FIELD AND LABORATORY TESTING OF EPOXY-COATED REINFORCING BARS IN CONCRETE

Şakir Erdoğdu and Theodore W. Bremner[*]

Corrosion of reinforcement in concrete exposed to chloride-contaminated environments is a common problem. If the corrosion process proceeds undetected, the safety of the reinforced concrete structures may be diminished. Therefore, information about the corrosion activity of reinforcing steel is essential. This paper presents the results of a study of the corrosion of epoxy-coated reinforcing steel in concrete exposed to chloride-contaminated environments using common test procedures including open-circuit potentials, linear polarization measurements, and AC impedance measurements. Testing was carried out both in the laboratory and in the field. Laboratory testing was accelerated in a simulated marine environment with four wetting and drying cycles each day using small-scale concrete slabs containing a single U-shaped epoxy-coated rebar. Corrosion activity was monitored continuously while specimens were exposed over a two year period. For field testing, concrete slabs containing U-shaped epoxy-coated reinforcing bars were placed at a natural marine environment exposure station in Treat Island, Maine. Electrochemical monitoring indicated that the corrosion rate of epoxy-coated rebar was negligible regardless of the degree of damage to the coating. Similarly epoxy-coated rebars removed from the slabs at the end of one and two years of exposure showed no propensity to cause cracking and spalling due to corrosion products and no visible signs of corrosion were found on the surface of concrete.

Keywords: corrosion, chloride ingress, oxygen access, diffusion, epoxy-coated reinforcement, pH, polarization, passivity, resistance, impedance, current density, corrosion rate

INTRODUCTION

Reinforcing steel embedded in uncarbonated, chloride-free concrete does not corrode due to the presence of alkali hydroxides in the Portland cement matrix. It is assumed that the high alkalinity of the concrete passivates the steel (1,2). Aggressive ions such as chloride are capable of destroying this passivity causing the steel to corrode at localized areas (3,4,5). The aggressiveness of the environment is also a function of available oxygen with which steel interacts to form corrosion products (6,7,8). The conditions which must be fulfilled if corrosion of steel is to be sustained are as follows:

- The relative concentration of chloride ions to hydroxyl ions at the steel surface must be sufficient to break down the passivity.

- The availability of oxygen at the cathodic areas must be sufficient to sustain a reaction. If oxygen is limited, the cathodic polarization curve indicates that the current passing from the anodic area to the cathodic area will be negligible. This is normally the case for reinforcing steel properly isolated from the surrounding environment.

A progressive accumulation of rust at the steel-concrete interface produces tensile stresses often higher than the ultimate stress of the concrete. Eventually, this will result in cracking and spalling of the concrete.

The ability to measure the rate of corrosion of rebar in concrete would be useful in determining the time for repair or replacement of structures in a given environment. Within the past decade there have been important advances in the development of electrochemical techniques for measuring the corrosion rate of reinforcement in concrete. These methods include open-circuit potentials (9,10), linear polarization technique (10,11,12), and AC impedance spectroscopy (13,14,15). However, monitoring the corrosion activity of rebar in concrete, particularly when it is covered with an epoxy compound, is very tedious and, in some cases, can be misleading. The work described in this paper concerns the applicability of commonly used electrochemical techniques to measure the corrosion rate of steel in concrete exposed to chloride-contaminated environments. The significance of this research is that the corrosion rate as determined by linear polarization is an effective method for predicting the behavior of reinforced concrete structures in aggressive environments.

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EXPERIMENTAL PROCEDURE

Program and Exposure Conditions

The investigation outlined in this paper was carried out in the field and under accelerated exposure conditions in the laboratory. For laboratory testing, a Marine Environment Simulated Setup (MESS) was used. For field work, a severe exposure site in the Bay of Fundy at Treat Island, Maine, was used.

All the concrete slabs tested were made with Type 10 Canadian Portland cement (ASTM Type I). The concrete was machine mixed and then tamped and vibrated during placement. The maximum aggregate size used was 12 mm (0.5 in). An air entraining agent was added to the mixes to produce 6.5±0.5% air content. After casting, the concrete slabs were moist cured for two weeks at 20±2°C (68±4°F) and a relative humidity of not less than 95% before exposure to simulated seawater and a natural marine environment.

Four series of mixes (mix-C, D, E, and F) with a water to cement ratio of 0.60 were cast. Concrete slabs from mix-C were exposed to simulated seawater in the laboratory while mix-D through mix-F were exposed to a natural marine environment at Treat Island. The slabs from mix-D were placed at mid-tide level on the beach while the slabs from mix-E and mix-F were placed at 0.5 m (1.6 ft) below high tide and 0.5 m (1.6 ft) above high tide level. Each mix yielded 12 concrete slabs containing U-shaped rebars. Four of the slabs in each series contained an uncoated bar and eight contained a coated bar. All the coated bars were initially tested with a holiday detector in conformance with ASTM G-62/79 and patched with an epoxy compound if a bare spot was noted. One half of the epoxy-coated bars were cast in the concrete without damage to the coating. The coating was damaged on two of the bars by removing 1% of the total coating area and on two other bars by removing 2% of the total area. The testing program is summarized in Table I. To obtain a 1% and 2% damage to the coating, 7 and 14 patches of epoxy in size 6 x 6 mm (0.24 x 0.24 in) were removed, respectively. The patches were between the ribs and evenly distributed over the surface of each rebar. The U-shaped bars fabricated from regular reinforcing steel were 15 mm (0.6 in) in diameter.

The slabs were 55 x 200 x 300 mm (2.2 x 8 x 12 in.). The concrete cover over the rebar was 20±2 mm (0.8±0.1 in) in all directions as shown in Figure 1. To keep concrete cover the same in all directions for all concrete slabs, the U-shaped rebars were adjusted so the legs of the bar were parallel to each other and in one plane. For corrosion rate measurements, a 100 mm (4 in) stainless steel rod (303 SS) was centrally located in each slab as a counter electrode. Wires were connected to the stainless steel rod and the rebar prior to casting the concrete. The electrical connections were coated with an epoxy compound.

Table I LAYOUT OF EXPERIMENTAL PROGRAM

Type of Exposure		Number of Concrete Slabs Cast			
		Uncoated Rebar	Epoxy-Coated Rebar		
			No Damage	1% Damage	2% Damage
ASTM Seawater (MESS) (SERIES-C)		4	4	2	2
Treat Island	Mid-Tide (SERIES-D)	4	2	2	2
	0.5 m below High-Tide (SERIES-E)	4	4	2	2
	0.5 m above High-Tide (SERIES-F)	4	4	2	2

Marine Environment Simulated Setup (MESS)

The apparatus used to simulate a moist chloride environment consisted of two fiberglass-coated wooden tanks, a pump, heaters and blowers. The tanks were hooked up such that the upper tank would be a container for the specimens while the bottom tank was the reservoir for water. A computer was programmed to engage and later disengage each of the electrical devices to generate the required wet-dry cycling process. In this manner, automatic cycling 24 hours a day over extended periods was possible. To accelerate the corrosion process, a two-hour period for the wet cycle portion and a four-hour period for the dry cycle portion were chosen so four complete cycles were performed each day. The wet portion of the cycle was operated at a temperature of $32 \pm 2°C$ ($90 \pm 3°F$) while the dry portion was at $69 \pm 3°C$ ($156 \pm 6°F$) for the entire test period. The concrete slabs were placed in the upper tank in such a way that during the dry cycle one-third and during the wet cycle two-thirds of each slab was submerged to simulate tidal effects. The seawater used to simulate a marine environment was a modified version of ASTM D-1141. The composition of seawater used is given in Table II. The solution was changed periodically to maintain a consistent pH.
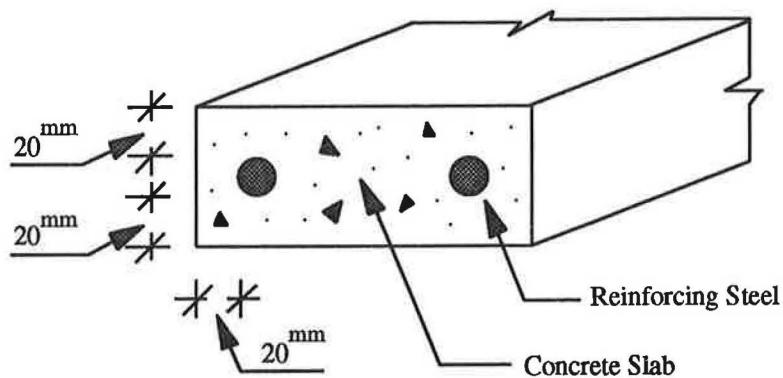

Figure 1 Location of the U-shaped rebar in concrete slab.

Natural Marine Exposure Station at Treat Island

The facility used for field testing is a severe exposure site in the Bay of Fundy at Treat Island near Eastport, Maine. The exposure station has been in use since 1936 and maintained by the U.S. Army Corps of Engineers. An average of 130 freeze-thaw cycles per year are experienced at the exposure site (16).

Instrumentation and Monitoring

The instantaneous corrosion rate of rebar in concrete was measured with a device designed using linear polarization principles. The computer-based data acquisition system is battery operated for field applications. The corrosion measuring system includes a Zenith Turbosport 386E laptop computer, Zenith Extender Chassis, Data Translation DT2801 data acquisition board and a 12-volt battery.

The system is able to polarize the rebar (working electrode) in concrete by impressing a voltage through a counter electrode. The impressed voltage causes current to flow between the working electrode and the counter electrode. A schematic layout of the setup is illustrated in Figure 2.

After the connections were made between the data acquisition system and the corroding system, the open-circuit potential (E_{corr}) of the reinforcing steel was determined. Scanning was then initiated. This was accom-

Table II COMPOSITION OF SEAWATER USED IN THE MESS

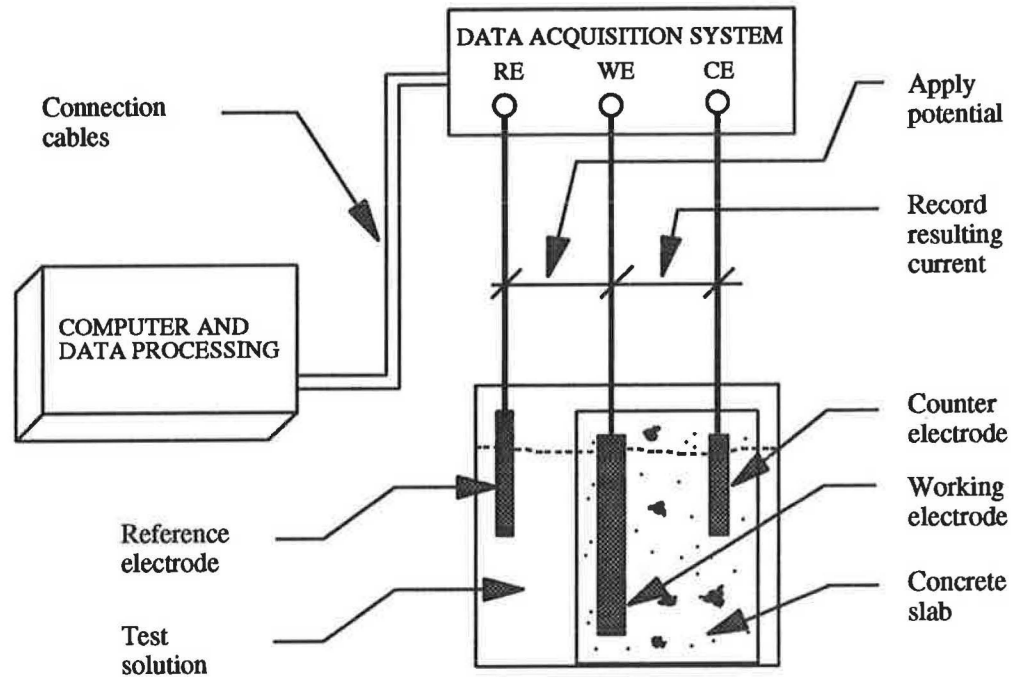| Ion	ASTM Seawater Concentration, mg/l	Synthetic Seawater Concentration, mg/l
Cl^-	19,500	17,500
Mg^{++}	1,329	1,020
$SO_4^=$	7,634	4,020

Figure 2 Schematic layout of corrosion rate measuring instrument.

plished automatically, anodically and cathodically, by changing the potential of the steel in the concrete in a range of ±10 mV about E_{corr}. The scan rate can be adjusted by modifying the software. During scanning, the difference in potential and the corresponding current was recorded each 15 seconds, and each data point was plotted on the screen of the computer. The relationship, though not perfect, is linear. The test could be restarted if abnormalities exist. The data at the end of the test was processed and the slope of the relationship calculated. This can be correlated to the corrosion current density using the Stern-Geary relationship:

$$i_{corr} = \frac{B}{R_p} [\mu A/cm^2] \qquad (1)$$

where, $R_p = \frac{\Delta E}{\Delta I} [ohm-cm^2]$ and, $B = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)}$

R_p is the slope of the linear portion of the polarization curve close to the open-circuit potential and it is often called linear polarization resistance. B is referred to as the proportionality constant which can be calculated using the Tafel slopes (β_a and β_c).

The corrosion intensity calculated from Equation (1) was then converted to corrosion rate (CR) in terms of steel consumption per year using Faraday's law:

$$CR = \frac{0.13 i_{corr}(EW)}{\rho} [MPY] \qquad (2)$$

where i_{corr} is the corrosion current density ($\mu A/cm^2$), EW is the equivalent weight (g/eq.) and ρ is the density of the steel (g/cm^3). The only inputs for the calculation of current density and corrosion rate are Tafel constants, equivalent weight, density, and area of the steel under test.

The AC impedance measurements were obtained using a Solartron Model 1255 Frequency Response Analyzer and a Solartron Model 1286 Electrochemical Interface. The frequency response analyzer used is capable of generating frequencies in the range of 10 µHz to 20 MHz. A 10 mV amplitude sinusoidal signal was used. The Solartron Model 1255 can measure signals as small as 1 mV. The data can be saved automatically for further use and manipulation.

At the end of testing the polarization resistance or charge transfer resistance (R_t) was either obtained

from a Nyquist plot or calculated empirically. The current density and corrosion rate were then calculated following the steps described in the linear polarization technique.

RESULTS AND DISCUSSION

Laboratory Testing

Open-circuit Potential Measurements

The open-circuit potential of rebar was measured against a saturated calomel electrode. The corresponding illustrations of rebars in the concrete slabs exposed to simulated seawater are presented in Figures 3 through 6. The open-circuit potentials were measured at 25-cycle intervals up to 1,000 cycles and then measurements were repeated at 50-cycle intervals for another 1,000 cycles. The measurements were taken at 100-cycle intervals thereafter.

Figure 3 illustrates the thermodynamic behavior of the uncoated bars in the concrete slabs for two years. The bars exhibited a similar potential change with time. After an initial drop in potential at the end of 275 cycles,

the open-circuit potential of the rebars began to increase. The potential drop was greater for rebars in concrete slabs C2 and C4 than those slabs C1 and C3. Repassivation continued for about 200 cycles, then, a sudden drop in potential was observed for all bars. Following this depassivation, active corrosion started and continued for the remainder of the test with a consistent potential trend. The first drop in potential is indicative of the arrival time of chloride ions at the steel surface.

Figure 4 shows the potential variation of the undamaged epoxy-coated reinforcing steel in the slabs. Initially, all bars showed a gradual increase in potential. This increase continued up to 650 cycles for the bars in the concrete slabs C5 and C6, and 900 cycles for bars in slabs C7 and C10. Following a period of fluctuation in potential, all bars showed a consistent potential variation thereafter. This is a good example the fact that properly coated steel in concrete remains passive in the absence of cathodic areas where reduction of oxygen is supposed to take place.

Figure 5 shows the thermodynamic behavior of 1% damaged epoxy-coated reinforcing steel in the concrete slabs. Up to 300 cycles, a continuous increase in the potential of both rebars was observed. Then, following a fluctuation period, both rebars displayed
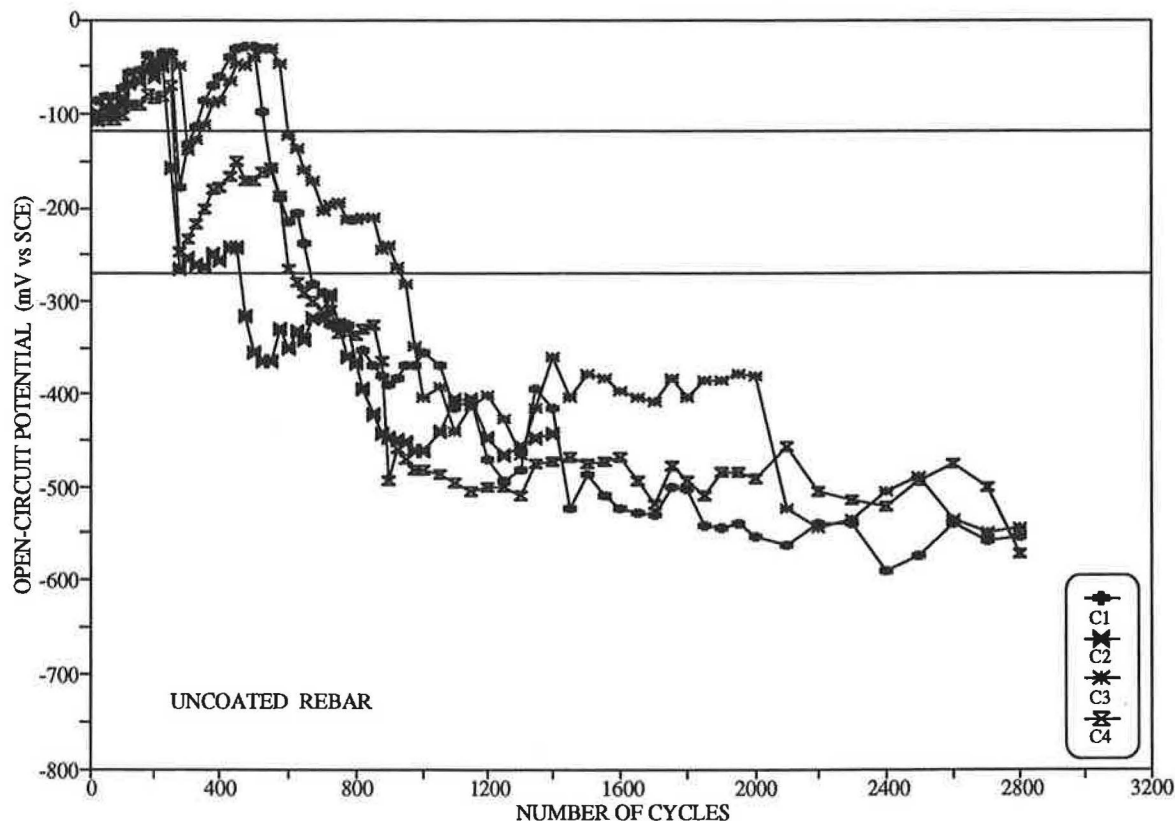

Figure 3 Potential of the uncoated rebar in concrete slabs exposed to simulated seawater.
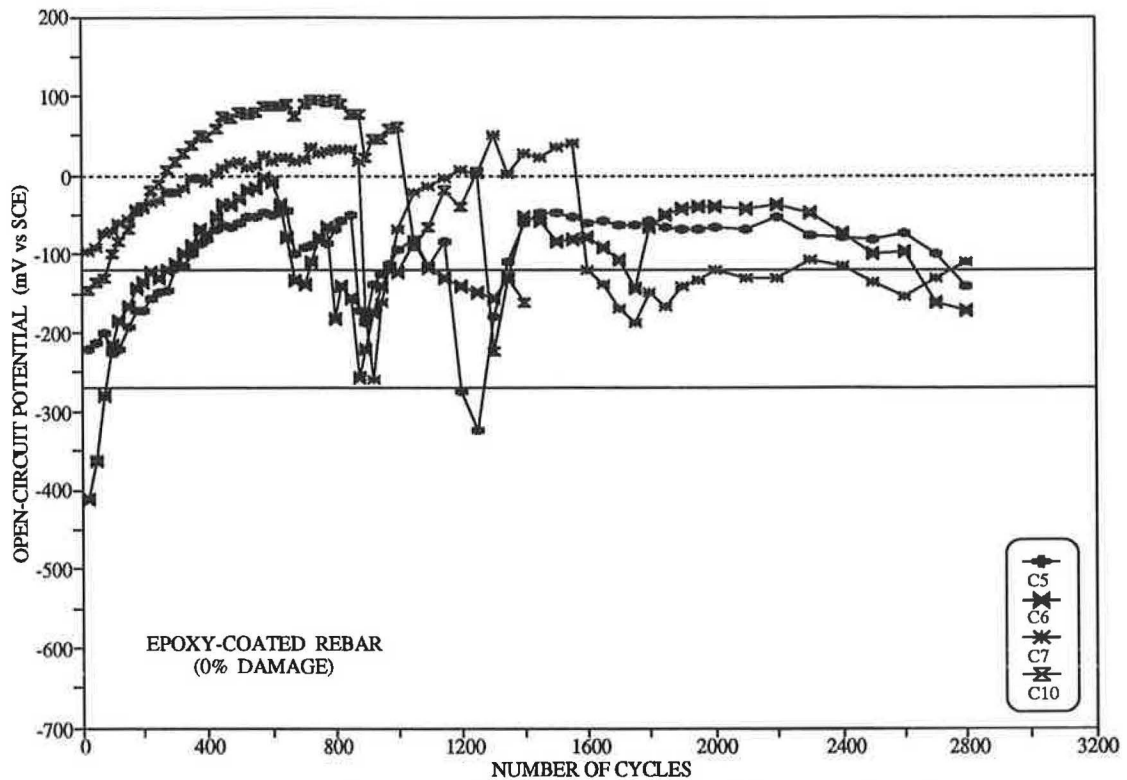
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Figure 4 Potential of the undamaged epoxy-coated rebar in concrete slabs exposed to simulated seawater.

consistent potential variation. The fluctuations indicate that the corrosion activity was controlled by the oxygen necessary for cathodic reaction and the amount of chloride ions available at the steel surface to break down the passivity.

Figure 6 illustrates the thermodynamic behavior of 2% damaged epoxy-coated rebar in concrete slabs with time. The potential variation is similar to that obtained from 1% damaged epoxy-coated bars. Following an initial increase in potential, both bars went from a passive to an active state by a series of intermediate steps depending on the availability of chloride ions at the reaction front. Then, both bars remained active for the remainder of the test. This indicates there were sufficient amounts of chloride ions available at the damaged areas of the steel surface to break down the passivity. As a result, the potential of the bars remained active without microcathode polarization owing to the presence of oxygen at the damaged areas of the steel.

Corrosion Rate Measurements

The corrosion rate measurements using the linear polarization technique were repeated periodically to measure the trend of current density over time. The polarization resistance (R_p) was directly determined by employing the linear polarization technique discussed earlier. Then, corrosion current density was calculated using Equation (1). For the proportionality constant B, a value of 52 mV was used to calculate the corrosion current density for the undamaged epoxy-coated rebar since the corrosion activity was passive, and a value of 26 mV was used for the rest of the cases since the corrosion process was active. Equation (2) was used to calculate the steel consumption per year in mils per year (MPY). The area considered in the calculation was the total area of the rebar (245 cm^2, 38 in^2) in the concrete slab. A sweep rate of 4 mV/min was applied during the linear polarization.

The average polarization resistances and current densities obtained from bars are summarized in Table III. The corresponding illustration is given in Figure 7. Although it differed from rebar to rebar, the magnitude of the average current density increased with time. There was a slight increase in the resistance of the undamaged epoxy-coated bars exposed to the same environment. The average polarization resistances (ohm-area) were over 10,000 kΩ-cm^2 (1,550 kΩ-in^2) for the entire test period. This resulted in negligibly low
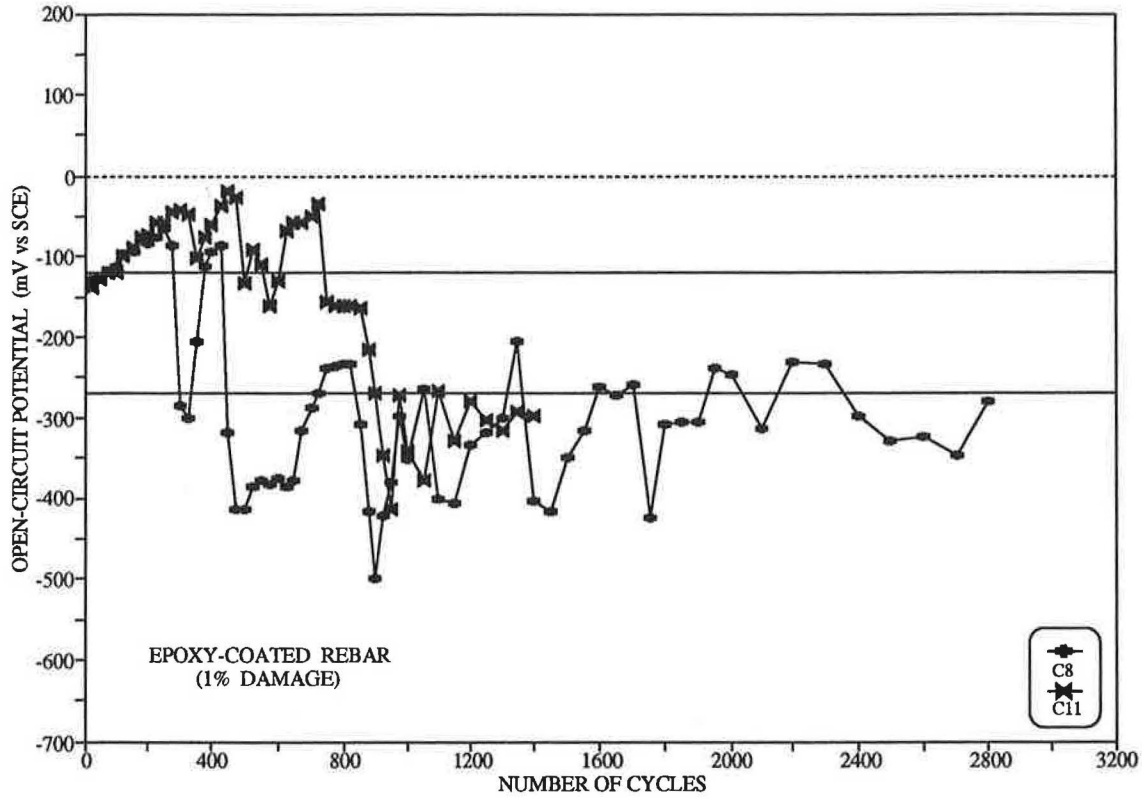
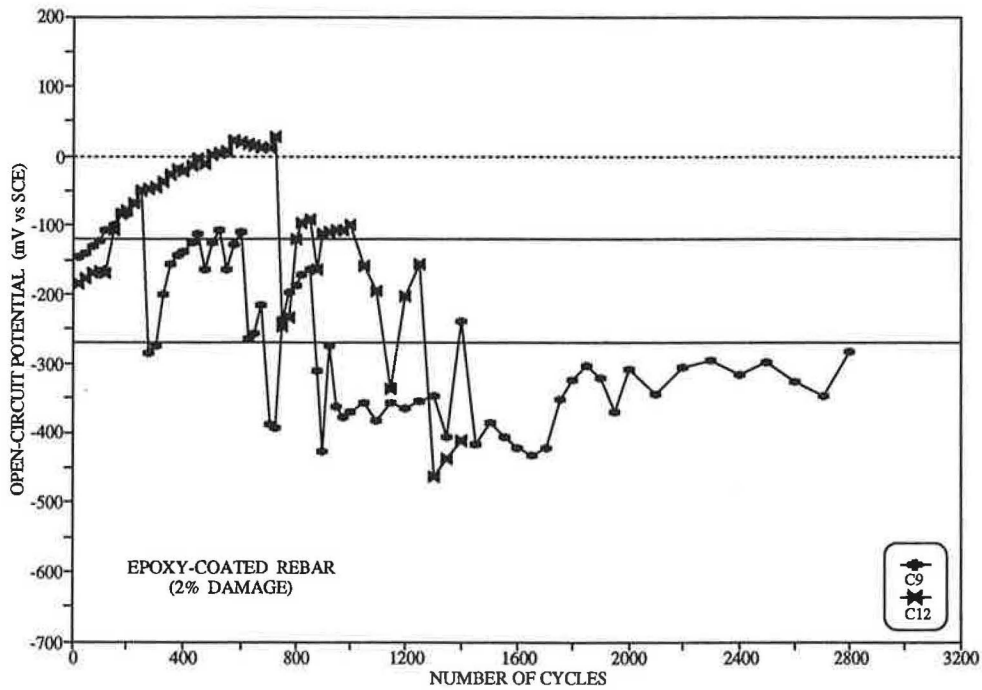**Figure 5** Potential of 1% damaged epoxy-coated rebar in concrete slabs exposed to simulated seawater.

Figure 6 Potential of 2% damaged epoxy-coated rebar in concrete slabs exposed to simulated seawater.

Table III AVERAGE CURRENT DENSITIES OBTAINED FROM REBARS IN CONCRETE SLABS EXPOSED TO SIMULATED SEAWATER USING THE LINEAR POLARIZATION TECHNIQUE

Exposure Time (Months)	Polarization Resistance, $K\Omega$-cm^2 (Current Densities, μA/cm^2)			
	Uncoated Rebar	Epoxy-Coated Rebar		
		No Damage	1% Damage	2% Damage
7	118 (0.32)	43,700 (0.00)	4,160 (0.01)	10,600 (0.00)
11	27.5 (1.82)	198,000 (0.00)	2,510 (0.02)	2,400 (0.02)
13	11.9 (3.94)	60,700 (0.00)	939 (0.03)	559 (0.05)
15	10.8 (5.15)	199,000 (0.00)	827 (0.03)	500 (0.05)
17	10.2 (7.87)	263,000 (0.00)	1,340 (0.02)	667 (0.04)
19	4.45 (7.42)	313,000 (0.00)	1,420 (0.02)	833 (0.03)
21	4.51 (7.50)	179,000 (0.00)	1,120 (0.02)	800 (0.03)
24	2.63 (10.1)	190,000 (0.00)	1,510 (0.02)	869 (0.03)

was determined from the AC impedance responses of individual rebars. The current densities and corrosion rates were calculated using Equation (1) and Equation (2).

The uncoated rebars in concrete slabs C2 and C4 had similar AC responses. Since the corrosion cells were resistive, the AC responses of the bars were flat. The rebar in slab C7 had a semicircle with a large diameter. The corrosion rate was negligible due to a high resistance. Rebars in slabs C8 and C9 indicated similar AC impedance responses with small semicircles. Following these semicircles, at low frequencies, they exhibited a linear segment with a slope smaller than 45 degrees. This was a good indication that the corrosion taking place at the damaged areas was small in magnitude.

Visual Observations

At the end of one and two years of exposure some concrete slabs were cut open to expose the bars for visual and microscopic examination of corrosion products formed at the rebar-concrete interface. At the end of two years, the uncoated rebars were heavily corroded. Because of the accumulation of corrosion products at the steel-concrete interface, cracks formed in the concrete slabs and extended to the surface where they were visible to the eye. The corrosion products formed at the steel surface were mainly black-green-brown in color.

The undamaged epoxy-coated rebar showed no signs of corrosion even at the end of two years of exposure to simulated seawater. However, the damaged rebars showed some degree of corrosion at the damaged areas. The rust products were usually black in color and formed as localized pits at the damaged spots. There was no sign of cracking of the concrete cover when examined at 100X with a stereo-microscope.
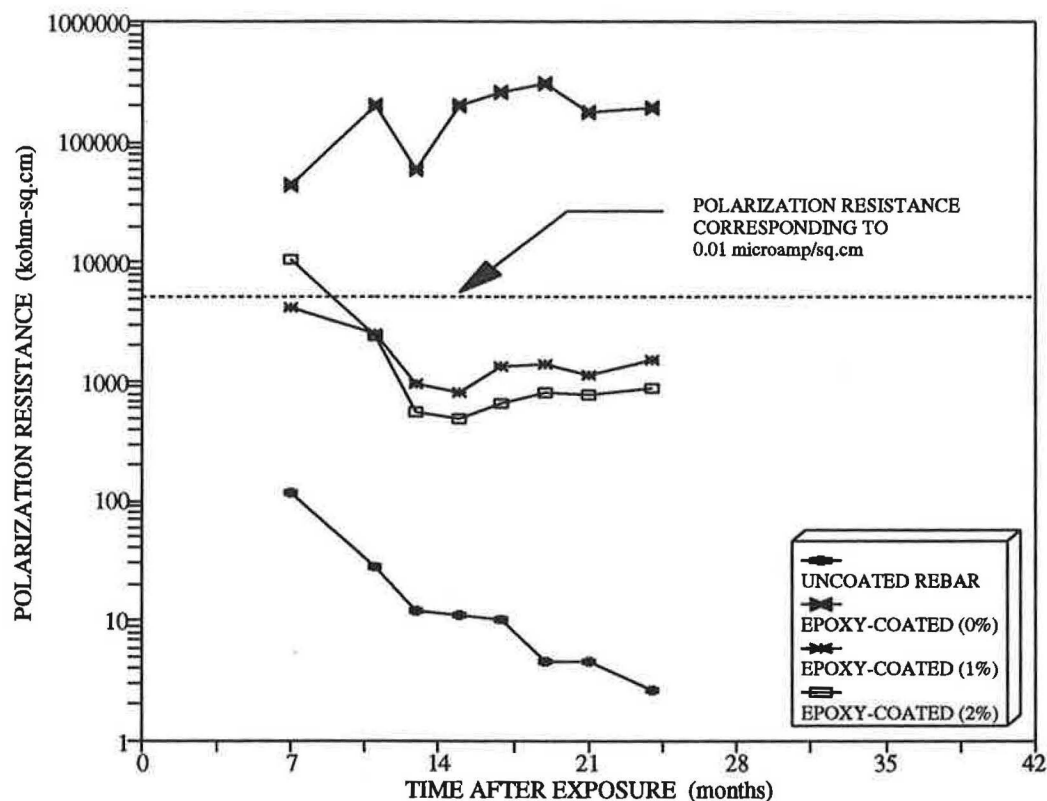
current densities. Obviously, this positive contribution for corrosion resistance is attributable to the dielectric characteristics and the high resistance of the epoxy coating to ionic diffusion.

From Figure 7, 1% and 2% damage epoxy-coated bars showed similar corrosion trends over time. There was an increase in the average polarization resistance measured for both groups of rebars. The magnitude of corrosion current density was higher than the 0.01 μA/cm^2 (0.01 mA/ft^2) which is recommended as the maximum current density normally considered for long-term maintenance-free performance.

Corrosion rate measurements based on the AC impedance technique are summarized in Table IV. Five bars were tested at the end of 7.5 months of exposure to simulated seawater. Two of them were uncoated and the rest were epoxy-coated with one undamaged, one 1% damaged and one 2% damaged. The value of charge transfer resistance (R_t) which corresponds to R_p

Figure 7 Polarization resistance of reinforcing steel in concrete slabs exposed to simulated seawater.

Field Testing

Corrosion Rate Measurements

The average polarization resistances obtained from rebars in the concrete slabs exposed to natural marine environment using the linear polarization technique are presented graphically in Figures 8 and 9. They illustrate the average polarization resistances measured at the end of one and two years of exposure. These graphs allow comparisons between the polarization resistance of rebars with regard to location at the exposure site. At the end of one year, the difference in polarization resistance of the damaged and undamaged epoxy-coated rebar, was not discernable re-

gardless of location within the exposure site. The magnitude of current density was negligible. However, at the end of two years, the damaged rebars showed high current densities with respect to those obtained at

Table IV CORROSION RATE OBTAINED FROM REBARS IN CONCRETE SLABS EXPOSED TO SIMULATED SEAWATER USING THE AC IMPEDANCE TECHNIQUE (7.5 MONTHS EXPOSURE)

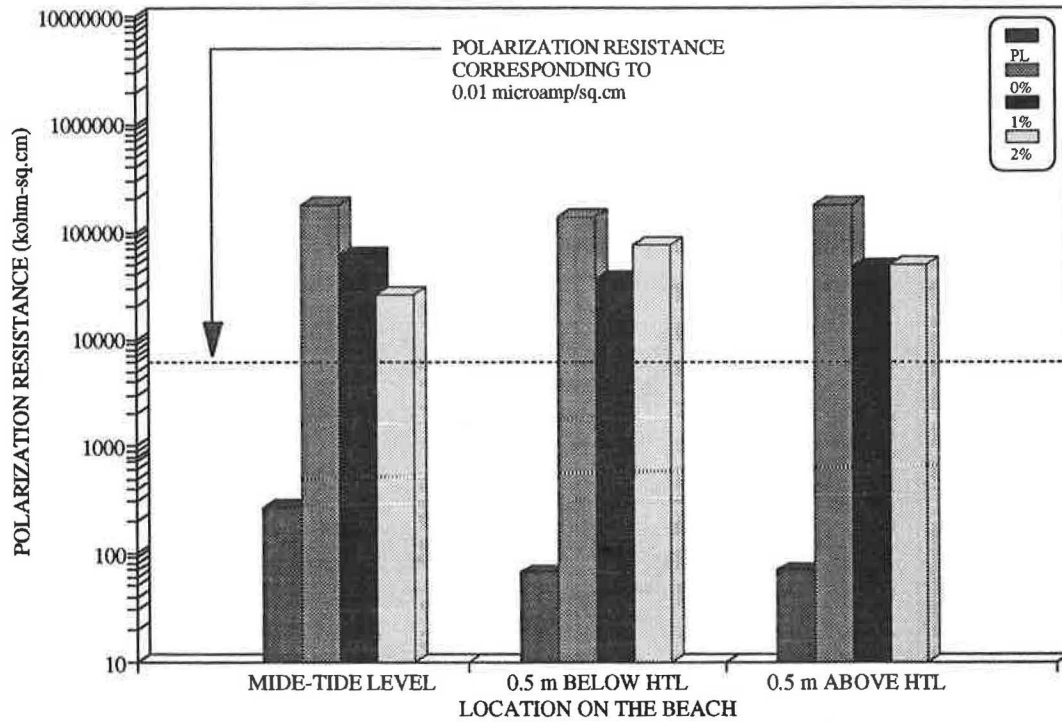| Parameter	Uncoated Rebar		Epoxy-Coated Rebar		
			No Damage	1% Damage	2% Damage
	C-2	C-4	C-7	C-8	C-9
R_t (kΩ-cm^2)	8.91	63.1	355,000	562	501
i_{corr}(μA/cm^2)	2.92	0.41	0.00	0.05	0.05
CR (MPY)	1.35	0.19	0.00	0.02	0.02

Figure 8 Polarization resistance of reinforcing steel in concrete slabs exposed to natural marine environment for one year.
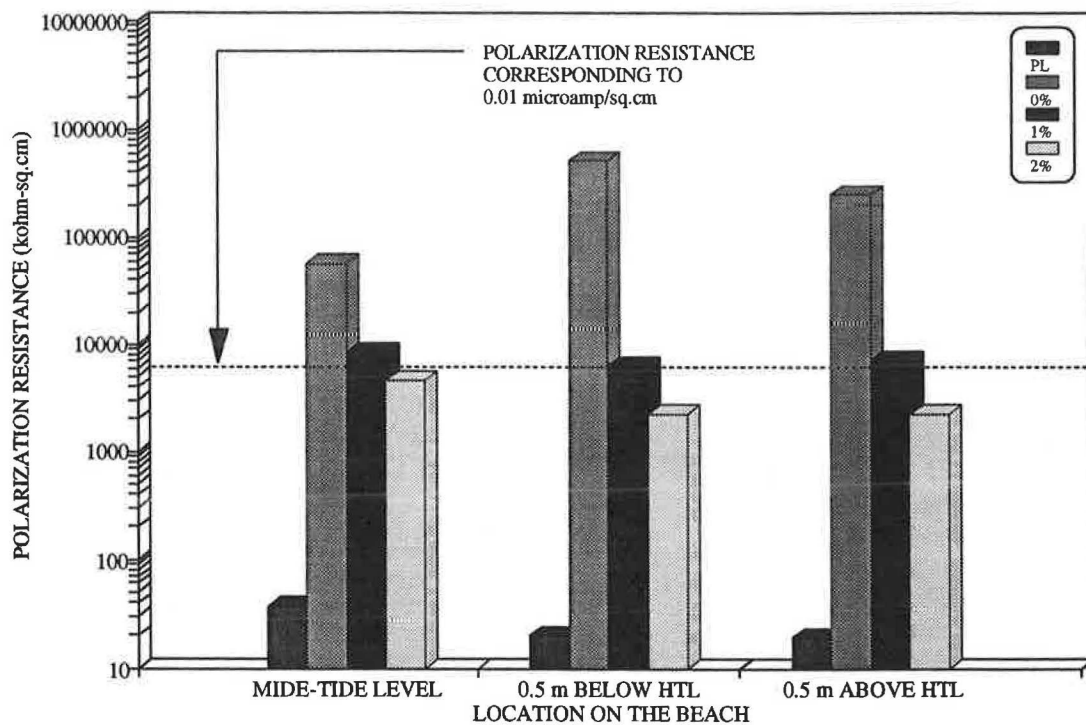

Figure 9 Polarization resistance of reinforcing steel in concrete slabs exposed to natural marine environment for two years.

the end of one year. Moreover, the two percent damaged bars showed an average current density slightly higher than 0.01 $\mu A/cm^2$ (0.01 mA/ft^2). A simple comparison revealed that the average current density obtained from the uncoated rebar at the end of two years was 2 to 3 times the average current density measured at the end of one year. Another discernable point is that the corrosion rate at the mid-tide level was slightly lower than that observed at the other locations on the exposure site.

Visual Observations

At the end of one and two years, some slabs from each location were cut open to expose the rebar for visual and microscopic examination of the corrosion products on the rebar surface. Regardless of the location at the exposure site, the uncoated bars had localized corroded spots over 10 to 15% of the total surface area of the bar. The rust products were usually black-green-brown in color. The undamaged epoxy-coated rebars were unchanged while the damaged epoxy-coated rebars were in good condition as well. The only corrosion products detected were some small pits at the damaged areas.

CONCLUDING REMARKS

The main conclusions from this investigation are as follows:
•   Time-to-active corrosion initiation for the uncoated rebar exposed to simulated seawater was about 5.5 months according to the criteria quoted in ASTM C-876.
•   Long-term open-circuit potentials revealed that epoxy-coated rebar in concrete exposed to simulated marine environment remains passive. This was also confirmed by the linear polarization measurements as no measurable corrosion was obtained for the entire test period.
•   The overall average corrosion current density of the uncoated steel was 2.88 $\mu A/cm^2$ (1.33 MPY) at the end of one year of exposure to simulated seawater, and 10.1 $\mu A/cm^2$ (4.65 MPY) at two years. The average corrosion current densities measured at the end of one year of exposure to a natural marine environment was 0.39 $\mu A/cm^2$ (0.18 MPY), and 1.19 $\mu A/cm^2$ (0.55 MPY) at two years. The current density at the end of two years increased more than three times the value obtained at the end of one year of exposure for both exposure conditions.
•   One percent damaged epoxy-coated rebars exposed to a natural marine environment for two years

showed a current density slightly higher than the 0.01 $\mu A/cm^2$ which is the recommended maximum current density for long-term maintenance-free performance.
•   The average current density of the uncoated rebars in concrete slabs placed at the high tide region was twice the current density experienced at mid-tide level.
•   After two years of exposure to marine environments in the tidal zone, there was no indication of rust stains or cracks on the surface of concrete slabs due to the corrosion of the epoxy-coated reinforcing steel regardless of the degree of the damage to the coating and exposure conditions.

ACKNOWLEDGEMENTS

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