocell corrosion current versus time for the three variables studied. For epoxy-coated bars in both mats (Figure 3), the average corrosion current was zero or negligible (less than 10 μA) for the test duration (overall average was 0.61 μA). Slabs with epoxy-coated bars in the top mat only (Figure 3) started with zero corrosion current and after about 0.4 year of salting, variable but very low corrosion currents were measured (overall average was 3.23 μA). Slabs with black steel in both mats (Figure 4) began to show measurable corrosion currents 0.2 year into the study. After 1.2 years of salting, corrosion currents increased drastically, averaging 886.87 μA through 3.7 years. Values were frequently more than 40 times the maximum current measured in the slabs with epoxy-coated bars in the top mat only and more than 100 times that for the slabs with epoxy-coated bars in both mats. Macrocell currents remained at high levels through the remaining test period,

TABLE 2 COATING THICKNESS

Slab Number	Variable	Coating Thickness, mils: Top Mat Ave.	Top Mat Range	Bottom Mat Ave.	Bottom Mat Range
1	Epoxy Both Mats	12.8	5.1 to 21.5	10.2	5.4 to 19.5
2	Epoxy Both Mats	12.2	8.0 to 19	10.1	7.2 to 17.5
3	Epoxy Both Mats	9.2	5.0 to 16	9.5	4.8 to 15.5
4	Epoxy Top Only	9.5	6.0 to 15.5	--	--
5	Epoxy Top Only	8.6	4.3 to 13	--	--
6	Epoxy Top Only	7.3	4.1 to 12	--	--
	All Epoxy Coated	9.9	4.1 to 21.5	9.9	4.8 to 19.5

TABLE 3 HOLIDAYS AND CUT AREAS

Slab Number	Variable	Total Holidays And Cut Areas: Top Mat	Bottom Mat
1	Epoxy Both Mats	22	34
2	Epoxy Both Mats	8	35
3	Epoxy Both Mats	35	29
4	Epoxy Top Mat Only	30	--
5	Epoxy Top Mat Only	31	--
6	Epoxy Top Mat Only	55	--
48	Epoxy Top Mat Only	17	--

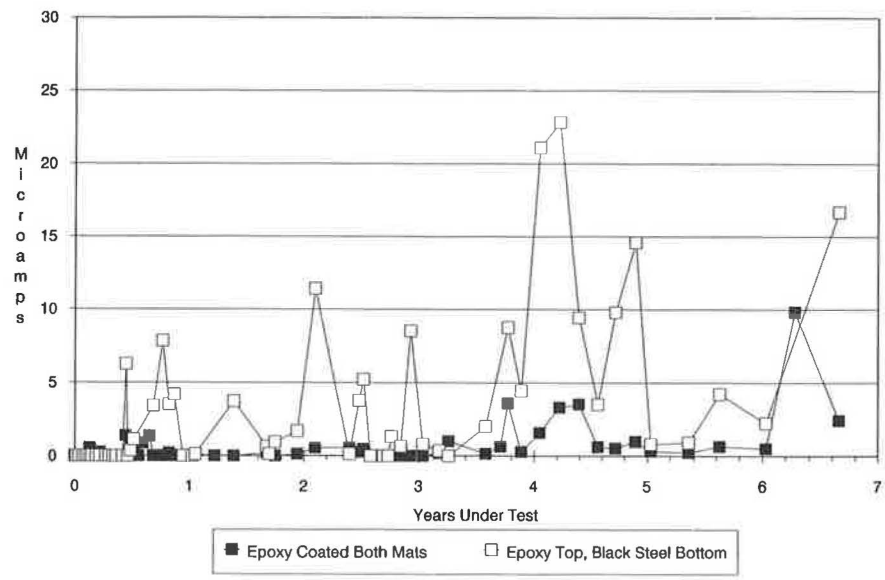

FIGURE 3 Average macrocell corrosion current (70°F) versus time.

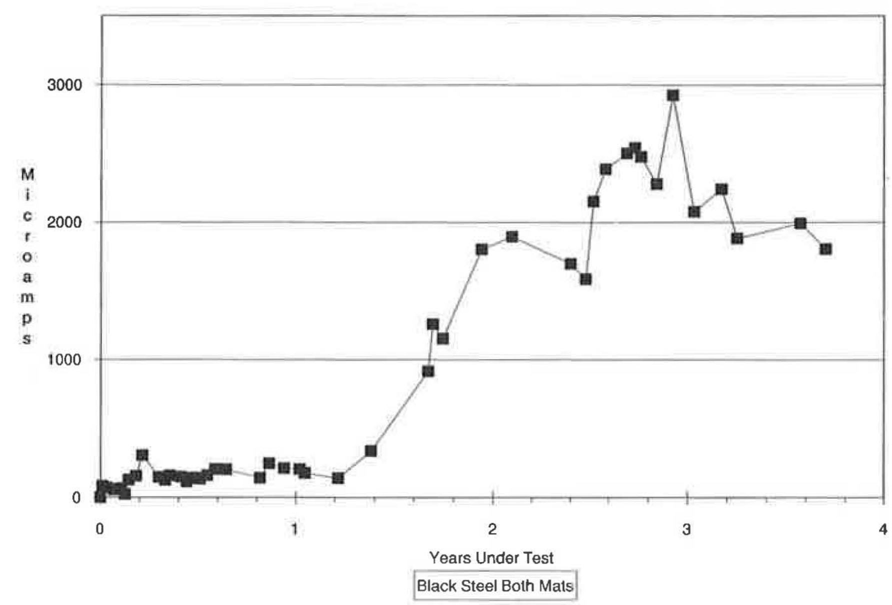

FIGURE 4 Average macrocell corrosion current (70°F) versus time.

although a decreasing trend was seen after about 3.7 years of testing as severe corrosion-induced cracking allowed chloride access to the bottom steel. These data support the results reported by Clear et al. (*5*) on nonspecification epoxy-coated bars in concrete with a higher water-to-cement ratio. They concluded that epoxy-coated reinforcing steel in salty concrete should be significantly more resistant to corrosion-induced concrete damage than uncoated steel. It was further reported that epoxy-coated bars perform best when all continuous bars are epoxy coated as compared with bars in one mat coated or bars in both mats uncoated (average corrosion current with bars in both mats uncoated was about 11 times greater than in the case of bars in the top mat only and 41 times greater than in the case of bars both mats coated).

Figure 5 plots the average adjusted mat-to-mat resistance versus time for the three cases studied. Both the slabs with epoxy-coated bars in the top mat only and in the top and bottom mats exhibited average resistances about two orders of magnitude higher than the slabs with black steel in both the top and bottom mats at the start of the test. Further, the slabs with epoxy-coated bars in the top mat and in both mats showed a marked increase in resistance with time. Overall test averages were 22 ohms for the slabs with the black steel bars in both mats, 2,151 ohms for the slabs with epoxy-coated bars in the top mat only, and 1,911 ohms for the slabs with epoxy-coated bars in both the top and bottom mats. These data indicate that (a) corrosion protection afforded by epoxy-coated reinforcing steel primarily results from its inherent

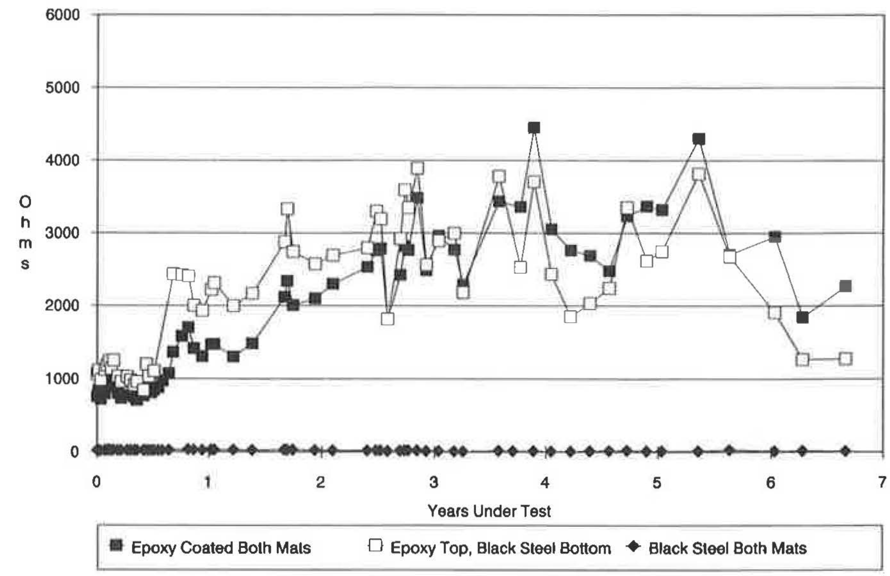

FIGURE 5 Average resistance (70°F) versus time.

effect on increasing the macrocorrosion cell resistive path, and (b) there is no observable tendency for the coating to deteriorate when embedded in salt-contaminated concrete in the long term (i.e., resistance did not decrease with time). Average top-mat potentials [millivolts copper-copper sulfate reference halfcell (CSE)] versus time and average potential differences (i.e., average bottom-mat potential minus average top-mat potential) versus time for the three variables evaluated are presented in Figures 6 and 7, respectively. For slabs with epoxy-coated rebars, the average top-mat potentials for years 1 through 6.66 were −226 mV for the epoxy top mat only slabs and −335 for the epoxy both mat slabs. During the middle portion of testing, epoxy both mats slabs showed average top-mat potentials in the range of −350 to −450 mV CSE. The average potential difference shows a general increase with time to values in the range of 200 mV (overall average for years 1 through 6 was 171 mV). However, as discussed previously, the macrocell corrosion currents have remained near zero. Thus, these data tend to support previous findings that, although corrosion will occur at small breaks in the coating once critical quantities of chloride penetrate, its magnitude is so low that significant iron consumption and tensile stresses high enough to crack the concrete will not occur for very long periods of time (*5*). Performance of the epoxy top mat only slabs has been similar to that of epoxy both mat slabs except that average top-mat rebar potentials are generally more positive in epoxy top mat only slabs. In the case when the bars in both mats were coated, more negative potentials were undoubtedly exhibited because of oxygen starvation (cathodic polarization), whereas such was not the case when the bottom mat was uncoated. Potential differences were similar throughout the test period (overall average for epoxy top

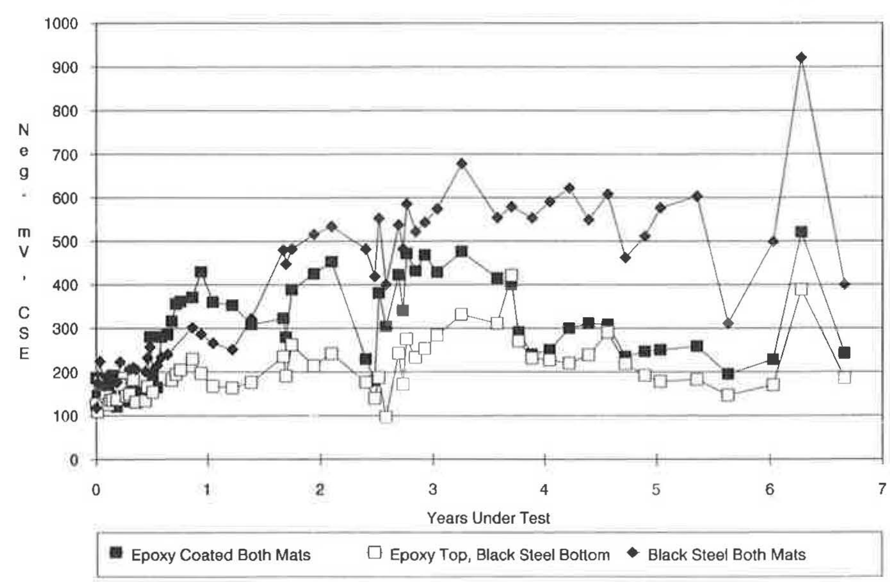

FIGURE 6 Average top mat potential versus time.

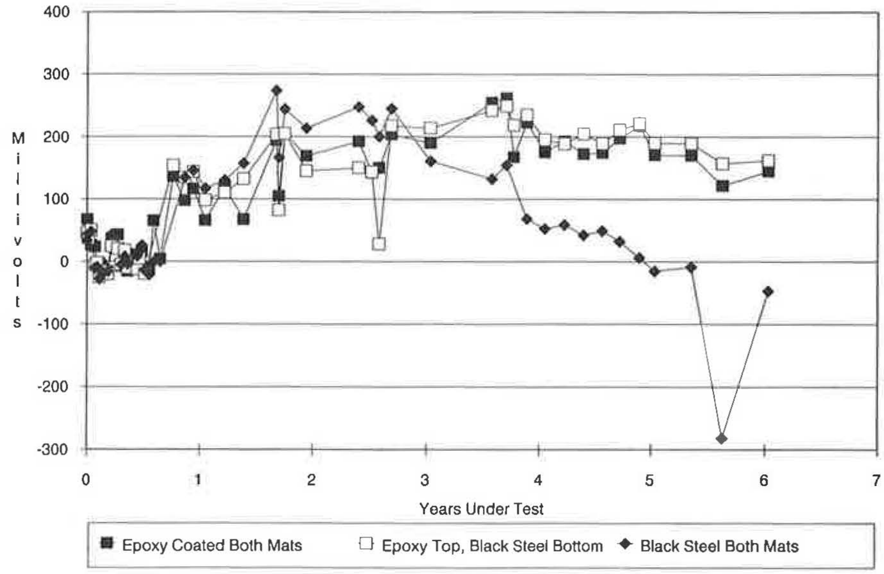

FIGURE 7 Average potential difference versus time.

mat only slabs for years 1 through 6 was 176 mV). Macrocell corrosion currents remained at low values throughout the test period, although at times they were about 5 to 10 times higher than the epoxy both mat slabs. Thus, these data indicate that specification epoxy-coated bars perform best when all bars are coated, although both variables (i.e., epoxy-coated bars in both mats and epoxy-coated bars in the top mat only) provide significantly enhanced resistance to corrosion-induced concrete damage as compared with uncoated steel (average top-mat potential and potential difference for years 1 through 3.7 was −486 and 191 mV, respectively). The decreasing trend in potential difference (average bottom-mat potential minus average top-mat potential difference) (Figure 7) for this variable was the result of corrosion activity on the bottom steel caused by chloride migration through large surface cracks. The formation of liquid corrosion product that does not lead to spalling is possible, particularly in a crevice or coating undercutting situation, although this was not seen on the full-depth cores as discussed in the following.

Figures 8 and 9 show the surface condition of each group of slabs after more than 6.5 years of outdoor exposure, including about 3.1 years of salt ponding. The *x*'s on the slab surfaces designate top-mat potential monitoring locations and the circular mounds on the slab surfaces represent the bottom-mat potential wells discussed previously. No surface cracking, staining, or other deterioration was found on any of the slabs containing epoxy-coated bars in both mats or epoxy-coated bars in the top mat only. However, extensive surface cracking and staining can be seen on the slabs containing black steel bars in both mats. Fine corrosion-induced cracking and minor staining were first observed on these slabs after only 0.9 year into the study.

Upon completion of the exposure period, full-depth cores representing each variable were obtained from one slab. These cores were then autopsied to determine the relative extent of corrosion-induced damage, if any, and the overall physical condition of the epoxy-coated bars. Figures 10 through 12 are photographs typical of those taken during autopsies. The top-mat steel in both the epoxy-coated both mats and epoxy top mat only situations exhibited similar results (Figures 10 and 11). There was no visible corrosion product at the rebar-concrete interface or beneath the coating (steel was bright and clean) when it was scraped off with a utility knife. No visible deterioration was observed on the coating itself; however, the coating was more easily removed from these specimens as compared with bar with a retained original coating that had never been embedded in concrete. Hence, the coating softened somewhat during exposure, but no obvious detrimental effects were discerned and there was no observed tendency for undercutting of the coating by corrosion. Similar results were found on the coated bottom-mat bar for the epoxy-coated both mats variable (Figure 10). Very minor corrosion was observed on the uncoated bottom bar in the epoxy top mat only situation (Figure 11).

Extensive corrosion product and section loss were observed on the top-mat steel representing the uncoated both mats variable (Figure 12). This was expected because of measured macrocell corrosion currents, half-cell potentials, and visual surface condition. Minor corrosion was found on the bottom-mat bar from the same variable.

CONCLUSIONS

The test program showed that straight specification epoxy-coated rebars are more resistant to corrosion-induced damage than uncoated bars when embedded in salt-contaminated concrete and coupled to coated or uncoated bars in salt-free concrete for over 6.5 years in an outdoor northern environment. Overall, best performance is achieved when the bars in both mats are epoxy coated. Active corrosion, as indicated by macrocell corrosion currents and half-cell potentials, occurred (presumably at small breaks in the coating) when the epoxy-coated bars were in the top mat only and when the bars in both mats were epoxy coated; however, the magnitudes of corrosion were so low (40 times lower than black

FIGURE 8 Surface condition after exposure. (Top: both mats coated; bottom: top mat only.)

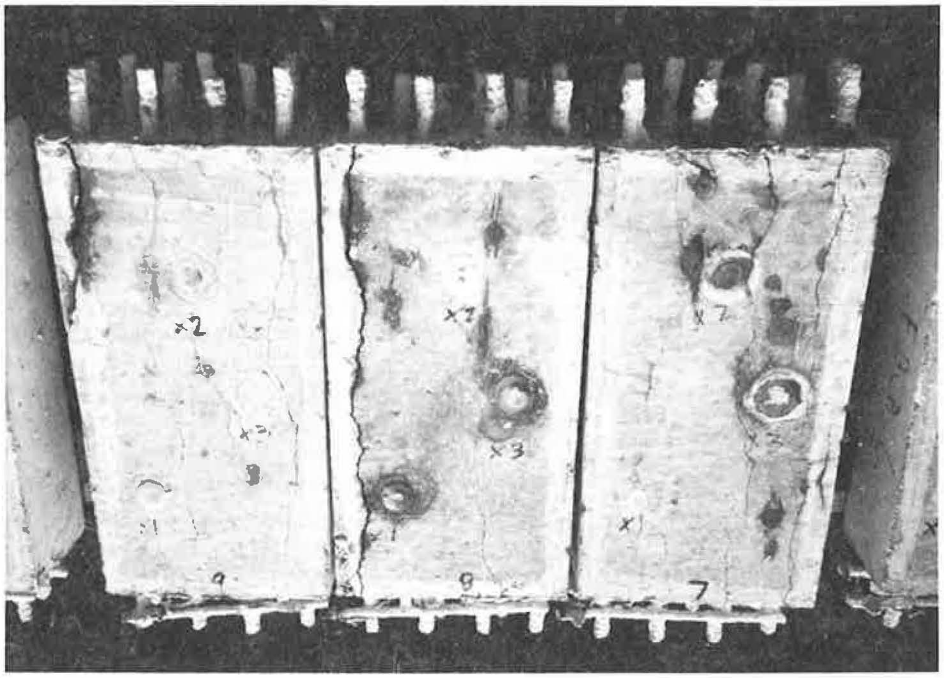

FIGURE 9 Surface condition after exposure (both mats uncoated).

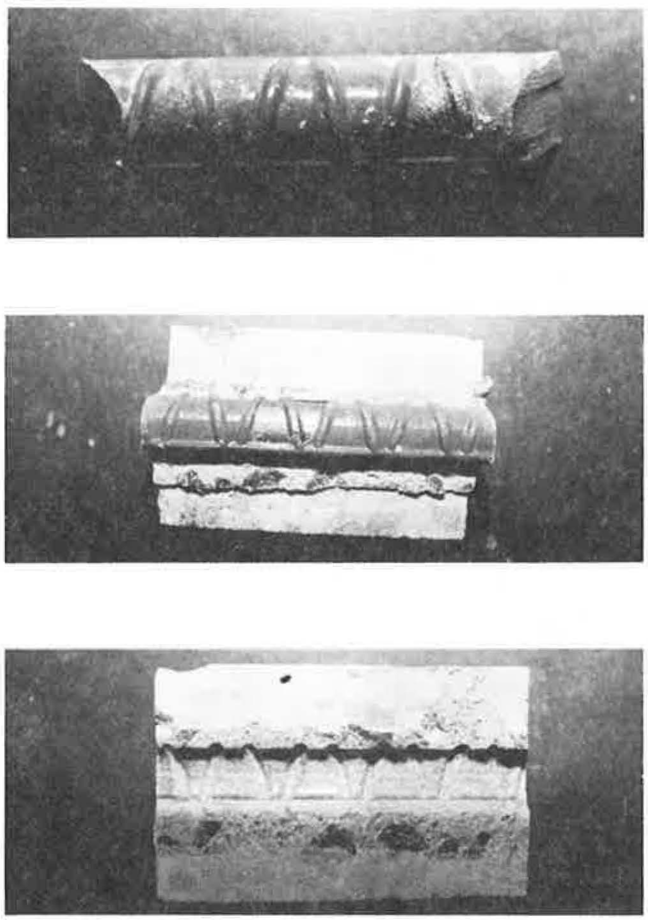

FIGURE 10 Autopsy photographs. (*Top*: top bar, epoxy-coated bars in both mats. *Middle*: bottom bar, epoxy-coated bars in both mats. *Bottom*: epoxy-coated rebar trace).

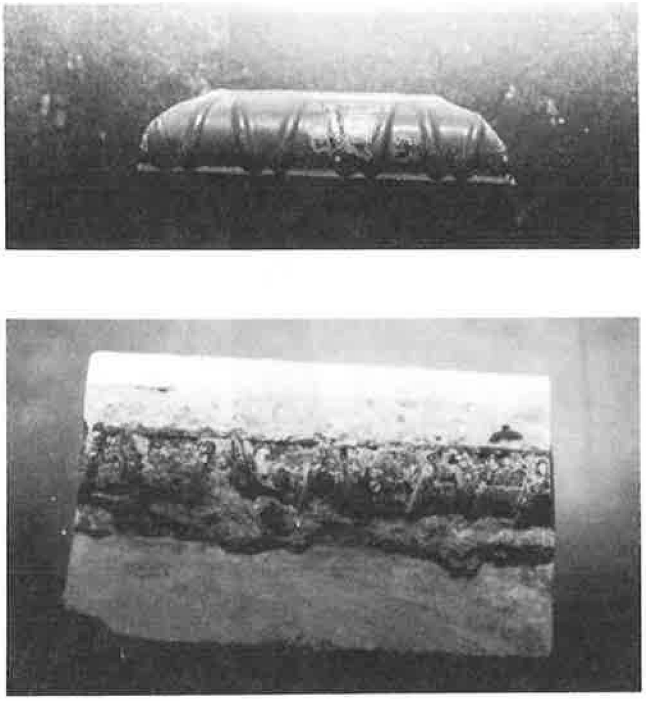

FIGURE 11 Autopsy photographs of slabs with epoxy-coated bars in top mat only. (*Top*: top bar. *Bottom*: bottom bar.)

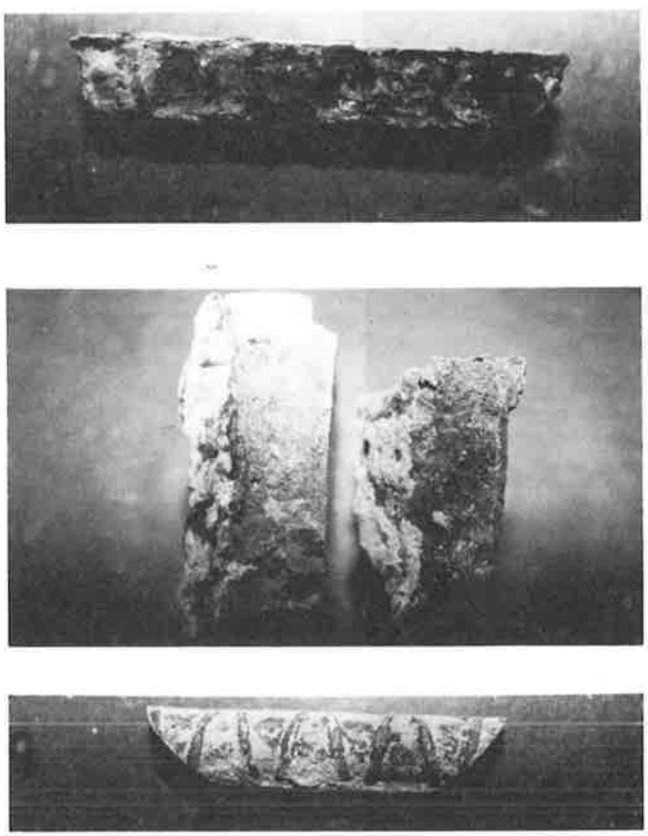

FIGURE 12 Autopsy photographs of slabs with black steel (uncoated) bars in both mats. (*Top*: top bar. *Middle*: top rebar trace. *Bottom*: bottom bar.)

steel in both mats for the slabs with coated bars in one mat and 100 times lower for the slabs with coated bars in both mats) that significant iron consumption and tensile stresses high enough to crack the concrete would not be expected for extended periods of time.

Some softening of the epoxy coating in top- and bottom-mat bars was found but no detrimental effect of the softening (i.e., no undercutting or rusting beneath the coating) or reduction in electrical resistance was noted. Future research should investigate physical and chemical changes that occur on the coating when exposed to a high-alkaline environment with oxygen and moisture present for extended periods.

Findings in this study concur with previous studies by NBS, FHWA and others, but conflict with statements in Florida Department of Transportation reports that concrete with epoxy-coated rebars is less resistant to corrosion damage than that with uncoated rebars.

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REFERENCES

1. D. P. Gustafson. Epoxy Update. *Civil Engineering*, Vol. 58, No. 10, 1988, pp. 38–41.
2. R. E. Weyers and P. D. Cady. Deterioration of Concrete Bridge Decks from Corrosion of Reinforcing Steel. *Concrete International*, Vol. 9, No. 1, 1989, pp. 15–20.
3. J. R. Clifton, H. F. Beeghly, and R. G. Mathey. *Nonmetallic Coatings for Concrete Reinforcing Bars*, Report FHWA-RD-74-18. FHWA, U.S. Department of Transportation, Feb. 1974.
4. K. C. Clear and Y. P. Virmani. *Research Update: Methods and Materials*. National Association of Corrosion Engineers, Sept. 1982.
5. K. C. Clear and Y. P. Virmani. *Corrosion of Non-Specification Epoxy-Coated Rebars in Salty Concrete*. Paper No. 114, Corrosion 83 (Anaheim, April 1983), National Association of Corrosion Engineers, Houston, Tex., 1983.
6. Y. P. Virmani, K. C. Clear, and T. J. Pasko Jr. *Time-to-Corrosion of Reinforcing Steel in Concrete Slabs*, Vol. 5: *Calcium Nitrite Admixture or Epoxy-Coated Reinforcing Bars as Corrosion Protection Systems*. Report FHWA-RD-83-012. FHWA, U.S. Department of Transportation, Sept. 1983.
7. R. Powers and R. Kesler. *Corrosion Evolution of Substructure, Long Key Bridge*. Corrosion Report 87-9A. Florida Department of Transportation, Gainesville, 1987.
8. R. Powers. *Corrosion of Epoxy Coated Rebars, Keys Segmental Bridges*. Corrosion Report 88-AA. Florida Department of Transportation, Gainesville, 1987.
9. A. M. Zayed, A. A. Saugues, and R. G. Powers. *Corrosion of Epoxy Coated Reinforcing Steel in Concrete*. Paper No. 379, Corrosion 89 (New Orleans, April 1989), National Association of Corrosion Engineers, Houston, Tex., 1989.
10. K. C. Clear. *Time-to-Corrosion of Reinforcing Steel in Concrete Slabs*, Vol. 4: *Galvanized Reinforcing Steel*. Report FHWA-RD-82-028, FHWA, U.S. Department of Transportation, Dec. 1981.

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