

# Effectiveness of Epoxy Coatings in Minimizing Corrosion of Reinforcing Steel in Concrete

ALI AKBAR SOHANGHPURWALA AND KENNETH C. CLEAR

Corrosion characteristics of straight and bent epoxy-coated reinforcing steel were studied under accelerated southern exposure (SE) cycling as described in *NCHRP Report 244*. Variables included seven different suppliers, bend diameter, coating thickness, coating application before and after fabrication of the bar, rate of bending, temperature of steel during bending, and patching of damaged areas before installation into concrete slabs. Specimens with uncoated steel were included as controls. A total of 40 small-scale concrete slabs, each consisting of two independent specimens—one bent-bar and one straight-bar specimen—were tested. Results after completion of 47 SE cycles for some specimens and 70 cycles for others are reported. Results indicate that straight and bent epoxy-coated bars provide significantly better resistance to chloride-induced corrosion than uncoated bars. Out of the 36 sets of epoxy-coated specimens tested, only seven showed measurable macrocell corrosion currents. The macrocell corrosion currents on the control slabs were more than an order of magnitude higher than the epoxy-coated bar slabs. Corrosion rates calculated from three-electrode linear polarization data correlated with macrocell current data. Ac resistance data indicated that the coatings did not deteriorate or disbond with time. Autopsy testing revealed little corrosion damage on epoxy-coated rebars. Corrosion found on epoxy-coated rebars initiated only at damaged areas and at holidays. The effects of various coating parameters on the ability of the epoxy coating to provide corrosion protection was not distinguishable. There were no differences discernible between the bent and straight epoxy bars, other than visible coating damage.

One of the most important and costly maintenance problems faced by bridge owners is the damage caused by chloride-induced corrosion of reinforcing steel. For more than a decade, FHWA, state departments of transportation, National Bureau of Standards (NBS), Concrete Reinforcing Steel Institute (CRSI), Fusion Bonded Coaters Association (FBCA), AASHTO, ASTM, and the private sector (1) have been working to find ways and means to prevent corrosion-induced damage in reinforced concrete.

The factors that initiate and sustain corrosion of reinforcing steel are chloride ions, oxygen, and water present at the steel-concrete interface. Therefore, to prevent, stop, or retard corrosion of reinforcing steel, access of some or all of these factors to the reinforcing steel should be minimized or eliminated. The characteristics of concrete that indirectly affect the phenomenon of reinforcing steel corrosion are permeability, which governs the access that water, chloride ions, and oxygen have to the steel; electrical resistivity, which determines the magnitude of corrosion current that can flow at a

given potential; and inherent alkalinity, which provides a passivating environment for the steel (2).

Many techniques and products, designed to completely stop or retard active corrosion of reinforcing steel or to prevent corrosion from initiating on new structures, have been identified and can be categorized as either mechanical or electrochemical. Most of these techniques and products are in experimental or developmental stages. However, some have gained acceptance in the bridge deck community.

The mechanical techniques are used to physically prevent the access of oxygen, chloride, and water to the steel. The electrochemical methods use an applied electrical current to either remove chlorides from the concrete (chloride removal) or alter the electrical characteristics of the reinforcing steel to make the steel less susceptible to corrosion (cathodic protection). The electrochemical category also includes additives called "inhibitors" that, when admixed into fresh concrete or combined with standard deicing salts, can prevent or minimize the formation of galvanic cells on the surface of steel. The mechanical category includes the use of silica fume admixtures and improvements in concrete mix designs and placement procedures to produce less-permeable concrete with higher electrical resistivity. Also included in this category are sealers and membranes used to prevent ingress of water and chloride ions into the concrete- and epoxy-coated reinforcing steel to isolate the steel from the aggressive environment. Early research performed by NBS for FHWA indicated that reinforcing bars, coated with select powdered epoxies using an electrostatic spray process after bar cleaning, performed well in salt contaminated concrete (3).

Epoxy resins are thermoset plastics belonging to the polyaddition plastics family. These resins are reported to have good long-term durability in concrete and against solvents, chemicals, and water (4). Epoxy resins also have desirable mechanical properties such as high ductility, small shrinkage in polymerization, and good heat resistance (5). Further, test results indicate that the chloride ion permeability of epoxy coatings is very low in the worst case (3,5).

One of the most important factors governing the performance of epoxy-coated bars is the quality control enforced during coating application and subsequent handling of the coated bars. If the coated bars are not handled properly, damage to the coating can result that could negate or reduce protection provided by the epoxy coating. ASTM specifications A775 and D3963, AASHTO specification M 284, and CRSI EDR 19 provide stringent guidelines to be followed

during coating application and subsequent handling and storage of the bars. However, laboratory research has indicated that even nonspecification epoxy-coated bars provide enhanced corrosion protection as compared to black (i.e. uncoated) steel (6).

Many states have used, and continue to use, epoxy-coated bars for construction of new bridge decks and full depth repair of old deck sections. Field performance studies have been conducted in Maryland, Minnesota, Virginia, and Pennsylvania (7–10). The Maryland and Minnesota studies did not provide unequivocal results because of early age evaluation and low chloride contamination levels in the concrete. The Virginia and Pennsylvania studies, however, found that epoxy-coated bars provided enhanced corrosion protection under extremely adverse conditions compared to uncoated bars.

In spite of positive laboratory and field studies, new concerns have been raised regarding the effectiveness of epoxy-coated bars in preventing corrosion and extending the life of structures as a result of recent failures in marine substructures of the Florida Keys (11). Some concerns are specifically targeted at the bent bar stirrups. When coated bars are bent into the required shape, there may be some loss of bond between the epoxy coating and the steel at the outer radius of the bend that may reduce the protection provided by the coating. Some researchers have also argued that a small imperfection in the coating may cause a small anode and large cathode situation that would be less desirable than using uncoated steel. Others are concerned that once corrosion starts at an imperfection in the coating it could spread underneath the coating (i.e., undercutting), leading to disbondment or—as suggested by Romano (12)—cathodic disbondment of epoxy coatings can occur adjacent to damaged areas because of the galvanic process occurring between the cathodic and anodic sites on the steel.

As a result, this research was undertaken to study the effectiveness of epoxy-coated bars in preventing or minimizing corrosion and to determine the influence, if any, the following variables have on the performance of epoxy-coated bars:

- Bend diameter,
- Thickness of the coating,
- Application of the coating before and after fabrication of the bar,
- Rate of bending,
- Temperature of steel during bending, and
- Patching of damaged areas before installation.

## EXPERIMENTAL PROCEDURE

To evaluate the consistency of standard, present-day, epoxy coating practices, coated bars were obtained in 1988 from seven different suppliers located in all major geographical regions of the continental United States. A total of 15 variables, including two controls (black steel) were included in the study (see Table 1). Six sets of one bent and two straight coated bars, along with a set of uncoated bent and straight bars, were received for each variable from the appropriate supplier. Each supplier provided bars that had been blasted to a bright clean metal finish, heated to near 450°F, and passed through a bin fitted with electrostatic spray guns. During the

latter stage, epoxy powder was applied by spray to provide a coating of appropriate thickness. The coated bars were subsequently passed through a cooling bath and then through the holiday detection and thickness measurement systems used by the supplier. Scotchkote 213 epoxy coating was used in all instances and all bars were production line coated (e.g., no special fabrication procedures were followed other than those needed to obtain the variables presented in Table 1).

For the purpose of this research, bars referred to as standard were manufactured as follows:

- No. 4 and No. 5 bars were coated with a 9-mil-thick epoxy coating.
- For bent bars, bending was achieved at a fast rate (an average of 3 sec per 180-degree bend) with the steel at room temperature. Each bar contained two 180-degree bends (see Figure 1).
- No. 4 bars were bent to a 2-in.-diameter (herein referred to as the small-bend study).
- No. 5 bars were bent to a 3.75-in.-diameter (herein referred to as the large-bend study).
- No patching was applied after fabrication on either the bent or the straight bars.

The controls contain black steel of each size bar and bend diameter.

All pertinent physical property information for coatings was documented before placing the bars in the forms. Coating thickness was measured at six locations along each bar using a Mikrotest Model II thumbwell magnetic gauge calibrated to NBS standards. The number of holidays was determined using a 67.5 v Tinker-Razor Model M-1 holiday detector. Additionally, any visible damage and its location were documented for each bar. The No. 5 bars were positioned in 13- × 14- × 7-in. wooden forms and the No. 4 bars were positioned in 10- × 12- × 7-in. wooden forms. Conventional concrete with a water/cement ratio of 0.47 was then placed. Clear concrete cover was 1 in. on all bars. The concrete mix design can be found in Table 2. The slabs were cured using wet burlap and polyethylene for 14 days, followed by laboratory air exposure through 45 to 52 days of age.

Three slabs were fabricated per variable. Each slab contained a coated set of one bent and two straight bars as top steel (see Figure 1). The bottom mat consisted of No. 5 and No. 6 black bars. The slabs were designed so that each slab effectively comprised two specimens. One-half of the slab was a bent-bar specimen and the remainder was a straight-bar specimen of the same variable. The bottom mat steel was sized to provide the same ratio of steel area between the top mat and the bottom mat for both halves of the slab. Thus, the ratio of epoxy-coated steel areas (top mat) to black steel areas (bottom mat) was the same for both halves of each epoxy-coated bar slab.

For the purpose of creating a macrocorrosion cell and to facilitate installation of instrumentation to measure macrocell currents, the bottom mat steel of each half of each slab was made electrically continuous (each bottom half remained discontinuous to the other bottom half within the same slab). The two straight bars in the top mat of each slab were also made continuous. All continuity was achieved outside the slab. A switch and a resistor were then installed between the

TABLE 1 DETAILS OF VARIABLES AND COATING PARAMETERS

VARIABLE SET	VARIABLE	# OF SLABS
V1	Control - Black, Uncoated Bars.	2
V2	Epoxy Coated After Fabrication - 6 mil Thick Coating.	2
V3	Epoxy Coated After Fabrication - 9 mil Thick Coating.	2
V4	Epoxy Coated After Fabrication - 12 mil Thick Coating.	2
V5	Standard Epoxy Coated Bar - 6 mil Thick.	2
V6	Standard Epoxy Coated Bar - 9 mil Thick, From sources 1,2,4,6, & 7.	10
V10	Standard Epoxy Coated Bar - 9 mil Thick, From source 5.	2
V12	Standard Epoxy Coated Bar - 12 mil Thick.	2
V13	Slow Bend Rate During Fabrication.	2
V14	Fabricated At High Temperature (approx. 125 F).	2
V15	100% Patch On The Outside Radius After Fabrication.	2
V16	Standard Epoxy Coated Bar - 9 mil Thick Coating, Small Bend Diameter.	4
V18	Fabricated At High Temperature (approx. 125 F), Small Bend Diameter.	2
V19	Epoxy Coated After Fabrication - 9 mil Thick Coating, Small Bend Diameter.	2
V20	Control - Black, Uncoated Bars, Small Bend Diameter.	2

**NOTE:** Except where noted all specimens were coated with a 9 mil thick Scotchkote 213 before fabrication. The bars were bent at a fast rate ( an average of 3 seconds per 180 degree bend) with steel at room temperature. No patching was applied after fabrication. Variables V1 to V15 were fabricated from #5 steel with a bend diameter of 3.75 inches and the remaining variables were fabricated from #4 bar with a bend diameter of 2 inches.

top and bottom mats of each half of each slab. The sides of the slabs were then coated with epoxy to simulate an infinite slab. Finally, ponding dams were installed on all slabs that were to be subjected to southern exposure (SE) testing as per *NCHRP Report 244 (13)*. Figure 2 shows a typical slab with the ponding dam in place.

Following completion of the lab air cure, two slabs per variable were exposed to SE cycling. Weekly SE cycling consisted of four days of continuous ponding of the top surface with a 15 percent (by weight) sodium chloride solution followed by draining and 3 days exposure to an air temperature of 100°F and ultraviolet lights. The third slab of each variable was exposed in a northern Virginia climate at an outdoor exposure facility. These slabs served as controls for each variable.

Periodically, at the end of the ponding portion of SE cycling, top-surface half-cell potential surveys were conducted as per ASTM C-876 and the magnitude of the macrocell corrosion current was measured (6). The three-electrode linear polarization technique was periodically used, on an experimental basis, to monitor the polarization resistance as a function of time of the variable under test. Polarization resistance is used

to calculate the rate of corrosion using the Stern-Geary equation (14). In addition, the ac resistance between the top and bottom mats was documented and visual and sounding surveys were conducted.

The slabs incorporating Variables 1 to 18 (excluding Variable 14) were subjected to a total of 70 SE cycles and have completed the accelerated test program, whereas the slabs incorporating Variables 14, 19, and 20 were subjected to a total of 47 SE cycles and are continuing accelerated testing. All control slabs (Variables 1 and 20) are presently demonstrating corrosion-induced staining on the top surface and on the sides of the slabs. To correlate the corrosion measurements on all slabs to the actual visible corrosion damage suffered by the coated bars, autopsy testing was conducted on 12 specimens after completing the accelerated test program.

## RESULTS AND DISCUSSION

### Visual Examination

Visual examination of all the control slabs exposed to SE cycling revealed stains of corrosion products on the surface

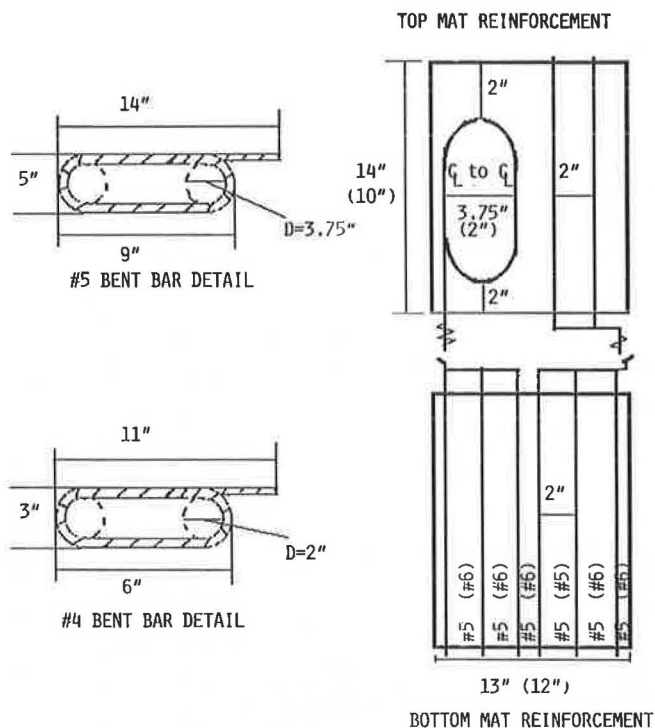


FIGURE 1 Slab and bent-bar fabrication details.

TABLE 2 CONCRETE MIX DESIGN

Materials	Amount
Cement, lb/cy	588
Coarse Aggregate, lb/cy	1915
Fine Aggregate, lb/cy	1250
Water, lb/cy	276
Daratard 17, ml	13
Air, %	7
Unit Weight., pcf	150
W/C=	0.47

of the slabs. Some corrosion products have also made their way out of the slabs adjacent to the bent and straight rebars protruding from the short side of the slabs. Some surface cracking parallel to the rebars was also seen. Sounding surveys did not reveal any delaminations at the end of 47 or 70 SE cycles on the slabs representing Variables 20 and 1 (control slabs), respectively, although detection of such is difficult on small-scale specimens. In comparison, epoxy-coated rebar slabs do not show any visible signs of corrosion-induced staining or cracking.

### Corrosion Rate Data

#### Macrocell Corrosion Current Data

Corrosion of steel can occur in many forms. The type most damaging to bridge decks is termed macrocell corrosion. The top mat steel in bridge decks becomes anodic to the bottom

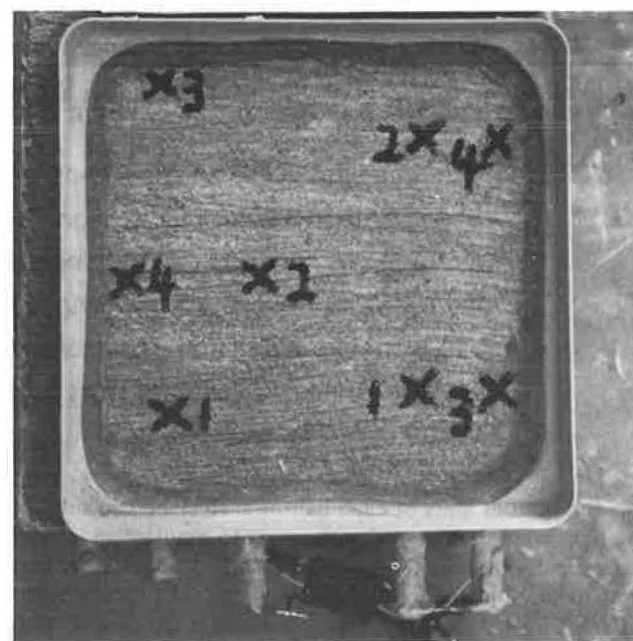
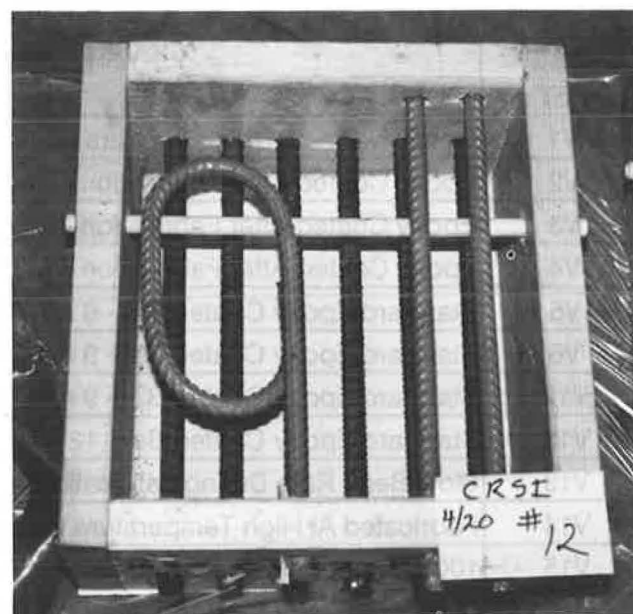


FIGURE 2 Top: epoxy-coated bars in forms before concrete placement. Bottom: completed slab before SE cycling.

mat because of the ingress of chlorides from deicing salts. A macrocell is then formed between the top and bottom mats and an electronic current flows from the top mat to the bottom mat through electrically continuous steel. An ionic current flows from the bottom mat to the top mat through the concrete. The ionic current is directly proportional to the loss of steel caused by corrosion and the algebraic sum of the ionic and electronic flow is zero. Therefore, the magnitude of the electronic macrocell corrosion current is directly proportional to the macrocell corrosion rate at the top mat steel.

Because the steel areas of the bent bar and the two straight bars in the top mat of the specimens are not equal, the macrocell currents have been analyzed in terms of milliamperes per



square foot of the top mat steel. Figures 3 and 4 present macrocell current data for all slabs that have values greater than 0.01 mamp/ft<sup>2</sup>. Also, the data for each variable are an average of several slabs (see Table 1 for number of slabs representing each variable).

Out of the 36 sets of epoxy-coated specimens tested, only seven showed macrocell corrosion currents in excess of 0.01 mamp/ft<sup>2</sup>. Of these seven sets, three (V10-Bent Bar, V13-Bent Bar, and V19-Bent Bar) had visibly identifiable coating damage such as nicks, scrapes, and cuts before placement in the concrete. The data in Figures 3 and 4 clearly highlight the difference in the rate of corrosion of the controls versus the epoxy-coated bars. The corrosion rate of the controls is more than an order of magnitude larger than the epoxy-coated bars (controls averaged 1.62 mamp/ft<sup>2</sup>, and all the epoxy-coated bars averaged 0.018 mamp/ft<sup>2</sup> while the average of the 7 sets presented was 0.072 mamp/ft<sup>2</sup>). The data indicate that epoxy-coated rebars are less susceptible to corrosion than uncoated rebars under accelerated corrosion conditions. Work performed in Finland also indicated that electrostatically epoxy-coated bars provide corrosion protection even in an aggressive environment (5). Corrosion initiation in the control specimens occurred after only about a maximum of 20 SE cycles, whereas in the epoxy-coated bar specimens (with macrocell currents greater than 0.01 mamp/ft<sup>2</sup>) it occurred between 45 and 60 SE cycles except for one set of specimens (V19-bent) where it occurred at about 28 SE cycles.

The low corrosion rates of the epoxy-coated rebar specimens may be explained by theorizing that corrosion initiated in the coating defects and that because the size of the anodic

(damaged) areas is small, the volume of corrosion products formed is not sufficient, at present, to cause corrosion-induced damage. When the autopsies are conducted, it will be possible to ascertain if the loss of steel cross section at the coating defects is significant or not. It may also be possible to evaluate whether corrosion initiated at a coating defect can lead to undercutting of the coating, although it may not be possible to determine whether coating disbondment around the coating defect is necessary for the spread of corrosion underneath the coating or if the corrosion process causes the disbondment.

Presently, there are no perceptible differences between the various coating parameters, such as speed of bending, temperature of bar during coating, bend diameter, coating thickness, and patching before or after fabrication. However, from the data collected, it appears that the bent epoxy-coated rebars are more likely to have coating damage.

### Three-Electrode Linear Polarization Data

Until recently, it was not possible to determine the corrosion rate of steel embedded in concrete. Potential surveys and chloride analysis of concrete samples only indicated the areas where corrosion activity was most likely. The three-electrode linear polarization technique applies a small dc current to the steel and measures the response. The mathematical relationship between the applied current and the response (potential shift) has been defined by Stearn and Geary (14) and can be used to calculate the corrosion rate of uncoated steel embedded in concrete. This technique, however, has not been

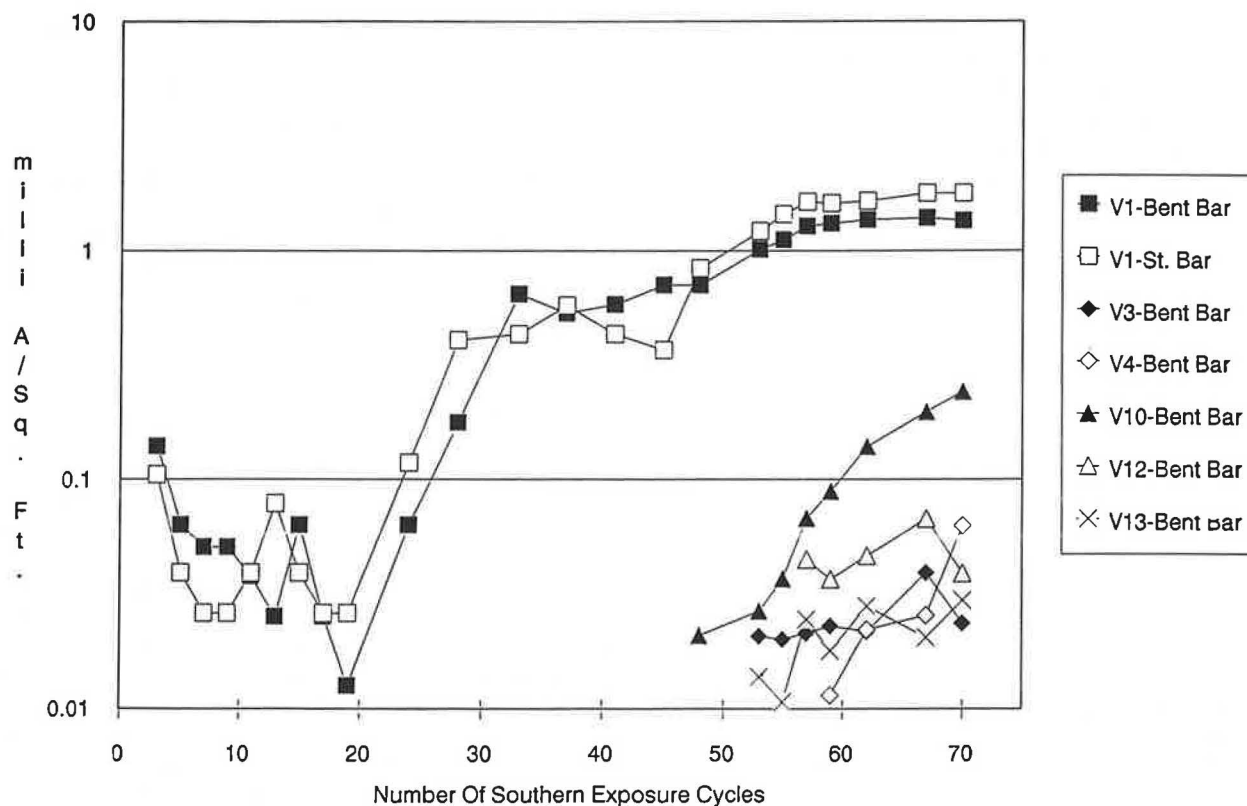


FIGURE 3 Large-bend study—controls and epoxy-coated bar specimens: macrocell current versus time.

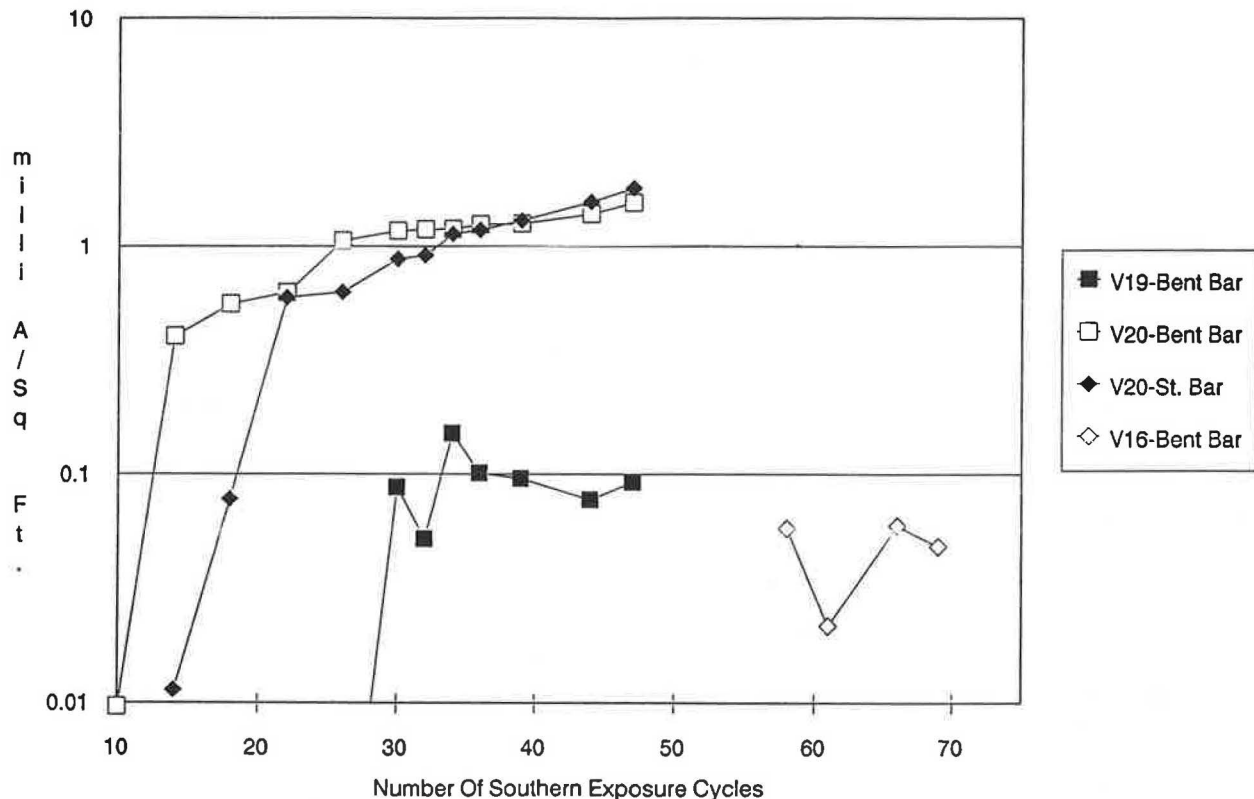


FIGURE 4 Small-bend study—controls and epoxy-coated bar specimens: macrocell current versus time.

validated for use on epoxy-coated bars. In this research, the technique was used to provide information on its suitability for use with epoxy-coated bars.

Corrosion rate data obtained from the same seven sets of specimens for which macrocell current data were presented are shown in Figures 5 and 6 and were calculated from the results of three-electrode linear polarization testing. The data reflect about an order of magnitude difference between the controls and the epoxy-coated bars, which was also indicated by the macrocell corrosion current data, but the data appear at present to fail to differentiate between epoxy-coated bar specimens.

#### Electrical Resistance Data

The electrical resistance between the top mat and the bottom mat through the concrete, with the mats electrically isolated from each other, significantly affects the phenomenon of macrocell corrosion. The magnitude of the ionic flow is inversely proportional to the electrical resistance between the mats. Also, the electrical resistance provides information regarding coating defects when epoxy-coated bars have been used in either or both mats. Figures 7 and 8 present typical resistance data obtained in this study. As expected, the epoxy-coated bars have a much higher electrical resistance between the mats, ranging from 1,300 to 129,500 ohms, compared to the controls that have electrical resistance in the range of a few hundred ohms. Although the mat-to-mat electrical resistance

of the epoxy-coated bars varies significantly from one specimen to another, the general trend is to remain constant with time. This observation indicates that the coating is not deteriorating or becoming disbonded with time. The concrete moisture content and temperature were about the same at the end of each SE ponding cycle when all data were collected. All epoxy-coated bars that had documented coating damage before installation in the concrete slabs demonstrated lower electrical resistance than those of the same variable with no damage. The epoxy-coated straight bars had a higher average electrical resistance (40,654 ohms) than the epoxy-coated bent bars (12,265 ohms). This difference may be partially because of the difference in geometry of the bars.

#### Potential Data

Figure 9 shows half-cell potential data for the control slabs and the coated bar specimens that exhibited the highest and lowest potentials. Except for the control slabs, the half-cell potentials are less negative than  $-350$  mV for the copper sulfate electrode. Potential measurements on epoxy-coated rebars are difficult to interpret. In this case, the less negative potentials are probably the result of the large uncoated bottom mat and the lack of cathodic polarization thereon. One should, therefore, concentrate on within-variable changes with time rather than absolute magnitude. When this is done, these findings correlate well with the macrocell corrosion current data. A summary of all potential data is presented in Table 3.

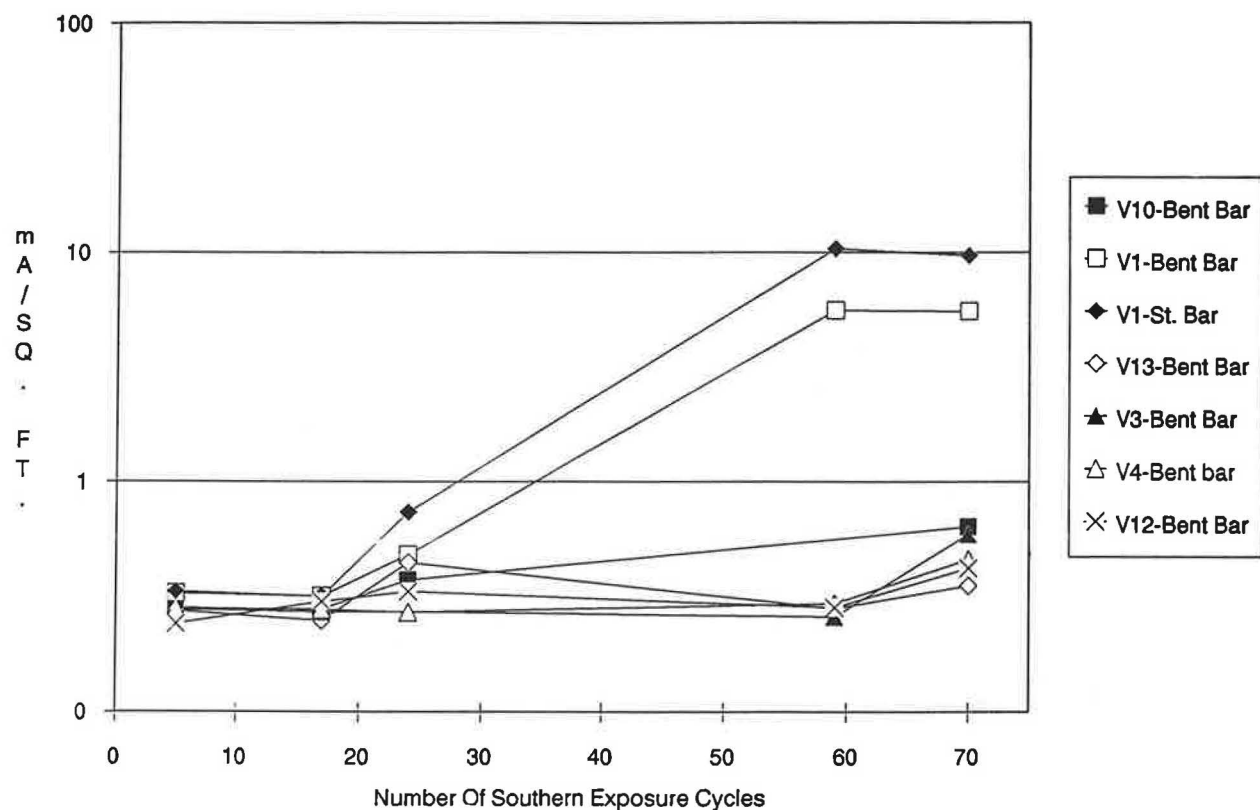


FIGURE 5 Large-bend study—controls and epoxy-coated bar specimens: corrosion rate versus time.

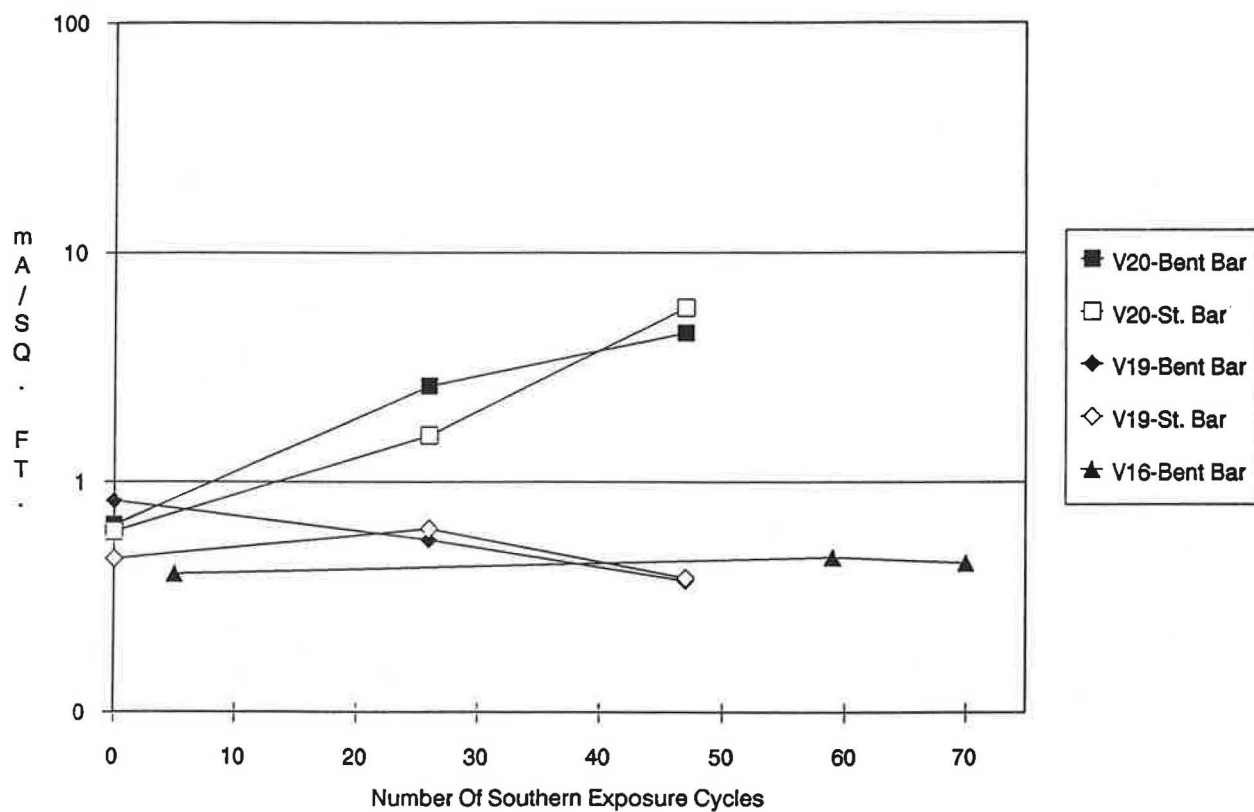


FIGURE 6 Small-bend study—controls and epoxy-coated bar specimens: corrosion rate versus time.

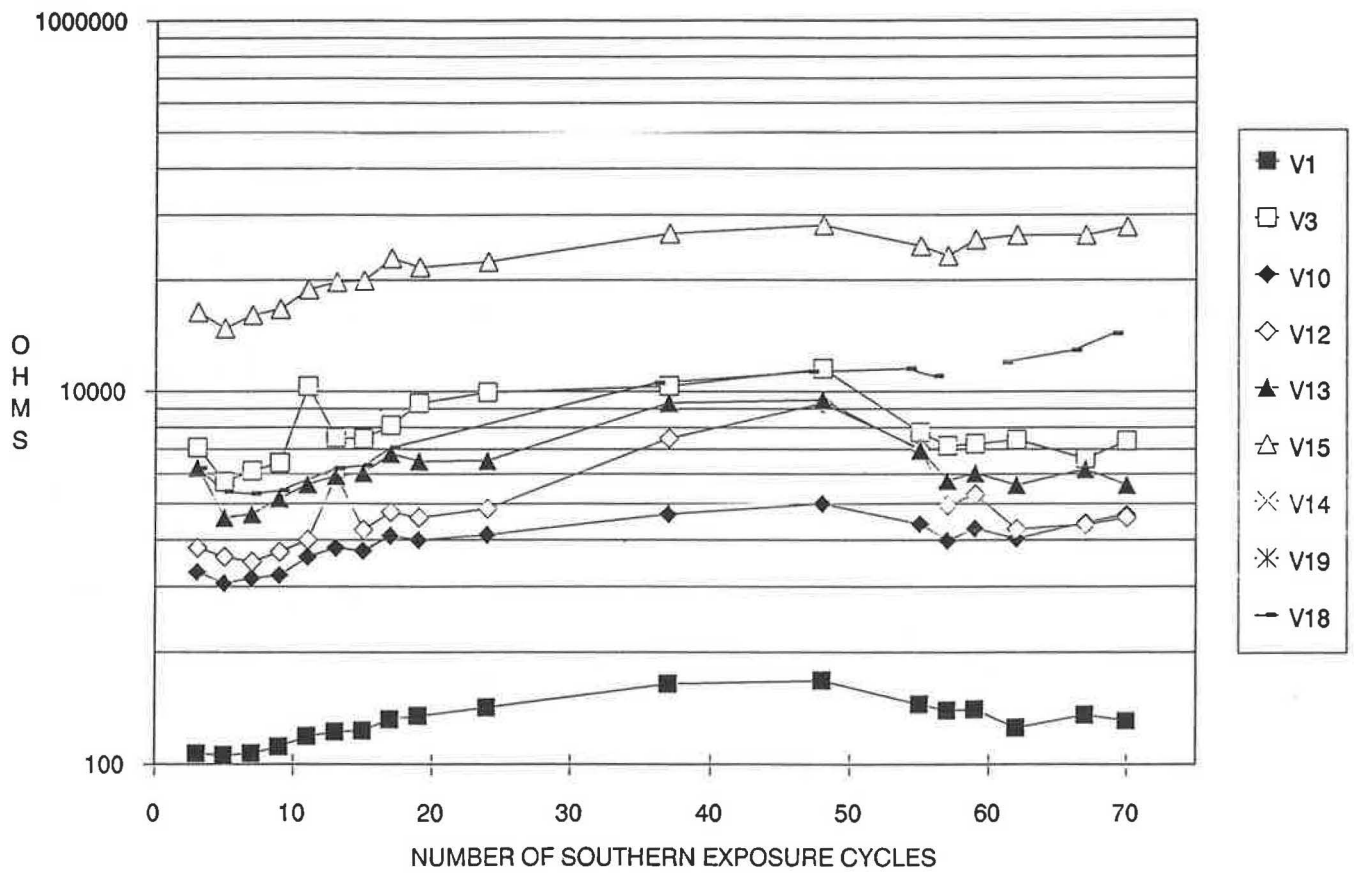


FIGURE 7 All bent bars—controls and epoxy-coated bar specimens: resistance versus time.

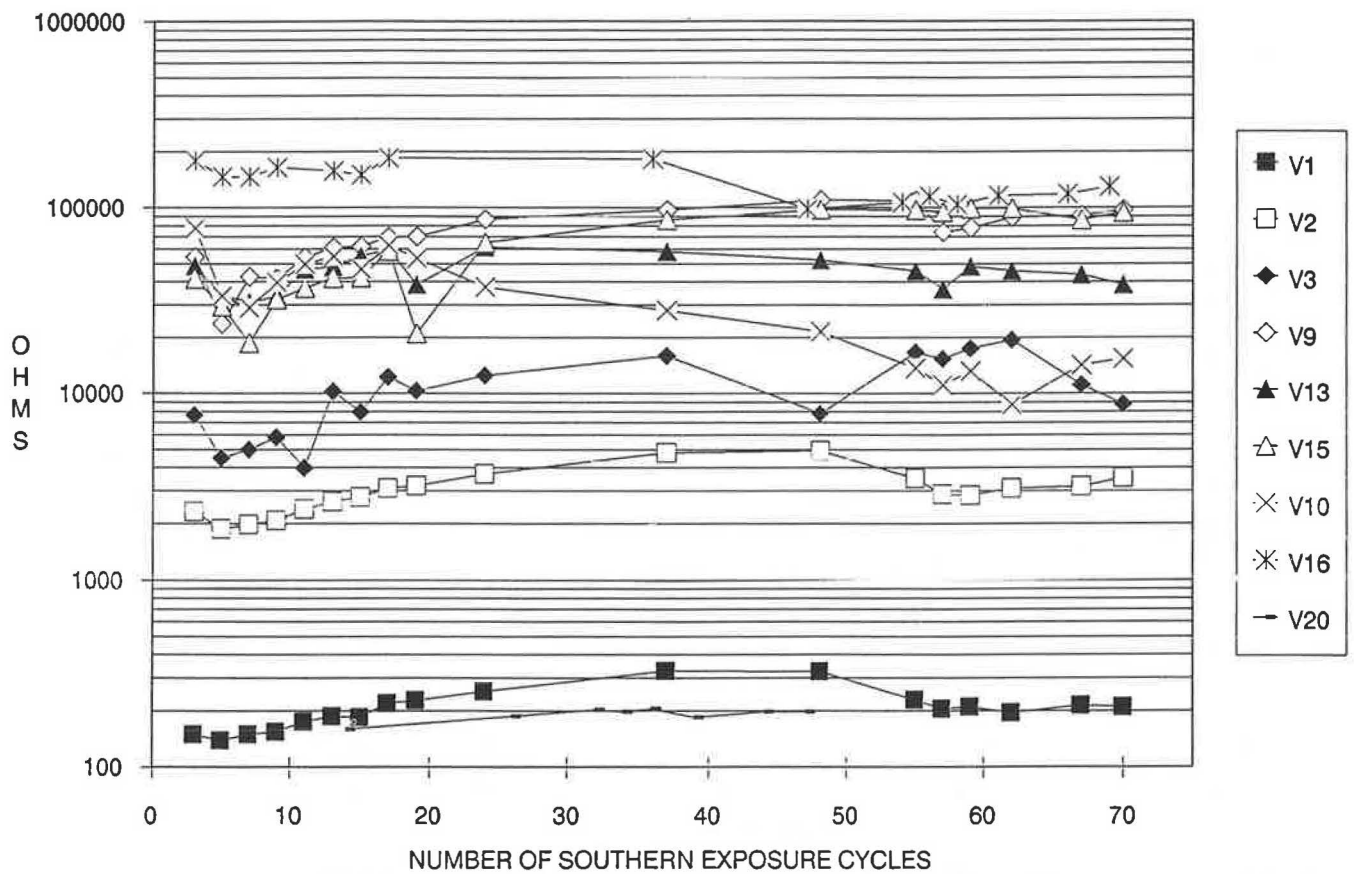


FIGURE 8 All straight bars—controls and epoxy-coated bar specimens: resistance versus time.



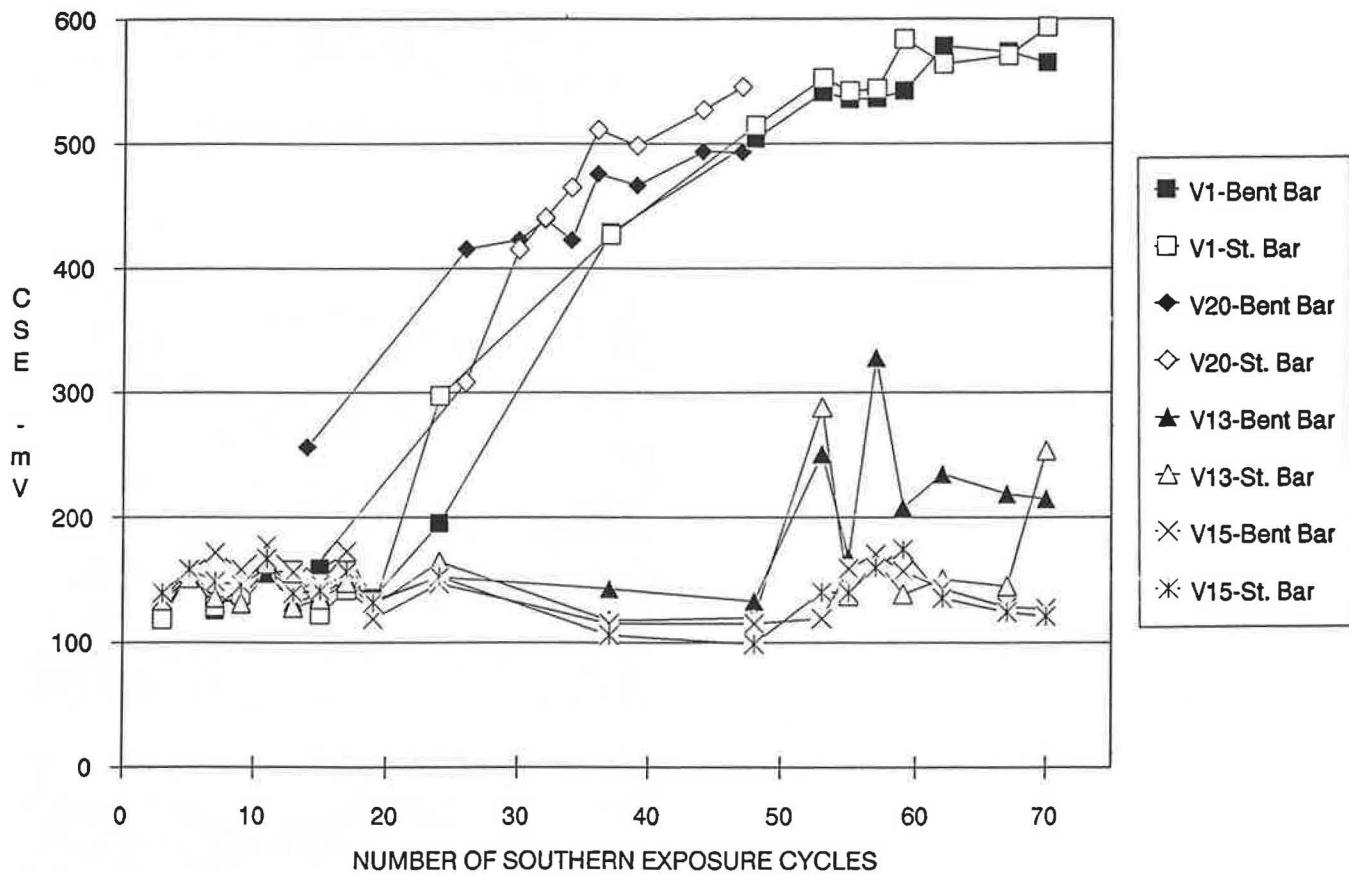


FIGURE 9 Controls and the highest and lowest epoxy-coated bar specimens: rebar potential versus time.

TABLE 3 REBAR HALF-CELL POTENTIAL DATA

Variable #	SE Cycles Completed	BENT BAR				STRAIGHT BAR			
		Initial Potential	Final Potential	Average Potential	Change in Potential. (Final - Initial)	Initial Potential	Final Potential	Average Potential	Change in Potential. (Final - Initial)
V1	77	-78	-565	-333	-487	-79	-594	-339	-515
V2	77	-113	-161	-145	-48	-117	-178	-152	-61
V3	77	-96	-236	-154	-140	-110	-201	-150	-91
V4	77	-94	-231	-170	-137	-95	-147	-158	-52
V5	77	-74	-210	-169	-136	-87	-201	-154	-114
V6	77	-77	-181	-154	-104	-78	-168	-148	-90
V10	77	-83	-262	-172	-179	-69	-201	-148	-132
V12	77	-70	-234	-167	-164	-71	-162	-139	-91
V13	77	-86	-215	-175	-129	-93	-253	-154	-160
V14	47	-96	-121	-127	-25	-106	-142	-132	-36
V15	77	-91	-127	-146	-36	-94	-121	-141	-27
V16	77	-91	-182	-152	-91	-115	-157	-155	-42
V18	77	-90	-169	-166	-79	-108	-169	-175	-61
V19	47	-101	-197	-198	-96	-128	-182	-182	-54
V20	47	-121	-403	-432	-372	-127	-545	-429	-418

NOTE : All potentials are expressed in negative mV CSE.

## Autopsy

Autopsy testing was conducted on 1 black bar control slab and 11 epoxy-coated bar slabs. The epoxy-coated bar slabs were selected to represent all variables and to include the slabs that demonstrated the maximum and minimum macrocell corrosion currents from both the large-bend and small-bend studies.

Saw cuts were made along the sides of the slabs parallel to the top mat steel. The concrete was then chiseled along the saw cuts to force failure in the top mat rebar plane and expose the bars. Additional chipping allowed complete removal of the bars from the concrete without damaging the coating or the bars. Figure 10 shows a typical slab after completion of autopsy testing. After removal of the rebars from the concrete slabs, any visual coating damage, rusting, or changes in coating parameters (such as softening or disbondment) were documented. The visual condition of the bar traces left on the concrete was also documented.

In general, the epoxy-coated rebars exhibited insignificant corrosion damage as compared to the black bar controls. Corrosion that was found on epoxy-coated bars had initiated at sites where visual coating damage existed before placement of the rebar in concrete and at original holidays. Corrosion initiation at holidays was primarily limited to locations on the ribs of the bars. The increase in volume caused by corrosion product in the vicinity of holidays caused a bubble to form in the coating. In the later stages of corrosion, these bubbles ruptured causing a loss of coating. The diameter of the bubbles ranged from approximately  $\frac{1}{16}$  to  $\frac{1}{8}$  in. No bond loss around the bubbled areas was found and no deep pits or severe section loss from the small anode or large cathode effect was found.

Photographs of black bars from the control slab are presented in Figure 11. Figure 12 shows photographs of epoxy-coated rebars obtained from the slab representing Variable 10. This slab exhibited the maximum corrosion current for epoxy-coated rebar slabs at the end of 70 SE cycles. Figure 13 shows photographs of epoxy-coated rebars obtained from the slab representing Variable 11. This slab exhibited the minimum corrosion current for epoxy-coated rebar slabs at the end of 70 SE cycles.

## CONCLUSION

Coated bars have performed significantly better than uncoated bars during the 70 and 47 SE cycles completed to date. Rust staining and cracking have occurred on the uncoated control slabs but not on any of the epoxy-coated rebar specimens.

Out of the 36 sets of epoxy-coated specimens tested, only seven showed macrocell corrosion currents greater than 0.01 mamp/ft<sup>2</sup>. Of these 7 sets, three had visibly identifiable damage before placement in the slab. The macrocell currents on the control slabs were more than an order of magnitude higher than those on the epoxy-coated bars; the controls averaged 1.62 mamp/ft<sup>2</sup>, all the epoxy-coated bars averaged 0.018 mamp/ft<sup>2</sup>, and the average of the seven sets was 0.072 mamp/ft<sup>2</sup>. Corrosion rates calculated from the three-electrode linear polarization data also correlated with the macrocell current data.

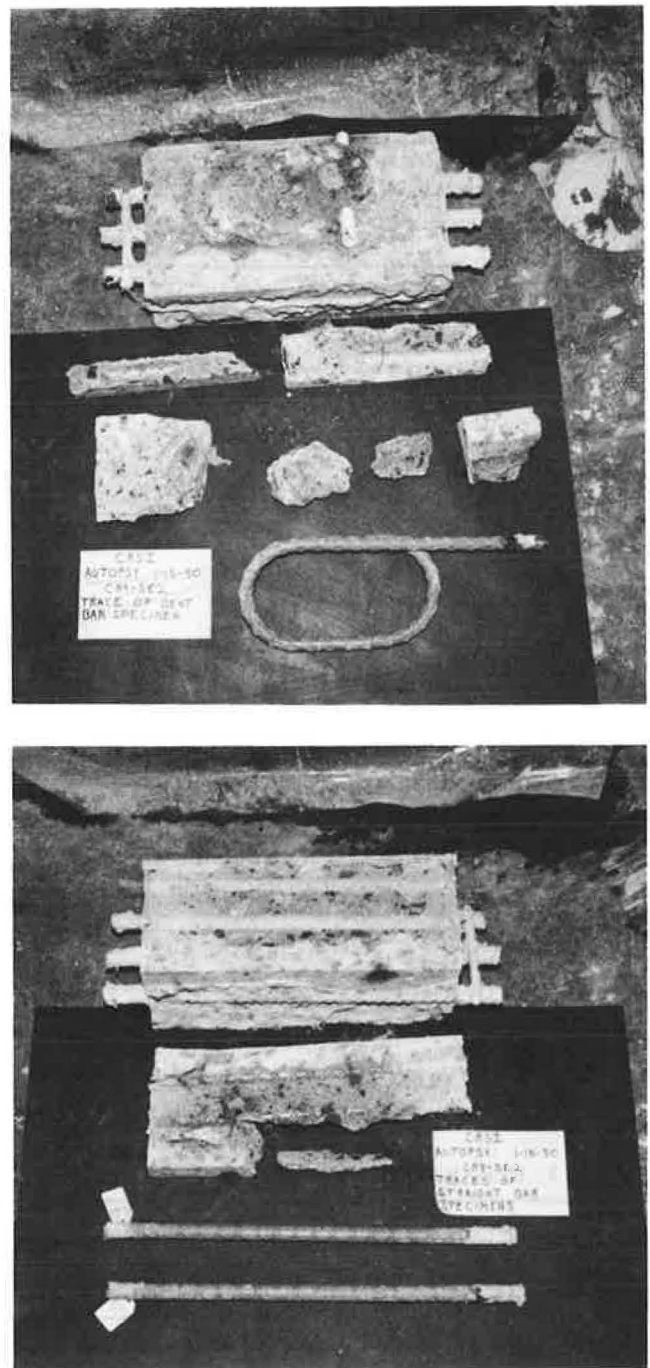
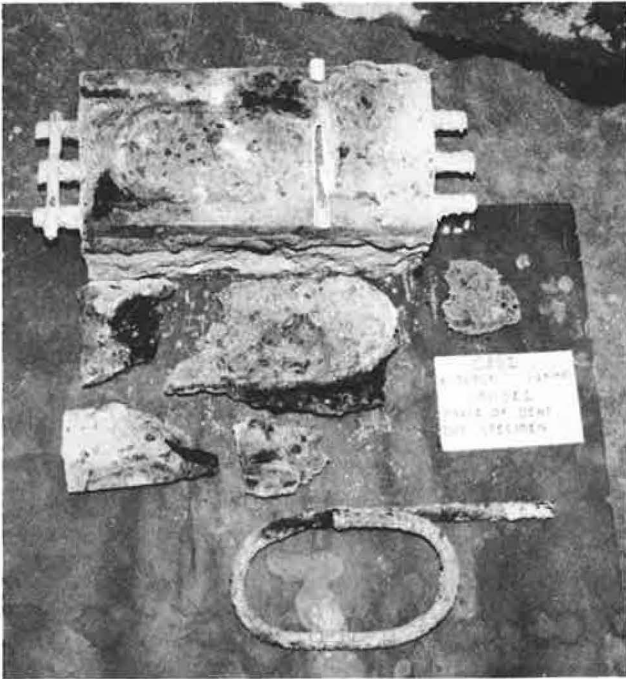
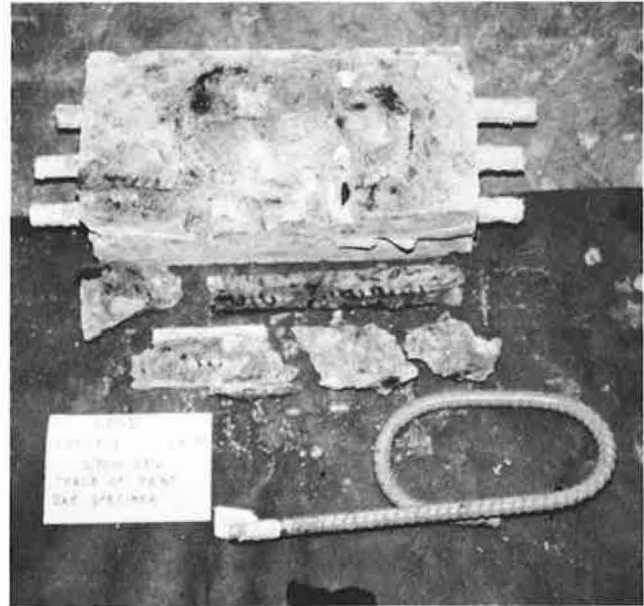


FIGURE 10 Rebars after completion of a typical autopsy.

The electrical resistance between the mats of the epoxy-coated bars ranged from 1,300 to 129,500. The average of epoxy-coated bent-bar specimens was 40,654 ohms, and that of epoxy-coated straight-bar specimens was 12,265 ohms. Although the mat-to-mat electrical resistance of the epoxy-coated bars varies significantly from one specimen to another, the general trend is to remain constant with time. This observation indicates that the coating is not deteriorating or becoming disbonded with time. A significant difference between the electrical resistance of coated straight and bent bars was noted.

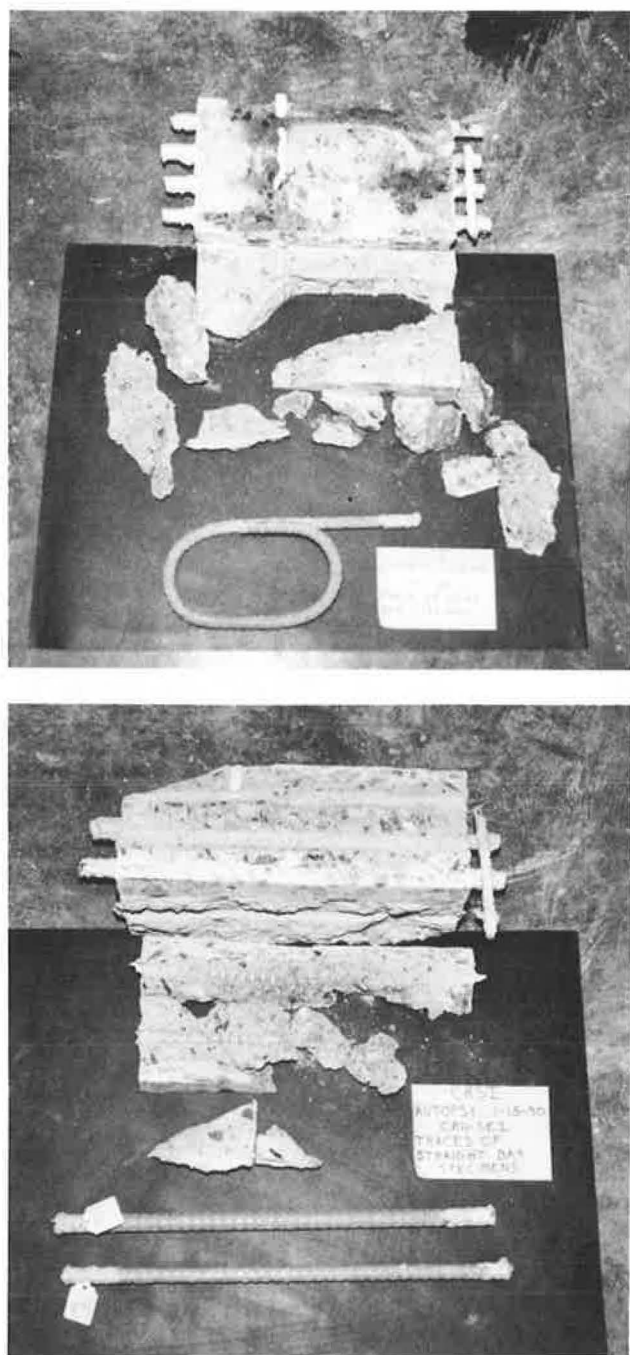


**FIGURE 11** Rebars after completion of autopsy of a slab representing black bar controls.



**FIGURE 12** Rebars after completion of autopsy of a slab representing Variable 10.





**FIGURE 13** Rebars after completion of autopsy of a slab representing Variable 11.

This may be partially because of the difference in geometry of the specimens.

Autopsy testing revealed little corrosion damage on epoxy-coated rebars. Corrosion that was found had initiated at sites where visual coating damage existed before concrete placement and at original holidays. Where corrosion initiated at

holidays, the volume of corrosion products caused a bubble to form in the coating, that eventually led to local coating loss as corrosion progressed and the bubble ruptured. No severe section loss or pitting caused by the small anode or large cathode effect was found.

Presently, the effects of the various coating parameters on the ability of the epoxy coating to provide corrosion protection are not distinguishable and no other differences between the bent and straight epoxy-coated bars, other than visible coating damage, are discernable.

## ACKNOWLEDGMENT

This research was supported by the Concrete Reinforcing Steel Institute.

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*The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the Concrete Reinforcing Steel Institute.*

*Publication of this paper sponsored by Committee on Corrosion.*