Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Components

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Foreword

Eleven systems combining epoxy-coated reinforcement with another corrosion protection system are evaluated using the rapid macrocell, Southern Exposure, cracked beam, and linear polarization resistance tests. The systems include bars that are pretreated with zinc chromate to improve the adhesion between the epoxy and the reinforcing steel; two epoxies with improved adhesion to the reinforcing steel; one inorganic corrosion inhibitor, calcium nitrite; two organic corrosion inhibitors; an epoxy-coated bar with a primer containing microencapsulated calcium nitrite; the three epoxy-coated bars with improved adhesion combined with the corrosion inhibitor calcium nitrite; and multiple coated bars with an initial 50-micrometer (μm) (2-mil) coating of 98 percent zinc and 2 percent aluminum followed by a conventional epoxy-coating. The systems are compared with conventional uncoated reinforcement and conventional epoxy-coated reinforcement. The results presented in this report represent the findings obtained during the first half of a 5-year study that includes longer-term ASTM G 109 and field tests.

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16. Abstract

Eleven systems combining epoxy-coated reinforcement with another corrosion protection system are evaluated using the rapid macrocell, Southern Exposure, cracked beam, and linear polarization resistance tests. The systems include bars that are pretreated with zinc chromate to improve the adhesion between the epoxy and the reinforcing steel; two epoxies with improved adhesion to the reinforcing steel; one inorganic corrosion inhibitor, calcium nitrite; two organic corrosion inhibitors; an epoxy-coated bar with a primer containing microencapsulated calcium nitrite; the three epoxy-coated bars with improved adhesion combined with the corrosion inhibitor calcium nitrite; and multiple coated bars with an initial 50-µm (2-mil) coating of 98 percent zinc and 2 percent aluminum followed by a conventional epoxy-coating. The systems are compared with conventional uncoated reinforcement and conventional epoxy-coated reinforcement. The results presented in this report represent the findings obtained during the first half of a 5-year study that includes longer-term ASTM G 109 and field tests. In the short-term tests used to date, the epoxy-coatings evaluated provide superior corrosion protection to the reinforcing steel. The results also indicate that the bars will continue to perform well in the longer term, although the tests do not evaluate the effects of long-term reductions in the bond between the epoxy and the reinforcing steel. The corrosion rate on the exposed regions of damaged epoxy-coated reinforcement is somewhat higher than the average corrosion rate on the surface of uncoated reinforcement subjected to similar exposure conditions. The use of concrete with a reduced water-cement ratio improves the corrosion performance of both conventional and epoxy-coated reinforcement in uncracked concrete but has little effect in cracked concrete. Increased adhesion between the epoxy and reinforcing steel provides no significant improvement in the corrosion resistance of epoxy-coated reinforcement. It appears that corrosion inhibitors in concrete and the primer coating containing microencapsulated calcium nitrite improve the corrosion resistance of the epoxy-coated steel in uncracked concrete, but not in cracked concrete. The zinc coating on the multiple coated bars acts as a sacrificial barrier and provides some corrosion protection to the underlying steel in both uncracked and cracked concrete. The degree of protection, however, cannot be evaluated based on the results available to date.

17. Key Words
adhesion, chlorides, concrete, corrosion, corrosion inhibitor, durability, epoxy-coated steel, zinc-coated steel

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

Epoxy-coated reinforcement has been in use for more than 30 years and, when used in conjunction with increased concrete cover, has provided significant improvements over uncoated bars in the corrosion performance of reinforcing steel.(1,2) The system, however, has not been without its problems or critics.(3,4) Problems include the poor performance of epoxy-coated reinforcement when the concrete remains saturated, such as occurs in bridge piers in the salt water(4) and the observation that, with time, the epoxy tends to lose its adhesion to steel. (See references 1, 4, 5, 6, and 7). The loss of adhesion is accelerated when the concrete remains wet.

In spite of the problems and the observation that portions of epoxy-coated reinforcement rusts, this rust has not resulted in the need for repairs when used in structures, such as bridge decks, that allow the concrete occasionally to dry.(1,2) Because epoxy-coated reinforcement is a good, but not perfect, corrosion protection system, there is strong impetus to develop methods that improve its performance.

With this in mind, the objective of this research is to evaluate a number of techniques for making epoxy-coated reinforcement (ECR) more corrosion resistant by using multiple corrosion protection strategies for ECR in bridge decks, as well as for bridge members in a marine environment where abundant salt, moisture, and high temperatures (tropical weather) are prevalent.

This interim report describes the results of ongoing tests of systems that include chemical pretreatments and epoxy formulations that increase the adhesion of the epoxy coating, conventional epoxy-coated reinforcement used in conjunction with inorganic and organic corrosion inhibitors, and bars that are initially coated with zinc prior to epoxy application.

The details of the study are presented in the following chapters.

CHAPTER 2. EXPERIMENTAL WORK

CORROSION PROTECTION SYSTEMS

This study involves the evaluation of 11 systems in which epoxy-coated reinforcement is combined with another corrosion protection system. The research includes seven bar types, one uncoated and six with a fusion-bonded epoxy coating. Uncoated conventional reinforcing steel and conventional epoxy-coated reinforcement serve as the controls. The multiple corrosion protection systems include conventional epoxy-coated reinforcement used in conjunction with one of three corrosion inhibitors, bars that are treated with a primer coating containing microencapsulated calcium nitrite (a corrosion inhibitor) prior to coating with conventional epoxy, bars with improved adhesion between the epoxy and the reinforcing steel, obtained through the use of either a zinc chromate pretreatment or special epoxies with higher adhesion, the combination of bars with an improved adhesion epoxy and the addition of calcium nitrite to the mortar or concrete used in the tests, and bars with multiple coatings, consisting of a 50-micrometers (μm) (2-milli-inch (mil)) layer of 98 percent zinc–2 percent aluminum that is, in turn, coated with a conventional epoxy.

The systems are listed in table 1, along with the shorthand notation that will be used in this report, and are described next.

Control Systems

Uncoated conventional steel (Conv.)—All tests of both uncoated and coated bars involve the use of a single heat of No. 16 (No. 5) Grade 420 (60) A 615[8] reinforcing steel. The chemical analysis of the steel is given in table 2.

Conventional epoxy-coated reinforcement (ECR)—The conventional fusion-bonded thermoset epoxy-coated reinforcement used as the control is coated with Scotchkote™ 413 manufactured by 3M Corporation.

Epoxies With Increased Adhesion

A number of techniques have been used to improve the adhesion of epoxy coatings to steel. Three systems are evaluated in this study. The first involves pretreatment of uncoated steel with zinc chromate prior to the application of the epoxy coating to improve adhesion. The procedure is used in Canada for all epoxy-coated reinforcement, but because it involves the use of hexavalent chromate, which represents a significant environmental problem, it is not widely used in the United States. As an alternative, DuPont and Valspar have developed epoxy powders with improved adhesion to reinforcing steel that do not require pretreating the bars. The three systems are identified, respectively, as ECR(Chromate), ECR(DuPont), and ECR(Valspar).

Table 1. Systems under study.

System	Abbreviation
Control	
Conventional uncoated reinforcing bars	Conv.
Conventional epoxy-coated reinforcement	ECR
Epoxies with increased adhesion	
Chromate pretreatment	ECR(Chromate)
DuPont coating	ECR(DuPont)
Valspar coating	ECR(Valspar)
Corrosion inhibitors in mortar or concrete	
ECR w/$Ca(NO_2)_2$	ECR(DCI)
ECR w/Hycrete	ECR(HY)
ECR w/Rheocrete 222$^+$	ECR(RH)
3M – primer containing $Ca(NO_2)_2$	ECR(primer/$Ca(NO_2)_2$)
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete	
Chromate pretreatment	ECR(Chromate)-DCI
DuPont coating	ECR(DuPont)-DCI
Valspar coating	ECR(Valspar)-DCI
Bars with multiple coatings	MC

Table 2. Chemical analysis of steel, percent.

Steel	Bar Size No.	Heat Number	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	N	B
Conventional	16 (5)	231159	0.43	0.95	0.21	0.014	0.046	0.20	0.17	0.038	0.49	–	0.0005

Corrosion Inhibitors

Three corrosion inhibitors, one inorganic and two organic, are under study. Calcium nitrite [$Ca(NO_2)_2$] is the most widely used inorganic corrosion inhibitor in U.S. practice. Because calcium nitrite acts as a set-accelerating admixture, the form of the admixture containing a retarder, DCI-S, produced by W. R. Grace, is used in this study. The organic corrosion inhibitors are Rheocrete 222$^+$, a water-based combination of amines and esters produced by BASF Admixtures, and Hycrete, a salt of alkenyl-substituted succinic acid, produced by Broadview Technologies. A fourth system is also evaluated in which an epoxy coating (Scotchkote 413) is applied to the bars after the application of a primer coating, also produced by 3M, that contains microencapsulated calcium nitrite. According to 3M, the latter system provides protection by releasing calcium nitrite as the epoxy coating is damaged. The systems are identified, respectively, as ECR(DCI), ECR(HY), ECR(RH), and ECR(primer/ $Ca(NO_2)_2$).

Epoxies With Increased Adhesion Plus $Ca(NO_2)_2$

The three types of epoxy-coated reinforcement with improved adhesion are also evaluated in mortar and concrete containing the corrosion inhibitor calcium nitrite. The systems are identified as ECR(Chromate)-DCI, ECR(DuPont)-DCI, and ECR(Valspar)-DCI.

Multiple Coatings

Western Coating has developed a patented process for multiple coated (MC) bars that involves the application of a layer of 98 percent zinc–2 percent aluminum to reinforcing steel prior to the application of the epoxy coating. The zinc layer has a nominal thickness of 50 μm (2 mils). Following application of the zinc, the bars in this study are coated with DuPont 8-2739 Flex West Blue, a conventional epoxy.

One applicator applied the epoxy to the conventional ECR and ECR(Valspar) bars. A second applicator handled the MC and ECR(DuPont) bars, while two other applicators individually handled the ECR(Chromate) and ECR(primer/$Ca(NO_2)_2$) bars.

PRETEST EVALUATION OF EPOXY-COATED BARS

Prior to corrosion testing, the bars used in this study were evaluated for coating thickness and number of holidays. The bars were also evaluated for coating adhesion using the cathodic disbondment test, performed in accordance with ASTM A 775[(9)] and ASTM G 8.[(10)] The results of these tests are summarized in table 3.

Table 3. Coating thickness.

Type of bar	Number of measurements[a]	Max. μm (mils)	Min. μm (mils)	Average μm (mils)	Coefficient of Variation
ECR	4 bars, 144 locations	307 (12.1)	175 (6.9)	244 (9.6)	0.10
ECR(Chromate)	1 bar, 36 locations	241 (9.5)	175 (6.9)	213 (8.4)	0.07
ECR(DuPont)	1 bar, 36 locations	249 (9.8)	160 (6.3)	213 (8.4)	0.08
ECR(Valspar)	1 bar, 36 locations	262 (10.3)	175 (6.9)	226 (8.9)	0.11
ECR(primer/ $Ca(NO_2)_2$)	4 bars, 126 locations	264 (10.4)	102 (4.0)	188 (7.4)	0.16
MC	1 bar, 36 locations	251 (9.9)	213 (8.4)	236 (9.3)	0.04

[a] Bars are 6.1 meters (20 feet) long; 15 to 18 measurements evenly spaced along each side of the test bar.

Evaluation of Coating Thickness and Holidays

The six types of epoxy-coated reinforcing bars used in this study were evaluated for coating thickness and number of holidays. The results are presented in table 3. All bars met the requirements of ASTM A 775(9) for coating thickness, with the exception of the bars with the calcium nitrite primer coating, which tended to have larger percentages of coating measurements below 175 µm (7 mils) and 125 µm (5 mils) than the maximum allowable values of 10 and 5 percent (ASTM A 775), respectively. Only the bars with the calcium nitrite primer coating exhibited holidays, although the number of holidays was below the maximum allowable of 3 holidays per meter (1 holiday per foot) specified in ASTM A 775. The other five bar types exhibited no measurable holidays on the full-size bars that were tested. Additional tests of small bar samples, however, indicated the presence of a small number of holidays on all bar types.

Cathodic Disbondment Tests

Cathodic disbondment tests involve the penetration of the epoxy coating on a test specimen using a 3-millimeter (mm) (0.12-inch) diameter drill bit. The specimen is then immersed for 168 hours in an electrolyte (3 percent sodium chloride (NaCl) solution) at 24 ± 2 degrees Celsius (°C) (75 ± 3.6 degrees Fahrenheit (°F)) and maintained at a –1.5 volt (V) potential difference with an anode, measured with respect to a saturated calomel electrode (SCE).

An examination is performed immediately upon termination of the test as follows: At the end of the test period, the test area is rinsed with warm tap water. The sample is immediately wiped dry, and the entire area of coating is visually examined at the edge of the intentional defect. A new defect, to serve as a reference, is then drilled in a portion of the coated area that was not immersed. Two radial cuts (at 90 degrees to each other, oriented 45 degrees with respect to the longitudinal axis of the bar) are made through the coating, intersecting the center of both intentional defects, using a sharp, thin-plated knife. An attempt is then made to lift the coating at both the reference defect and the submerged defect with the point of the knife. The bond at the reference defect is then used to judge the quality of the bond at the submerged holiday. Finally, the increase in radial area and total area of the disbonded coating at the submerged defect are measured and recorded.

In this study, three rounds of cathodic disbondment tests were performed, with one specimen per round for each of the six types of epoxy-coated reinforcement. Tests were also performed on conventional epoxy-coated bars that had been used in a previous study. In accordance with ASTM A 775,(9) four radial measurements were taken of the disbonded region, at 0, 90, 180, and 270 degrees with respect to the longitudinal axis of the bar, and the values were averaged. The cathodic disbondment tests were recorded in terms of both the area of the disbonded coating (in accordance with ASTM G 8(10)) and the average coating disbondment radius (four measurements). The results are summarized in table 4. The area of the disbonded coating and the radius do not include the original penetration through the coating. As shown in table 4, the average coating disbondment radius was above 4 mm (the maximum allowed in Annex A1 of ASTM A 775) for the conventional ECR (5.9 mm) and the high adhesion Valspar [ECR(Valspar)] bars (4.9 mm), indicating that these bars failed the coating disbondment requirements. The multiple coated (MC) reinforcement (1.7 mm), high adhesion DuPont

Table 4. Cathodic disbondment results.

Type of Bar	No. of Test	Thickness µm (mils)	Coating Disbondment Radius[a] (mm)					Area of Disbonded Coating[b] (mm^2)
			0°	90°	180°	270°	Average	
ECR	1st		6.5	6.5	6	5.5	6.1	183
	2nd		6.5	5	3.5	4	4.8	133
	3rd	249 (9.8)	6.5	6.5	7.5	6.5	6.8	219
	Average						5.9	178
ECR[c]	1st	300 (11.8)	5.5	6.5	5.5	5	5.6	170
	2nd	274 (10.8)	5.5	4.5	4.5	5.5	5.0	161
	3rd	241 (9.5)	6.5	5.5	5.5	5.5	5.8	174
	Average						5.5	168
ECR(Chromate)	1st		0.5	1	0	0	0.4	6
	2nd		1	0.5	2	2.5	1.5	35
	3rd	279 (11.0)	1.5	0.5	0.5	1.5	1.0	19
	Average						1.0	20
ECR(DuPont)	1st		4	3	3.5	3.5	3.5	93
	2nd		1.5	1	1.5	1	1.3	19
	3rd	224 (8.8)	3.5	4	3.5	4	3.8	83
	Average						2.8	65
ECR(Valspar)	1st		4.5	4	4.5	4	4.3	133
	2nd		6	4.5	5.5	4.5	5.1	167
	3rd	269 (10.6)	6.5	4.5	5.5	4.5	5.3	154
	Average						4.9	151
ECR (primer/$Ca(NO_2)_2$)	1st		1.5	2	2	2	1.9	58
	2nd		3.5	2.5	4.5	2.5	3.3	77
	3rd	203 (8.0)	3	2.5	2.5	2.5	2.6	67
	Average						2.6	67
MC	1st		2.5	1.5	1	1	1.5	22
	2nd		2	1.5	1.5	3	2.0	35
	3rd	284 (11.2)	0.5	2.5	1.5	1.5	1.5	25
	Average						1.7	27

[a] Coating disbondment radius is measured from the edge of a 3-mm (0.12-inch) diameter hole.

[b] Area of disbonded coating is the total area after disbondment minus the original area of a 3-mm (0.12-inch) diameter hole.

[c] Conventional epoxy-coated reinforcement from previous study.

[ECR(DuPont)] bars (2.8 mm), ECR with chromate pre-treatment [ECR(Chromate)] (1.0 mm), and ECR with the calcium nitrite primer [ECR(primer/$Na(NO_2)_2$)] (2.6 mm) met the coating disbondment requirements. Table 4 shows that the conventional epoxy-coated reinforcement exhibited the highest area of disbonded coating, with an average value of 178 mm^2. The high adhesion Valspar bars had an area of disbonded coating of 151 mm^2, followed by ECR with the calcium nitrite primer at 67 mm^2 and the high adhesion DuPont bars at 65 mm^2. The MC bars and ECR(Chromate) had the lowest areas of disbonded coating, with average values of 27 and 20 mm^2, respectively. Like the conventional ECR used in this study, the conventional ECR from the previous study also exhibited an average disbondment radius, 5.5 mm, that exceeded the 4 mm allowed by ASTM A 775; the disbonded area equaled 168 mm^2.

The criteria in Annex A1 of A 775 are qualification requirements for the epoxy coating itself and are not meant to be applied to production bars, such as those used in this study. Thus, although all bars did not all meet the qualification criteria, they are all considered to be representative of bars that are used in practice. Further, as has been observed in earlier tests by McDonald et al.,(11) the performance of the bars in the cathodic disbondment tests has not proven to be a predictor of their performance in the corrosion tests in this study.

CORROSION TEST PROCEDURES

The multiple corrosion protection systems are being evaluated using a combination of laboratory and field tests. The results of the laboratory tests, most of which are still ongoing, are presented in this report. The performance of each system is compared to that of conventional epoxy-coated reinforcement and uncoated mild steel reinforcement. The tests include rapid macrocell tests, bench-scale tests, and linear polarization resistance. Each of these techniques is discussed briefly.

Rapid Macrocell Tests

Summary of Method

The response of the multiple corrosion protection systems was first evaluated using the rapid macrocell test, originally developed at the University of Kansas under the SHRP program(12,13) and since updated. (See references 14 through 21). The goal of the test is to obtain a realistic measure of the performance of corrosion protection systems in a short time period. The basic test specimen consists of either a bare reinforcing bar or a bar clad in mortar (mortar-wrapped), as illustrated in figures 1, 2, and 3. The contact surface between the mortar and the bar simulates the contact obtained between concrete and reinforcing bars in structures through the use of realistic water-cement and sand-cement ratios.

The macrocell tests (figures 1 and 2) require two containers. The test specimen, either a bare or mortar-wrapped No. 16 (No. 5) bar, is placed in a 1.5-L (1.6-quart) container, along with simulated pore solution containing a preselected concentration [1.6 or 6.04 moles per kilogram of solvent (molal)-ion (4.68 or 15 percent) concentration] of sodium chloride. Two specimens

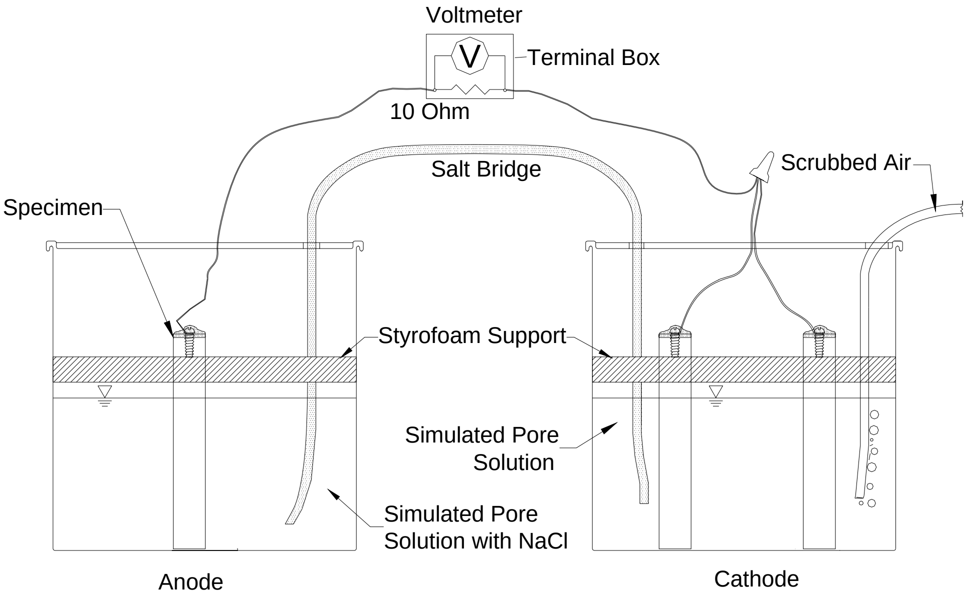

Figure 1. Diagram. Schematic of macrocell test with bare bar specimens.

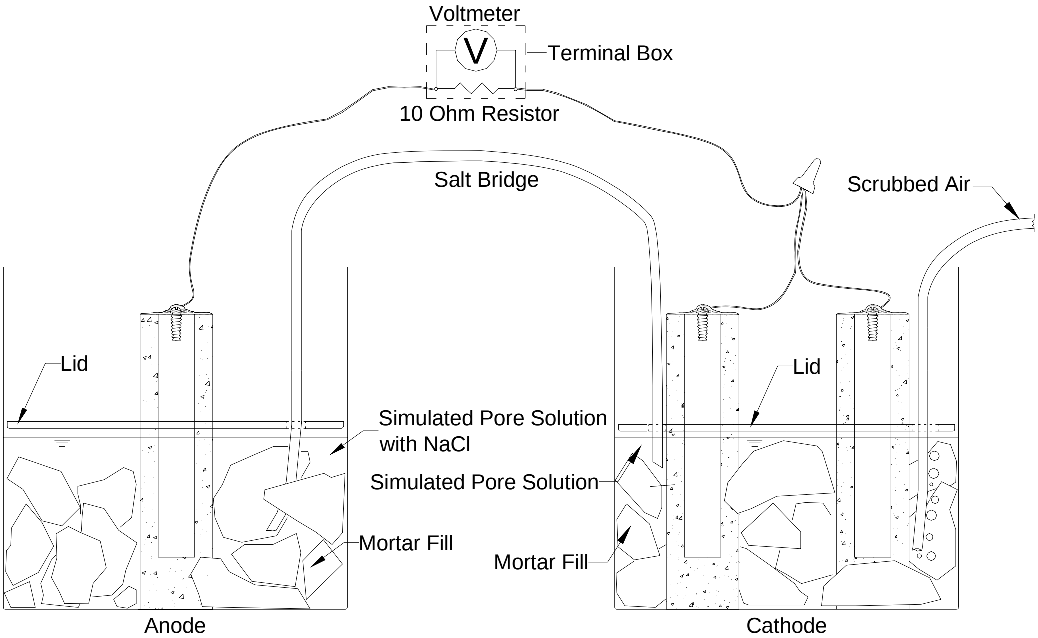

Figure 2. Diagram. Schematic of macrocell test with mortar-clad specimens.

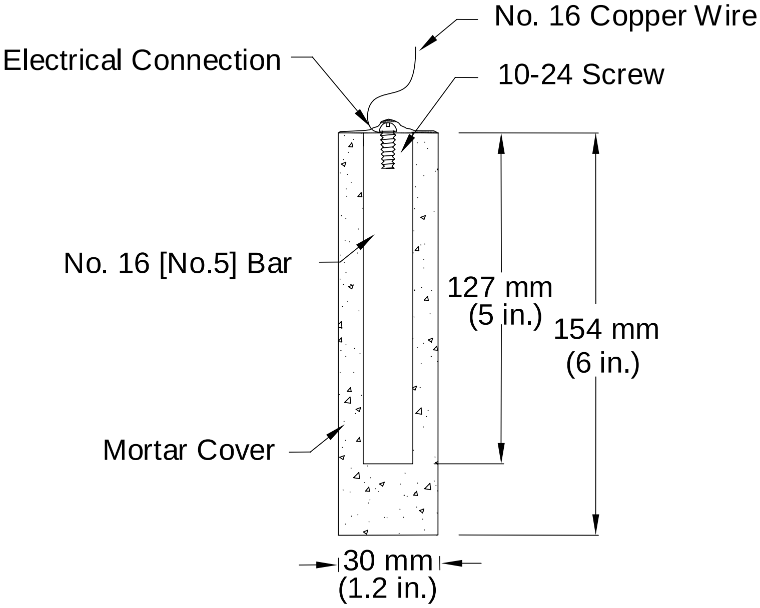

Figure 3. Diagram. Schematic of mortar-wrapped specimen containing a conventional reinforcing bar.

are placed in a second container and immersed in simulated pore solution (with no chlorides added). For mortar-wrapped specimens, crushed mortar fill is added to the containers to more closely simulate the concrete environment. The solution depth exposes 76 mm (3 inches) of a bar [including the 12.7 mm (0.5 inch) plastic cap used to protect the end of epoxy-coated bars] below the level of the solution. The two containers are connected by a salt bridge, and the test specimen in the pore solution containing sodium chloride (anode) is electrically connected across a single 10-ohm resistor to the two specimens in the simulated pore solution (cathode). The resistors are mounted between binding posts in a terminal box to consolidate the specimen wires. Air (scrubbed to remove CO_2) is bubbled into the liquid surrounding the cathode to ensure an adequate supply of oxygen. Plastic lids are placed just above the surface of the solution to hold the specimens in place and reduce the evaporation of the solution. Holes are cut in the lids to introduce the specimens, a salt bridge, and the air supply. The air causes some evaporation, which is countered by adding deionized water to the container to maintain a constant volume of solution. The solutions in both containers are changed once every five weeks to further protect against carbonation.[*] The corrosion current and the rate of corrosion can be determined by measuring the voltage drop across the resistor. The open circuit corrosion potential of the cathode and anode are also measured with respect to a saturated calomel electrode (SCE) after the circuit has been open for two hours to allow the potentials to stabilize. The simulated pore solution, consisting of sodium hydroxide and potassium hydroxide, matches that obtained in a pore solution analysis.(22,23) Epoxy-coated steel is evaluated using specimens in which the coating is breeched by four 3-mm (1/8-inch) diameter holes to simulate defects in the epoxy coating (damaged area = 1.0 percent of total exposed area in the solution). In the rapid macrocell test, bare conventional bars exhibit corrosion initiation within the first 24 hours and conventional bars cast in mortar exhibit corrosion within the first week. The tests last 15 weeks.

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[*] The five-week interval is satisfactory to maintain the pH of the solutions above 13.3.

Corrosion Rate and Corrosion Loss

The *corrosion rate* of reinforcing steel (measured in the bench-scale tests as well as the rapid microcell tests) indicates how fast reinforcing steel is being oxidized. It may be expressed as a current density, microamps per square centimeter ($\mu A/cm^2$), which is obtained by measuring the rate of electron flow from anodes to cathodes. Based on Faraday's law, current density can be converted to another expression for corrosion rate, a rate of loss of metal from the surface of the steel in μm/year.(24) For iron,

$$R = k\frac{ia}{nF\rho} = 11.6i \qquad \text{(Eq. 1)}$$

where

R = corrosion rate, given as rate of metal loss, μm/year;

i = corrosion rate, given as current density, $\mu A/cm^2$;

k = conversion factor = 31.5×10^4 amp·μm ·sec/μA·cm·year;(24)

a = atomic weight of the metal = 55.8 g/mol for iron;

n = number of electrons transferred = 2 for iron;

F = Faraday's constant = 96500 Coulombs/equivalent;

ρ = density of the metal, g/cm^3 = 7.87 g/cm^3 for iron.

As an example of how equation (1) is used to calculate corrosion loss for a bare conventional bar, a voltage drop across the 10-ohm resistor of 0.70 millivolts (mV) = 700 microvolts (μV) represents a total current of 70.0 μA. For a No. 16 (No. 5) bar and a solution depth of 76 mm (the values used in the test), the total surface area in contact with the solution (including the end of the bar) is 4021 mm^2 = 40.21 cm^2, giving a current density i of 1.74 $\mu A/cm^2$. Applying equation (1) gives

$$R = 11.6i = 11.6 \times 1.74 = 20.2 \text{ μm/year} \qquad \text{(Eq. 1a)}$$

For zinc, the first coating layer on the MC bars, equation (1) becomes

$$R = k\frac{ia}{nF\rho} = 15.0i \qquad \text{(Eq. 2)}$$

where

a = atomic weight of the metal = 65.38 g/mol for zinc;

n = number of electrons transferred = 2 for zinc;

ρ = density of the metal, g/cm^3 = 7.14 g/cm^3 for zinc.

For reinforced concrete bridge decks, the measurement of the macrocell current is generally not possible because the top and bottom mats of reinforcing steel are usually connected by steel wire ties and bar supports in the concrete slab. In laboratory tests that simulate the corrosion of steel in bridge decks, however, ties and bar supports are not used and the macrocell current can be determined by measuring the voltage drop across a resistor that electrically connects the anode and the cathode through an external circuit.

$$i = \frac{V}{RA} \qquad \text{(Eq. 3)}$$

where

i = corrosion current density, $\mu A/cm^2$;
V = voltage drop across the resistor, mV;
R = resistance of the resistor, kilo-ohms ($k\Omega$);
A = area of exposed metal on the anode bar, cm^2.

The measured macrocell current density, and hence the calculated corrosion rate, can be affected significantly by the test methods(25) and the details of the test configuration, such as the anode to cathode area ratio and the size of the resistor connecting the anode and the cathode.(11) Thus, the corrosion rate calculated from the measured macrocell current should be used only to compare the relative performance of corrosion protection systems under same test conditions.

Corrosion loss represents cumulative metal loss, expressed in micrometers, and is calculated by numerically integrating the corrosion rate.

Test Specimens

The specimens in the rapid macrocell test consist of 127 mm (5 inches) long, No. 16 (No. 5) reinforcing bars, either bare or embedded in mortar, as illustrated in figure 4 for epoxy-coated bars. Fabrication of the specimens is described next:

(1) Preparation of reinforcing bars: One end of the bar is drilled and tapped 13 mm (0.5 inch) to accommodate a No. 10-24 machine screw. The sharp edges on the bar ends are removed by grinding. Uncoated bars are cleaned with acetone to remove grease and dirt from the surface. For epoxy-coated reinforcing steel, the bars are cleaned with soap and water. The epoxy coating is penetrated by four 3.2 mm (0.125 inch) diameter holes to simulate defects in the coating. The holes are made to a depth of 0.5 mm (0.020 inch) using a 3.2-mm (0.125-inch) diameter four-flute end mill. Two of the holes are placed at the midlength of the bars and the other two are placed about 32 mm (1.25 inch) from the untapped end, which will be submerged in the solution. This submerged end is protected using a plastic cap filled with a repair epoxy. The four holes represent 1 percent damage to the evaluated area of the epoxy-coated bars.

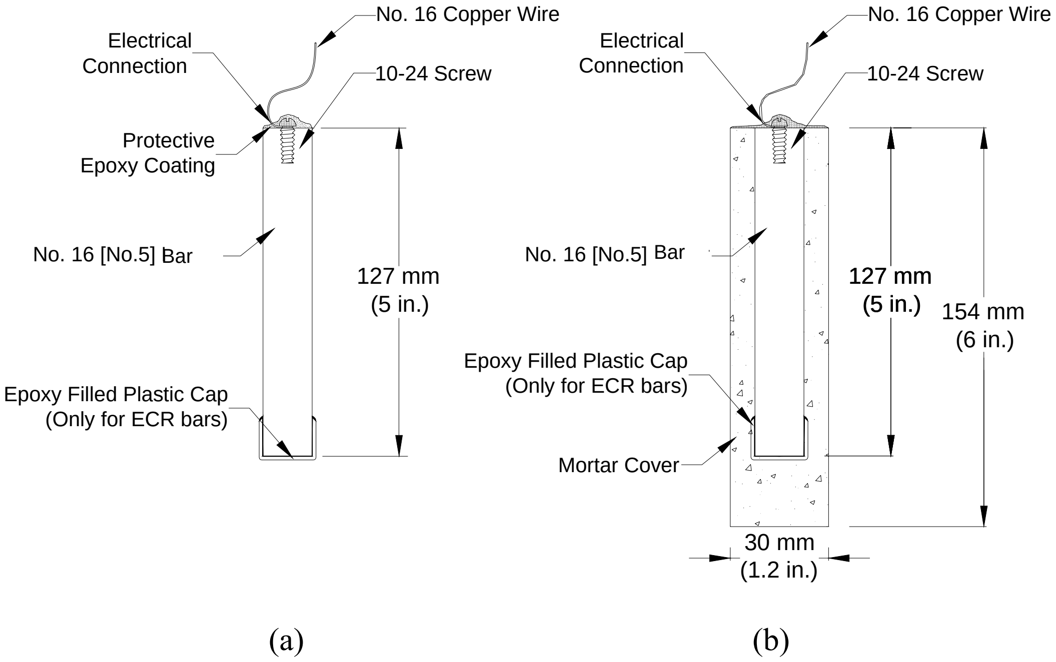

Figure 4. Diagram. Rapid macrocell specimens: (a) bare bar and (b) mortar-wrapped specimens with cap to protect the exposed end of epoxy-coated bars.

When a mortar-wrapped specimen is used, a prepared bare bar is symmetrically embedded in a 154 mm (6 inch) long mortar cylinder (figure 4b). The cylinder has a 30 mm (1.2 inch) diameter and provides a 7 mm (0.28 inch) mortar cover over the reinforcing bar. Mortar-wrapped bars are cast in a mold consisting of polyvinyl chloride (PVC) pipes and fittings.(19-21)

(2) Casting: Mortar is placed in a cylindrical PVC mold in four layers. Each layer is rodded 25 times using a 2-mm (0.08-inch) diameter rod, followed by vibration for 30 seconds on a vibration table with an amplitude of 0.15 mm (0.006 inch) and a frequency of 60 Hz.

(3) Curing: Specimens are cured in the molds for one day at room temperature and then removed from the molds and cured in saturated lime water (pH ≈ 12.4) for 13 days to reach a passive condition. After this period, the specimens are surface-dried with compressed air and then vacuum dried for one day.

(4) Wiring and coating: For both bare and mortar-wrapped bars, a 16-gage copper electrical wire is attached to the tapped end of each specimen with a 10-24×1/2 (13 mm [0.5 in] long) screw. The electrical connection is then coated with two layers of Herberts O'Brien epoxy for bare bars and two layers of Ceilgard 615™ epoxy by Ceilcote, Inc. for mortar-wrapped specimens.

Test Materials

(1) Simulated Concrete Pore Solution: Simulated concrete pore solution is used at the cathode. One liter of the solution contains 974.8 grams (g) of distilled water, 18.81 g of potassium hydroxide (KOH), and 17.87 g of sodium hydroxide (NaOH), based on pore solution analysis by Farzammehr et al.(22,23)

(2) Simulated Concrete Pore Solution with Sodium Chloride: The solution is used at the anode and is prepared by adding 45.6 or 172.1 g of NaCl to one liter of the simulated concrete pore solution to obtain a 1.6 or 6.04 molal ion concentration solution, equal to a 0.8 or 3.02 molal NaCl solution, respectively.

(3) Salt Bridges: A salt bridge provides an ionic path between the cathode and the anode. It consists of a 0.45 m (1.5 ft) long plastic tube filled with a conductive gel. To prepare a salt bridge, 4.5 g of agar, 30 g of potassium chloride (KCl), and 100 g of distilled water are mixed and then heated over a hot plate until the solution starts to thicken. The heated mixture, enough to produce four salt bridges, is poured into plastic tubes using a funnel. The tubes are then placed in boiling water for one hour to firm the gel, keeping the ends of the tubes above the surface of the water. The gel in the salt bridges must be continuous, without interruption by air bubbles.

(4) Mortar: The mortar has a water-cement (*w*/*c*) ratio of 0.5 and sand-cement ratio of 2.0 by weight, and is made with Type I/II portland cement (ASTM C 150(26)), distilled water, and ASTM C 778(27) graded Ottawa sand. The mix proportions represent the mortar constituent of concrete. The mortar is mixed in accordance with the procedures outlined in ASTM C 305.(28)

(5) Mortar Fill: Mortar fill is placed in containers with mortar-wrapped specimens. It consists of the same mixture as used in the test specimens. The fill is cast in a metal baking sheet to a depth of about 25 mm (1 inch). The mortar in the sheet is air-cured at room temperature for 15 days and is broken into 25 to 50 mm (1 to 2 inch) pieces prior to use.

Data acquisition

A voltmeter with a resolution of 0.001 mV resolution is used to measure corrosion potential of the anode and cathode and the voltage drop across the 10-ohm resistor. The voltage drop tends to fluctuate between –0.003 and 0.003 mV when the corrosion current is close to zero. Only voltage drop readings outside of this region are used to evaluate the corrosion performance of different corrosion protection systems. Values between –0.003 and 0.003 mV are treated as zero.

Bench-Scale Tests

During the past two decades, bench-scale tests, such as the Southern Exposure, ASTM G 109,(29) and cracked beam tests, have been used most often to evaluate the corrosion performance of reinforcing steel.(25,30) Of these tests, the Southern Exposure and cracked beam tests have proven to give useful data in a relatively short period. The ASTM G 109 test gives similar results over a longer period of time, but is perhaps the best choice for corrosion protection systems that contain zinc because of the poor performance of zinc in saturated concrete. All three test methods are used in this study; the results for the first two are reported here.

Southern Exposure Test

The specimen used in the Southern Exposure, or SE, test(31) consists of a small slab containing two mats of reinforcing steel (figure 5). The concrete is wet cured for three days and then air cured until the test begins at 28 days. The top mat consists of two No. 16 (No. 5) bars; the bottom mat consists of four No. 16 (No. 5) bars. The mats are connected electrically across a 10-ohm resistor, a dam is placed around the edge of the top surface (cast integrally with the specimen in this study), and the sides of the concrete are sealed with epoxy. A 15 percent (6.04 molal ion) sodium chloride solution is placed inside the dam, allowing the chlorides to penetrate into the concrete. The slabs are subjected to a seven day alternate ponding and drying regime, with ponding at 23 ± 2°C (73 ± 3°F) for four days and drying at 100 °F (38 °C) (thus the name Southern Exposure) for three days. Prior to drying, the solution is removed from the upper surface using an industrial vacuum cleaner. The ponding and drying regime is continued for 12 weeks. The specimens are then subjected to continuous ponding for 12 weeks at 23 ± 2 °C (73 ± 3 °F), after which the alternate ponding and drying regime begins again. The two regimes are continued for 96 weeks. Corrosion current and the corresponding corrosion rate are determined by measuring the voltage drop across the resistor. The corrosion potentials of the top and bottom bars are measured.* Corrosion performance is also evaluated using monthly linear polarization resistance readings on selected specimens. The test provides a severe corrosion environment that is generally believed to simulate 15 to 20 years of exposure for marine structures under tropical conditions and 30 to 40 years of exposure for bridges within a 48-week period.(32)

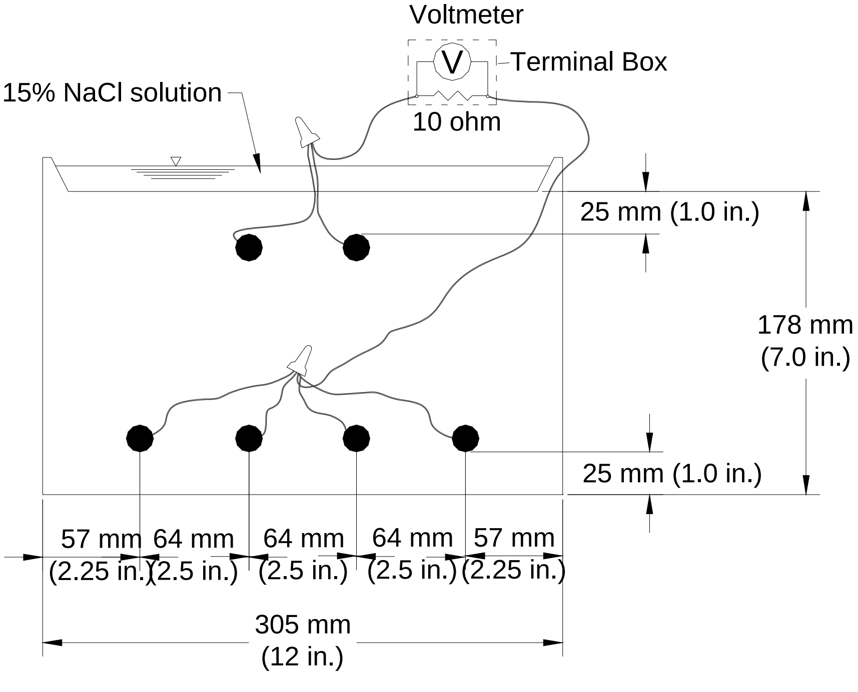

Figure 5. Diagram. Southern Exposure test specimen.

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* Corrosion potentials are measured with respect to a saturated calomel electrode (SCE) on ponded specimens and a copper-copper sulfate (CSE) electrode for dry specimens. Potentials with respect to CSE are approximately 0.075 V more negative than those with respect to SCE.

Cracked Beam Test

The cracked beam specimen (figure 6) is used to model the corrosion of reinforcing steel in which cracks directly expose the steel to deicing chemicals. The specimen is half the width of the SE specimen, with one bar on top and two bars on the bottom. A crack is simulated parallel to and above the top reinforcing bar through the insertion of a 0.3 mm (12 mil) stainless steel shim when the specimen is fabricated. The shim is removed within 12 hours of casting, leaving a direct path for chlorides to the reinforcing steel and simulating the effects of a settlement crack over the bar. An integral dam is used in manner similar to that used for the SE specimen around the upper surface of the specimen. Like the SE specimen, the cracked beam specimen is subjected to cycles of wetting and drying with a 15 percent sodium chloride solution, continuing up to 96 weeks.

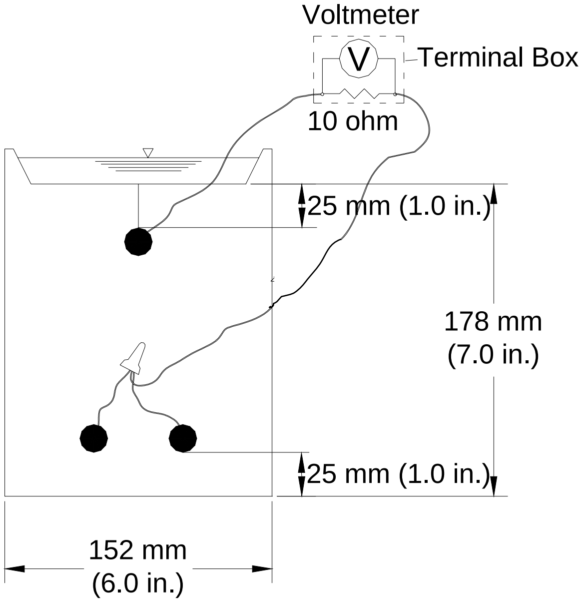

Figure 6. Diagram. Cracked beam test specimen.

Specimen Fabrication

Fabrication of the SE and CB specimens is described next.

(1) Preparation of reinforcing bar: Each reinforcing bar is cut to a length of 305 mm (12 inches). Both ends of the bar are drilled and tapped 13 mm (0.5 inch) to accommodate a No. 10-24 machine screw. The sharp edges on the bar ends are removed with a grinder. Uncoated bars are cleaned with acetone to remove grease and dirt from the surface. Epoxy-coated reinforcing bars are cleaned with soap and water. The epoxy coating is then penetrated by four or ten 3.2 mm (0.125 inch) diameter holes to simulate defects in the coating. The holes are made to a depth of 0.4 mm (16 mils) using a 3.2-mm (0.125-inch) diameter four-flute end mill. Two or five holes are placed evenly along the length on each side of the bars. On the multiple coated (MC) bars, specimens are evaluated with both layers penetrated and with only the epoxy penetrated. The epoxy is penetrated without damaging the zinc using a soldering gun set to a temperature of 205 °C (400 °F), which is above the melting temperature of epoxy but below the melting

temperature of zinc. The burned epoxy regions are cleaned with acetone. Four holes represent 0.2 percent damage and 10 holes represent 0.52 percent damage to the exposed surface of the epoxy-coated bar.

(2) Mold Assembly: The mold is made to cast the specimen in an inverted position. It consists of several pieces of 19 mm (0.75 inch) thick plywood, including 4 sides and a bottom. Inside the mold, a smaller beveled wooden piece is bolted to the bottom to create the integral concrete dam after casting. For the cracked beam molds, a 152 mm (6 inches) long, 0.3 mm (0.012 inch) wide longitudinal slot is made in the center of the beveled wood to accommodate a 0.3 mm (0.012 inch) thick stainless steel shim. The shim projects 25 mm (1 inch) from the slot and just touches the test bar. After demolding, the shim is removed from the concrete to form the crack. All parts of the mold are fastened with angles and clamps. The inside corners are sealed with clay. The bars are supported by 10-24×1 (25 mm [1.0 in] long) screws through 4.8 mm (0.19 inch) diameter holes in two side molds. When epoxy-coated bars are tested, two of the holes in the coating face up and the other two face down.

(3) Casting: Concrete is mixed in accordance with the requirements of ASTM C 192(33) for mechanical mixing. The concrete mixture proportions are given in table 5. The concretes have a *w/c* ratio of 0.45 or 0.35 and a nominal air content of 6 percent. The specimens are cast in two layers. Each layer is vibrated for 30 seconds on a vibrating table with amplitude of 0.15 mm (0.006 inch) and a frequency of 60 Hz. The concrete surface is finished with a wooden float.

Table 5. Concrete mixtures.

w/c	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate**	**Air-Entraining Agent**	**DCI**	**Hycrete**	**Rheocrete**	**S.P.[a]**
	kg/m^3 (lb/yd^3)	**kg/m^3 (lb/yd^3)**	**kg/m^3 (lb/yd^3)**	**kg/m^3 (lb/yd^3)**	**mL/m^3 (oz/yd^3)**	**L/m^3 (gal/yd^3)**	**kg/m^3 (lb/yd^3)**	**L/m^3 (gal/yd^3)**	**L/m^3 (gal/yd^3)**
0.45	355 (598)	160 (269)	852 (1435)	881 (1484)	90 (2.33)	-	-	-	-
	355 (598)	147.4 (248.2)	852 (1435)	881 (1484)	140 (3.62)	15 (3.03)	-	-	-
	355 (598)	154.0 (259.4)	852 (1435)	881 (1484)	35 (1.18)	-	8.0 (13.5)	-	-
	355 (598)	155.7 (262.2)	852 (1435)	881 (1484)	300 (7.74)	-	-	5 (1.01)	-
0.35	438 (738)	153 (258)	764 (1287)	862 (1452)	355 (9.16)	-	-	-	2.12 (0.43)
	438 (738)	140.4 (236.4)	764 (1287)	862 (1452)	740 (19.1)	15 (3.03)	-	-	2.12 (0.43)
	438 (738)	145.6 (245.2)	764 (1287)	862 (1452)	330 (8.52)	-	9.9 (16.7)	-	2.25 (0.45)
	438 (738)	148.7 (250.4)	764 (1287)	862 (1452)	1480 (38.2)	-	-	5 (1.01)	2.25 (0.45)

[a] S.P. = superplasticizer, Rheobuild 1000 by BASF Admixtures, Inc.

(4) Curing: The specimens are cured in the mold for 24 hours at room temperature, except the CB specimens, which usually require earlier demolding (8 to 12 hours) to facilitate the removal of the shim. After being removed from the mold, specimens are cured at room temperature in a plastic bag with water until 72 hours after casting. The specimens are then removed from the bag and air-cured for 25 days. Testing starts 28 days after casting.

(5) Wiring and coating: Two days before testing begins, 16-gage copper electrical wire is attached to one end of each bar embedded in the specimens with 10-24×1/2 (13 mm [0.5 inch] long) screw. The other end of the bars is sealed with the same kind of screw. All four sides of the specimens, including the electrical connections, are then coated with two layers of epoxy such as Ceilgard 615™ by Ceilcote, Inc. or ThoRoc SewerGuard HBS™ by ChemRex, Inc. The epoxy is mixed and applied according to manufacturer's recommendations.

Test Materials

The properties of the materials are as follows: Type I/II portland cement; coarse aggregate: crushed limestone with maximum size = 19 mm (0.75 inch), bulk specific gravity (SSD) = 2.58, absorption (dry) = 2.27 percent, unit weight = 1536 kg/m^3 (95.9 pounds per cubic foot (lb/ft^3)); fine aggregate: Kansas River sand with bulk specific gravity (SSD) = 2.62, absorption (dry) = 0.78 percent, fineness modulus = 3.18; air-entraining agent: Daravair 1400 by W.R. Grace.

A 15 percent NaCl solution (6.04 molal ion concentration) is used to pond the test specimens; 600 ml of the solution is used to pond one SE specimen and 300 ml is used to pond one CB specimen.

Data Acquisition

The same voltmeter and rules for data conversion described for the rapid macrocell tests are used for the bench-scale tests.

Linear Polarization Resistance Test

A measure of both microcell and macrocell corrosion can be obtained with the polarization resistance test, which uses a noncorroding counter electrode and a reference electrode to establish a polarization curve by imposing a range of potentials on the metal and measuring the corresponding corrosion currents using a potentiostat. Polarization resistance measurements have been obtained from selected bench-scale specimens throughout the test period.

Polarization resistance tests are used in this study to obtain the microcell corrosion rates for bench-scale specimens. In the tests, microcell current readings are taken during a short, slow sweep of bar potential. The sweep typically is from –20 to +20 mV relative to the open circuit potential E_{oc}. In this range, the current versus voltage curve is roughly linear. The slope of the linear region is proportional to the resistance of the metal. The total corrosion current density then is obtained using the relationship

$$i = \frac{B}{R_p} \qquad \text{(Eq. 4)}$$

in which i is the corrosion current density (A/cm^2), B is the Stern-Geary constant (typically taken as 26 mV for both reinforcing steel and zinc in concrete), R_p is the slope determined from the polarization curve (k$\Omega\cdot$cm^2). The microcell corrosion rate in µm/year (µm/yr) is calculated using Eq. (1) and (2) for iron and zinc, respectively. In this study, the tests are performed using a PC4/750 Potentiostat and DC105 corrosion measurement system from Gamry Instruments.

The tests are performed every 4 weeks for bench-scale specimens to obtain the microcell corrosion rates for the top mats with the bottom mats disconnected. In the tests, the top mat of reinforcing steel is used as the working electrode, a saturated calomel electrode immersed in salt solution on the top of the specimen is used as the reference electrode, and a platinum strip immersed in salt solution on the top of the specimen is used as the counter electrode.

The data file from a polarization resistance test is analyzed using the data analysis package provided with the DCI 105. This analysis software can read the data file and plot a graph based on the data in the file. When a new graph is created in this package, the user picks a range of voltage in the graph and the software automatically uses a linear fit of the data in the selected range to calculate the polarization resistance. The corrosion current density and corrosion rate can then be determined using the polarization resistance.

TEST PROGRAM

The test program, summarized in table 6, compares the corrosion performance of the 11 multiple corrosion protection systems with that of conventional reinforcing steel and conventional epoxy coated reinforcement. As shown in table 6, rapid macrocell and bench-scale tests are used for all systems, but all versions of the tests are not used for every system. In all, the work reported here includes 126 macrocell tests, 93 Southern Exposure tests, and 84 cracked beam tests.

Rapid Macrocell Test Program

As shown in table 6, the rapid macrocell test with mortar-wrapped specimens is used for all systems, while the macrocell test with bare bars is not used to evaluate the effects of corrosion inhibitors. The macrocell tests for the bare and mortar-wrapped specimens for the multiple coating system include bars with penetrations through both layers, as well as bars in which only the outer layer of epoxy has been penetrated. The coating on each bar in the rapid macrocell tests is penetrated by four 3.2-mm (1/8-inch) diameter holes, representing damage to 1.0 percent the bar area that is exposed to solutions in these tests. Six specimens are used for each system.

Bench-Scale Test Program

Southern Exposure and cracked beam tests are used to compare the performance of corrosion protection systems cast in concrete. A *w/c* ratio of 0.45 is used in all cases. In addition, concrete with a *w/c* ratio of 0.35 is used to evaluate the performance of the corrosion inhibitors (as well as the control specimens) because the performance of concrete containing calcium nitrite has been observed to improve as the *w/c* ratio decreases.(34) The coatings on bars in the bench-scale tests are penetrated with four or ten 3.2 mm (1/8-inch) holes, representing damage to 0.21 and 0.52 percent of the bar surface, respectively.

Table 6. Test program—number of specimens.

	Test			
	Macrocell[a]		SE[b]	CB[b]
System	**Bare**	**Mortar-wrapped**		
Control				
Uncoated bars	6	6	9	9
ECR	6	6	9	9
Epoxies with increased adhesion				
Chromate pretreatment	6	6	6	6
DuPont coating	6	6	6	6
Valspar coating	6	6	6	6
Corrosion inhibitors in mortar or concrete				
ECR w/$Ca(NO_2)_2$	--	6	9[c]	9[c]
ECR w/Hycrete	--	6	9[c]	9[c]
ECR w/Rheocrete 222 $^+$	--	6	9[c]	9[c]
3M – primer containing $Ca(NO_2)_2$	--	6	9[c]	9[c]
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete				
Chromate pretreatment	--	6	3[d]	--
DuPont coating	--	6	3[d]	--
Valspar coating	--	6	3[d]	--
Bars with multiple coatings				
Both layers penetrated	6	6	6	6
Epoxy only penetrated	6	6	6	6

[a] *w/c* = 0.5. six specimens with four 3.2-mm ($^1/_8$-inch) diameter holes in coating.

[b] *w/c* = 0.45. All systems tested using three specimens with four 3.2-mm ($^1/_8$-inch) diameter holes in coating and three specimens with ten 3.2-mm ($^1/_8$-inch) diameter holes in coating.

[c] Includes three additional specimens with *w/c* = 0.35 and ten 3.2-mm ($^1/_8$-inch) diameter holes in coating.

[d] three specimens with four 3.2-mm ($^1/_8$-inch) diameter holes in coating.

Bench-Scale Test Program

Southern Exposure and cracked beam tests are used to compare the performance of corrosion protection systems cast in concrete. A *w/c* ratio of 0.45 is used in all cases. In addition, concrete with a *w/c* ratio of 0.35 is used to evaluate the performance of the corrosion inhibitors (as well as the control specimens) because the performance of concrete containing calcium nitrite has been observed to improve as the *w/c* ratio decreases.(34) The coatings on bars in the bench-scale tests are penetrated with four or ten 3.2 mm (1/8-inch) holes, representing damage to 0.21 and 0.52 percent of the bar surface, respectively.

Following the tests, specimens are photographed to record cracking and corrosion products visible on the exterior of concrete or mortar and corrosion products on reinforcing steel and surrounding cementitious materials following the removal of concrete or mortar.

Linear Polarization Resistance Test Program

Linear polarization resistance measurements are performed on a single Southern Exposure and cracked beam specimen for each configuration and corrosion protection system in the study (table 6). The results are used in conjunction with the readings obtain from the macrocell and bench-scale tests to evaluate the performance of the corrosion protection systems.

CHAPTER 3. TEST RESULTS

The test results presented in this chapter demonstrate that conventional fusion-bonded epoxy coating significantly reduces the corrosion of reinforcing steel. Using concrete with a reduced *w/c* ratio lowers the corrosion rate for both conventional and epoxy-coated reinforcement under all conditions in intact concrete, but provides limited corrosion protection, at best, when cracks allow direct access of chlorides to reinforcing bars. Corrosion inhibitors consistently provide improved corrosion protection when used in conjunction with epoxy-coated reinforcement in intact concrete, but not in cracked concrete. Finally, the results demonstrate that a multiple coating, consisting of 98 percent zinc–2 percent aluminum and conventional epoxy appears to provide some additional protection; the results in this case, however, are not conclusive. Specific findings, discussed next, are presented in terms of average values at 15 weeks for the rapid macrocell tests and at a minimum of 56 weeks for the bench-scale tests.

RAPID MACROCELL TESTS

All systems were evaluated using rapid macrocell tests. The bare bar test, however, was not used to evaluate corrosion inhibitors. The results presented in this section represent the average of six specimens. The epoxy on all bars was penetrated with four 3.2 mm (1/8-inch) diameter holes, as described earlier.

Corrosion losses (total thickness of metal lost due to corrosion – calculated by integrating the corrosion rate) for the individual specimens in the rapid macrocell test are summarized in tables 7a and b, which, respectively, express the results based on the total area of the bars in contact with the test solutions and the area of steel exposed by the four holes through the coating on each epoxy-coated bar.

Bare Bar Tests

The average corrosion rates for the systems evaluated using bare bars are shown in figures 7a and b. The two figures differ in the scale of the vertical axis. The corrosion rate represents the average based on the total area exposed to the test solution.

The results indicate that conventional steel corrodes at a much higher rate then any of the epoxy-coated bars in the test, with a rate that ranges between 7 and 40 μm/yr during the 15-week test. Based on corrosion rate, the epoxy-coated bars fall into two groups (figure 7b), with conventional ECR, ECR(DuPont) and ECR(Valspar) corroding at an average rate between 0.5 and 1.7 μm/yr and ECR(Chromate) and the multiple coated bars [MC(both layers penetrated) and MC(only epoxy penetrated) corroding at an average rate between −0.1 and 0.6 μm/yr. The negative corrosion rate, which indicates more corrosion at the cathode than at the anode, can be explained by the amphoteric nature of zinc, as describe in the next paragraph. As demonstrated in the figures, corrosion rates vary significantly from week to week. Conventional reinforcement (Conv.) exhibits significant increases in corrosion between weeks 5 and 6 and between weeks 10 and 11 when the solutions are changed, as described in chapter 2.

Table 7a. Corrosion loss at 15 weeks (in µm) for rapid macrocell specimens based on total area.

Steel Designation[a]	**Specimen**						**Average**	**Standard Deviation**
	1	**2**	**3**	**4**	**5**	**6**		
Control								
Conv.	7.1	5.3	4.7	7.4	6.5	5.2	6.0	1.12
M[b]-Conv.	5.8	6.7	3.5	3.8	3.8	5.4	4.8	1.33
ECR	0.256	0.649	0.215	0.381	0.494	0.018	0.336	0.222
M-ECR	0.000	0.000	0.000	0.000	-0.004	0.000	-0.001	0.001
Epoxies with increased adhesion								
ECR(Chromate)	0.101	0.000	0.000	0.000	0.000	0.055	0.026	0.043
M-ECR(Chromate)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ECR(DuPont)	0.000	0.438	0.336	0.361	0.425	0.418	0.330	0.166
M-ECR(DuPont)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ECR(Valspar)	0.266	0.389	0.599	0.083	0.056	0.499	0.315	0.221
M-ECR(Valspar)	0.000	-0.003	0.000	0.000	0.000	0.000	0.000	0.001
Corrosion inhibitors in mortar								
M-ECR(DCI)	0.000	-0.003	0.000	0.000	0.000	0.000	0.000	0.001
M-ECR(RH)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(HY)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(primer/Ca(NO2)2)	0.000	0.000	0.000	0.000	0.008	0.009	0.003	0.004
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete								
M-ECR(Chromate)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(DuPont)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(Valspar)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bars with multiple coatings								
MC(both layers penetrated)	0.043	0.041	0.007	0.007	-0.038	0.023	0.014	0.030
M-MC(both layers penetrated)	-0.004	0.001	0.001	0.000	-0.011	0.000	-0.002	0.005
MC(only epoxy penetrated)	0.064	0.022	0.108	0.050	0.039	0.060	0.057	0.029
M-MC(only epoxy penetrated)	0.020	0.030	0.017	0.024	0.006	0.022	0.020	0.008

[a] Conv. = conventional steel. ECR = conventional epoxy-coated reinforcing bars . ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(RH) = conventional ECR with Rheocrete inhibitor. ECR(HY) = conventional ECR with Hycrete inhibitor.

MC(both layers penetrated) = multiple coating bars with both layers penetrated.

MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.

[b] M- prefix indicates mortar wrapped specimen, otherwise bare bar specimen.

Table 7b. Corrosion loss at 15 weeks (in µm) for rapid macrocell specimens based on area exposed at holes through coating.

Steel Designation[a]	Specimen						Average	Standard Deviation
	1	2	3	4	5	6		
Control								
Conv.	-	-	-	-	-	-	-	-
M[b]-Conv.	-	-	-	-	-	-	-	-
ECR	25.6	64.9	21.5	38.1	49.4	1.8	33.6	22.2
M-ECR	0.000	0.000	0.000	0.000	-0.352	0.000	-0.059	0.144
Epoxies with increased adhesion								
ECR(Chromate)	10.14	0.00	0.00	0.00	0.04	5.49	2.61	4.29
M-ECR(Chromate)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ECR(DuPont)	0.0	43.8	33.6	36.1	42.5	41.8	33.0	16.6
M-ECR(DuPont)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ECR(Valspar)	26.6	38.9	59.9	8.3	5.6	49.9	31.5	22.1
M-ECR(Valspar)	0.000	-0.282	0.000	0.000	0.000	0.000	-0.047	0.115
Corrosion inhibitors in mortar								
M-ECR(DCI)	0.000	-0.282	0.000	0.000	0.000	0.000	-0.047	0.115
M-ECR(RH)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(HY)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(primer/Ca(NO2)2)	0.000	0.000	0.000	0.000	0.774	0.925	0.283	0.441
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete								
M-ECR(Chromate)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(DuPont)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
M-ECR(Valspar)-DCI	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Bars with multiple coatings								
MC(both layers penetrated)	4.26	4.13	0.65	0.66	-3.82	2.27	1.36	2.99
M-MC(both layers penetrated)	-0.35	0.12	0.08	0.00	-1.06	0.00	-0.20	0.45
MC(only epoxy penetrated)	6.35	2.21	10.78	5.00	3.86	6.03	5.70	2.91
M-MC(only epoxy penetrated)	1.96	2.97	1.66	2.37	0.57	2.18	1.95	0.81

[a] Conv. = conventional steel. ECR = conventional epoxy-coated reinforcing bars . ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(RH) = conventional ECR with Rheocrete inhibitor. ECR(HY) = conventional ECR with Hycrete inhibitor.

MC(both layers penetrated) = multiple coating bars with both layers penetrated.

MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.

[b] M- prefix indicates mortar wrapped specimen, otherwise bare bar specimen.

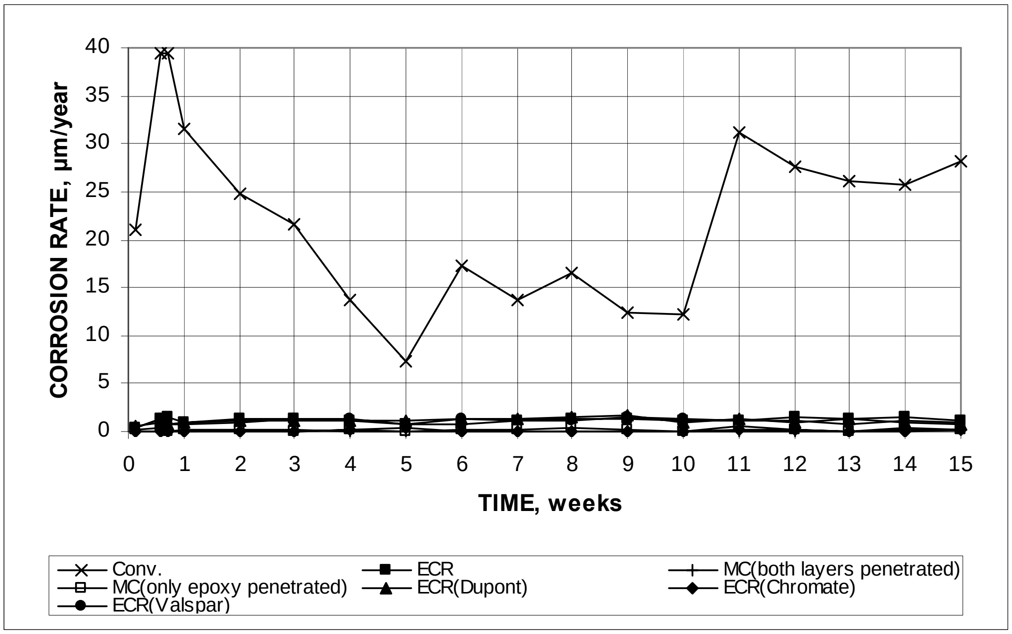

Figure 7a. Graph. Macrocell test—average corrosion rate. Bare conventional, epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

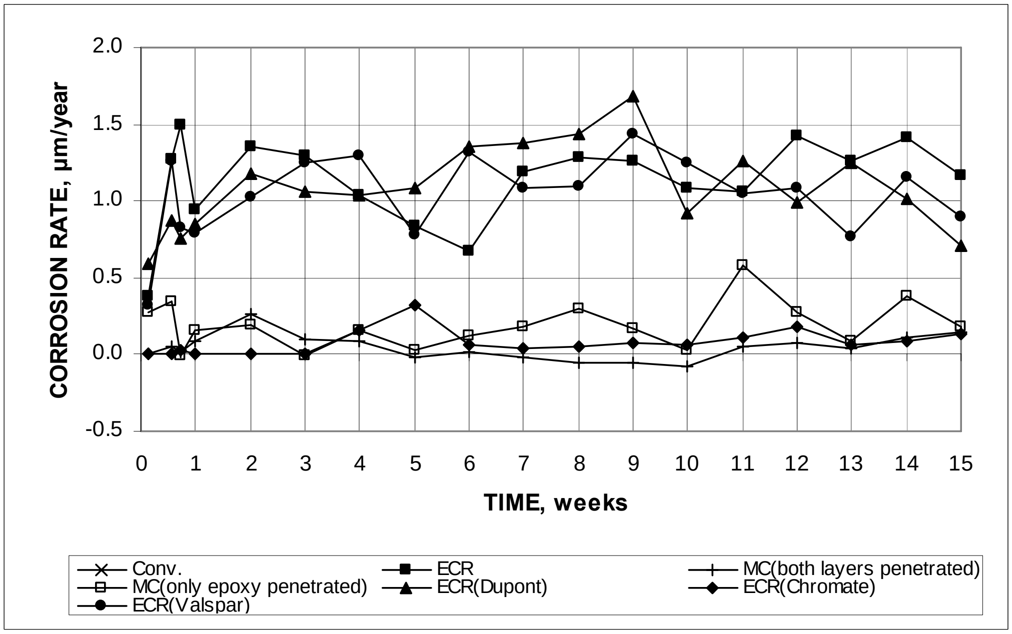

Figure 7b. Graph. Macrocell test—average corrosion rate. Bare conventional, epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

Total corrosion losses which are calculated by integrating the corrosion rate over the test period, are shown in figures 8a and b and tables 7a and b. Figure 8a expresses the losses based on the total area of the bars in contact with the text solutions, while figure 8b expresses the losses in terms of the area of steel exposed by the holes through the epoxy coating, which for macrocell specimens equals the values based on total bar surface multiplied by a factor of 100. Over the 15-week period, total losses equal approximately 6 μm for conventional steel, between 0.31 and 0.34 μm based on total area, and between 31 and 34 μm based on exposed area for conventional ECR, ECR(DuPont) and ECR(Valspar), and below 0.057 μm based on total area and 5.7 μm based on exposed area for the ECR(Chromate) and MC bars. The low macrocell corrosion rates for the MC bars, with both layers penetrated and with only the epoxy penetrated, result because the test measures macrocell, not microcell corrosion and because, as an amphoteric material, zinc is attacked by the alkaline solution at the cathode as well as by the combined alkaline and salt solution at the anode, reducing the net macrocell current.

The corrosion potentials, shown in figures 9a and b (top and bottom bars disconnected for two hours), provide additional information on the behavior of the specimens. With the exception of ECR(Chromate), all specimens exhibit corrosion potentials at the anode more negative then –0.275 V with respect to a saturated calomel electrode (SCE) [approximately equivalent to –0.350 V for a copper-copper sulfate electrode (CSE)], indicating that the bars are undergoing active corrosion. In contrast to bars with only steel exposed to the test solutions, the MC bars initially exhibit corrosion potentials at both anode and cathode of approximately of –1.200 V, indicating

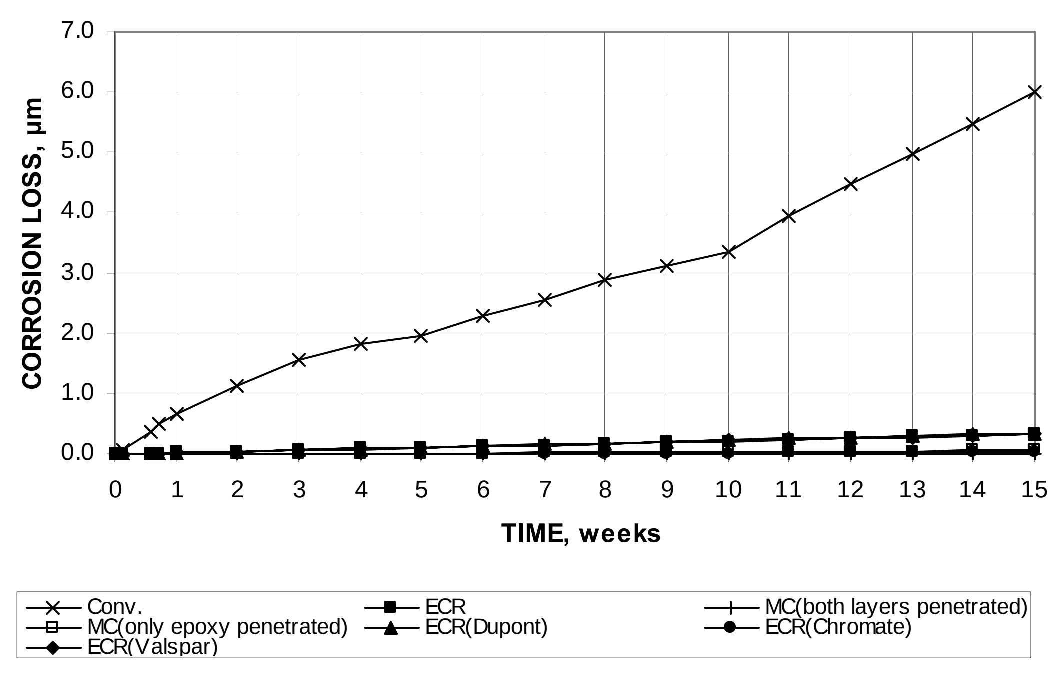

Figure 8a. Graph. Macrocell test—average corrosion loss. Bare conventional, epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

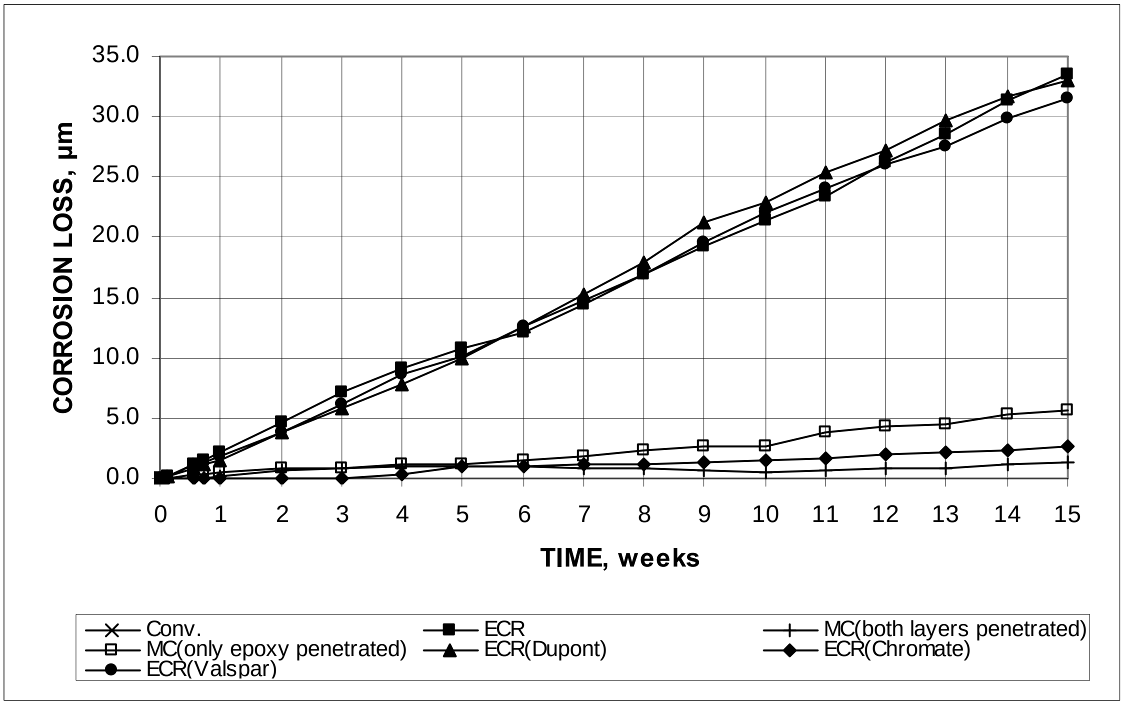

Figure 8b. Graph. Macrocell test—average corrosion loss based on area exposed at holes through coating. Bare epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

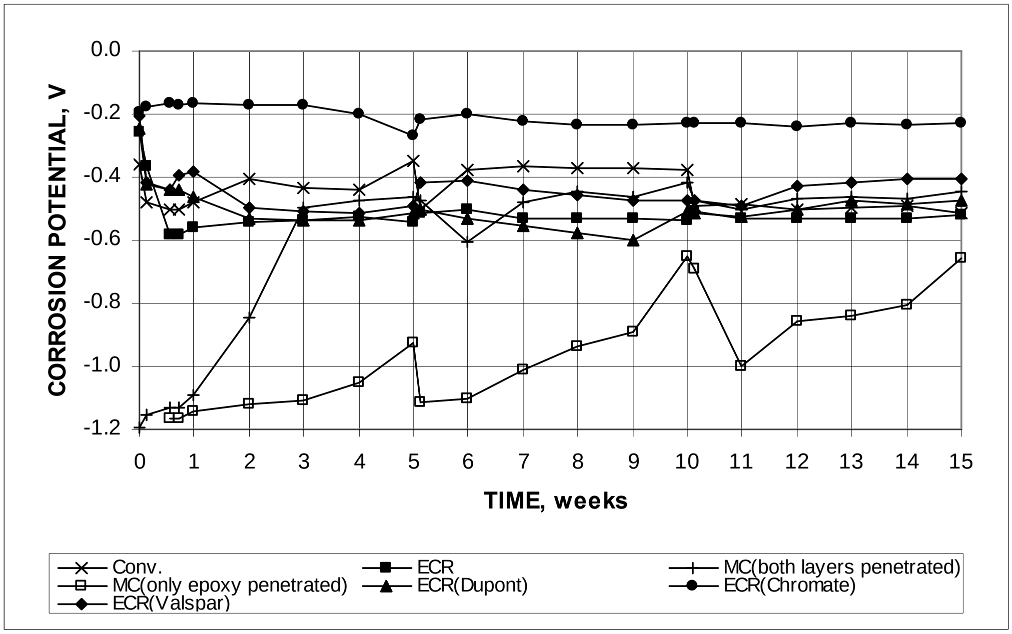

Figure 9a. Graph. Macrocell test—average corrosion potential, anode. Bare conventional, epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

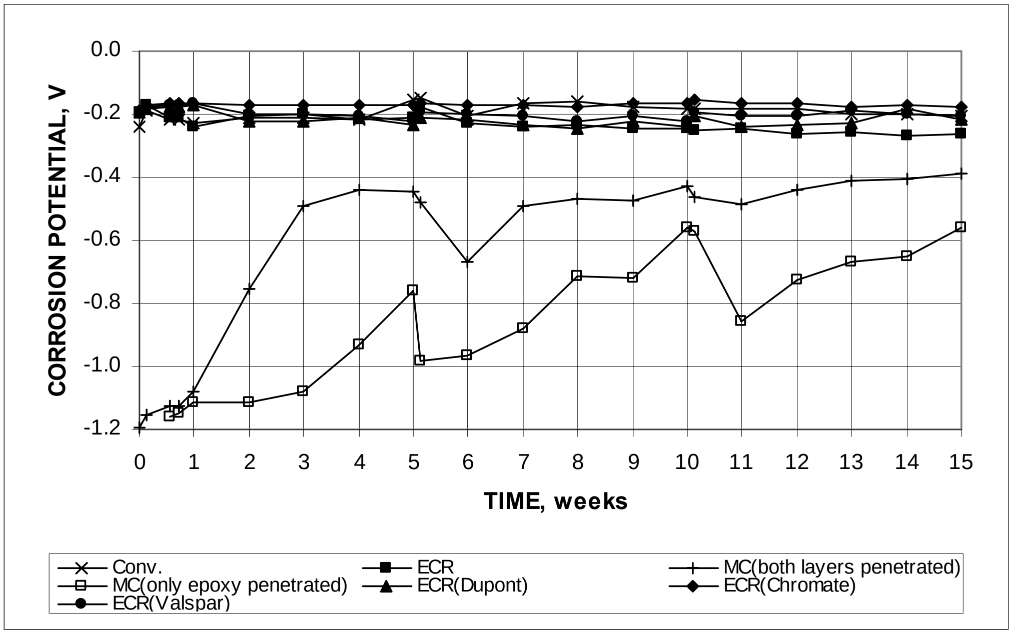

Figure 9b. Graph. Macrocell test—average corrosion potential, cathode. Bare conventional, epoxy-coated, increased adhesion ECR, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

active corrosion of the zinc layer. The MC bars with both layers of coating penetrated reach a corrosion potential of about –0.500 V after three weeks, indicating that the effect of the zinc surrounding the holes has been largely reduced and that the exposed area of steel is governing the corrosion process. In contrast, the MC bars with only the epoxy penetrated maintain a significantly more negative corrosion potential than the other anode bars, indicating that the zinc was still providing some protection for the underlying steel for a significant portion of the test period. Interestingly, the MC cathode bars (figure 9b) exhibit corrosion potentials that are quite similar to those at the anode throughout the test period. The fact that the MC cathode bars never reach a corrosion potential more positive then –0.275 V, exhibited by all of the other bars, indicates that the zinc is likely contributing to the performance of the system. With the exception of ECR(Chromate), the corrosion potentials exhibited by the other corrosion protection systems show a strong similarity to that of uncoated conventional reinforcement, indicating that the differences in observed corrosion rates (figures 7a and b) are primarily based on the role of the epoxy coating in limiting the exposed bar surface at both the anode and the cathode. In terms of total metal loss (tables 7a and b and figures 8a and b), that effect is significant.

As a general rule in the bare bar tests, the corrosion rates for epoxy-coated reinforcement based on the area exposed at the holes through the coating (table 7b) are significantly higher than they are for conventional reinforcement based on the total area of the bar (table 7a). This behavior, however, does not necessarily mean that corrosion losses on damaged regions of epoxy-coated reinforcement are higher than local metal losses due to corrosion on uncoated conventional reinforcement because the losses recorded for uncoated conventional steel represent values that are averaged over the full contact surface. In practice, corrosion losses on uncoated bars are not uniformly distributed over the bar surface but, rather, may be much greater in some areas than others. In addition, the losses calculated for the coated bars may include losses that occur under the coating, not just on the exposed regions.

The test specimens were evaluated visually following the tests, and all specimens in the group were found to exhibit significant corrosion, as shown in figures 10, 11, and 12 for conventional reinforcement, conventional ECR, and MC with only the epoxy layer penetrated, respectively. Figure 12 shows that the zinc has been fully consumed on the MC bars, in spite of the fact that the total corrosion loss on the exposed area based on the macrocell current (figure 8b) amounts to less than 6 μm for a coating that is 50 μm thick. This observation demonstrates the impact of microcell corrosion, which is not measured in this test, on the loss of the zinc, and indicates that macrocell measurements may underestimate total corrosion losses.

Figure 10. Photo. Bare conventional anode bar, at 15 weeks, showing corrosion products that formed below the surface of the solution.

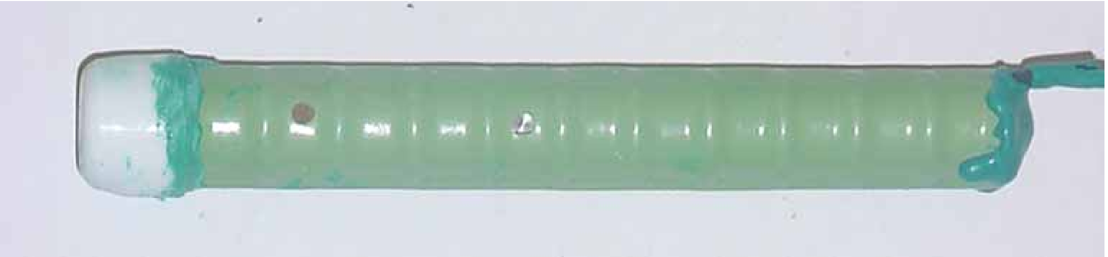

Figure 11. Photo. Bare ECR anode bar, at 15 weeks, showing corrosion products that formed at holes though the epoxy.

Figure 12. Photo. Bare MC anode bar with only epoxy penetrated, at 15 weeks, showing corrosion products that formed at holes though the epoxy.

Mortar-Wrapped Bar Tests

The corrosion rates using mortar-wrapped specimens for conventional steel, conventional ECR, ECR(primer/$Ca(NO_2)_2$), and MC bars with both layers penetrated and only the epoxy penetrated are shown in figures 13a and b. In figure 13b, the corrosion rate is based on the exposed area at the holes through the coating.

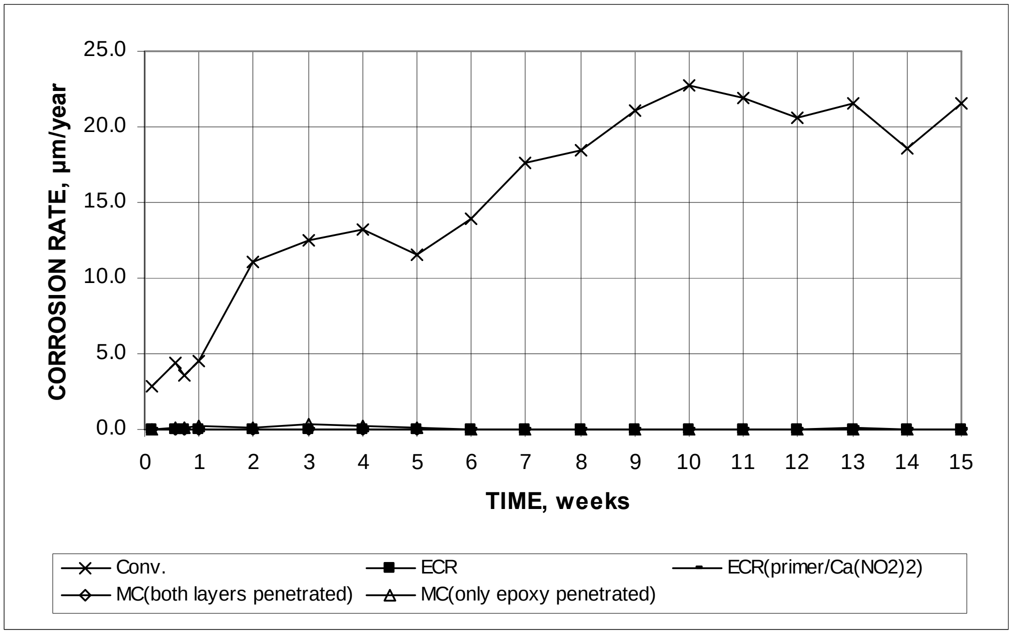

Figure 13a. Graph. Macrocell test—average corrosion rate. Mortar-wrapped conventional, epoxy-coated, ECR with calcium nitrite primer, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

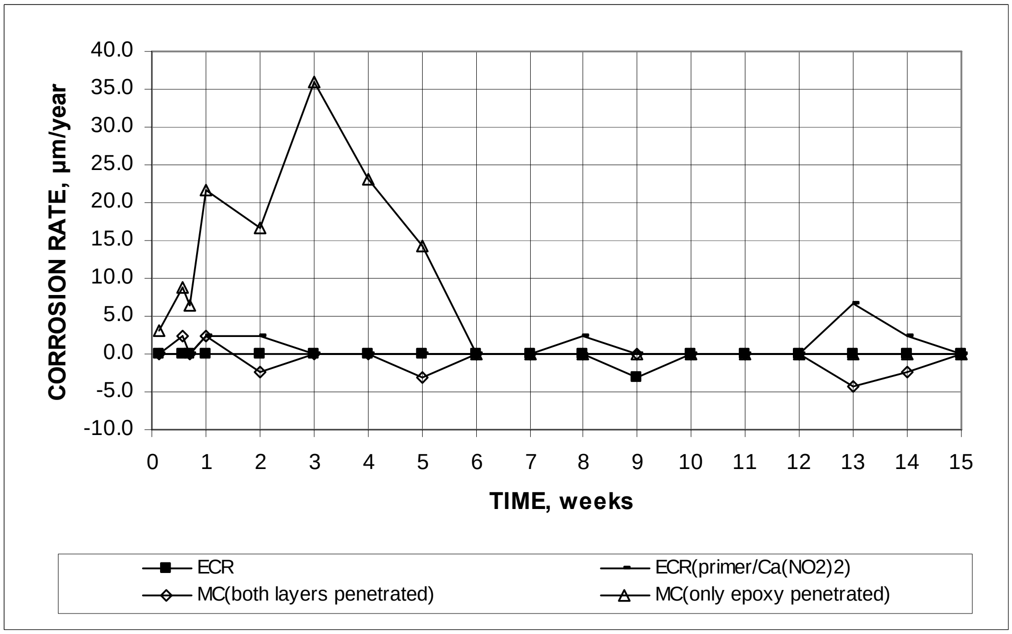

Figure 13b. Graph. Macrocell test—average corrosion rate based on area exposed at holes through coating. Mortar-wrapped conventional epoxy-coated, ECR with calcium nitrite primer, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

The corrosion rate based on total area for conventional steel starts at approximately 2.5 μm/yr, increasing to about 21 μm/yr at week 9, and remaining between 18 and 23 μm/yr thereafter. As shown in figure 13b, conventional ECR exhibits essentially no corrosion during the test, while the corrosion current exhibited by the other test specimens shown in the figure is relatively minor. The other systems tested, including ECR with improved adhesion [ECR(Chromate), ECR(DuPont), and ECR(Valspar)], ECR in mortar with a corrosion inhibitor (calcium nitrite, Rheocrete 222^+ or Hycrete) and the three epoxies with improved adhesion in mortar with calcium nitrite, exhibited no corrosion in the test.

Corrosion losses based on total and exposed area for the systems that did exhibit corrosion are shown in figures 14a and b, respectively. Corrosion losses at 15 weeks for all specimens are presented in table 7. Total losses for conventional steel amount to 4.8 μm at 15 weeks, compared to values of less than 0.02 μm based on total area for other systems and a value of less than 2 μm for the MC bars with only the epoxy penetrated and less than 0.5 μm for the other systems based on exposed area.

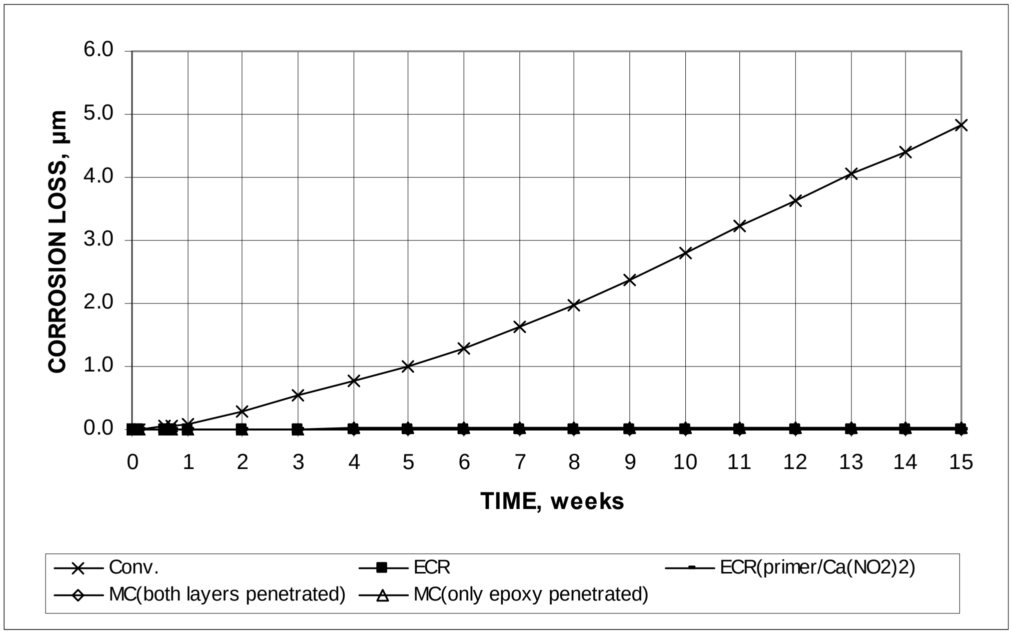

Figure 14a. Graph. Macrocell test—average corrosion loss. Mortar-wrapped conventional, epoxy-coated, ECR with calcium nitrite, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

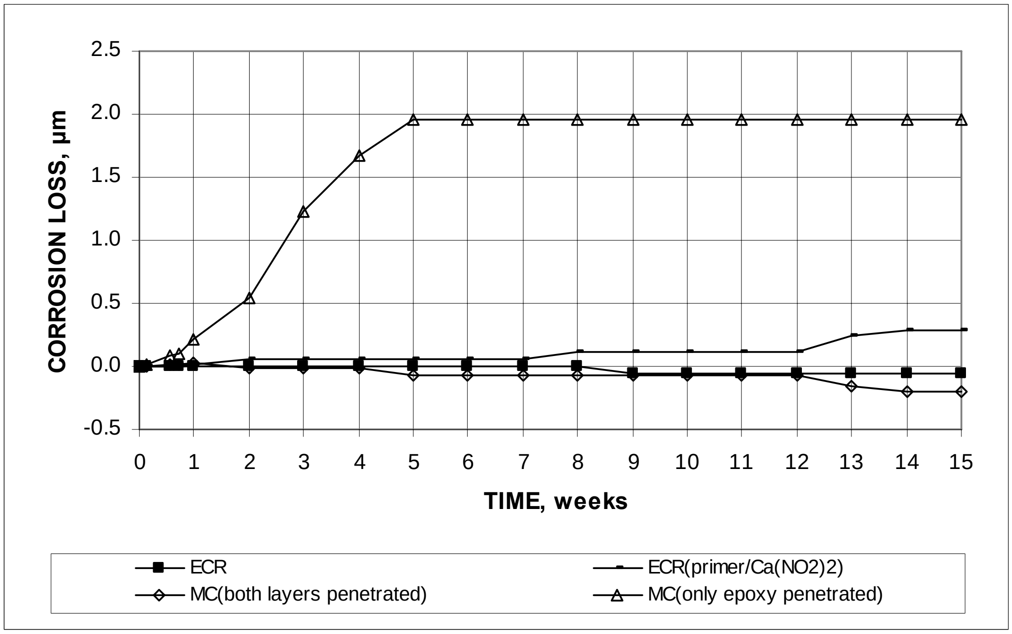

Figure 14b. Graph. Macrocell test—average corrosion loss based on area exposed at holes through coating. Mortar-wrapped conventional, epoxy-coated, ECR with calcium nitrite, and multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

The average corrosion potentials during the tests, shown in figures 15 and 16, demonstrate that at the anode, only those steels that exhibited some corrosion loss (tables 7a and b) had corrosion potentials more negative than –0.275 V, with the exception of ECR(Chromate) in mortar containing calcium nitrite [ECR(Chromate)-DCI], which dropped below –0.275 V after week 12. The potential of the ECR(primer/Ca(NO_2)$_2$) bars, which did exhibit corrosion, dropped to approximately –0.400 V at 7 weeks, maintaining that value thereafter. The MC specimens with both layers penetrated and with only epoxy penetrated (figure 16), exhibited progressively more negative potentials as the test progressed. For MC bars with both layers penetrated, the corrosion potential started at approximately –0.400 V, dropping to a value somewhat more negative then –0.700 V at 15 weeks at both the anode and the cathode. The MC bars with only epoxy penetrated started at approximately –0.600 V, ending at a value equal to that for the same bars with both layers penetrated. The corrosion potentials of the cathodes for the MC bar tests started at only slightly more positive values than exhibited by the anodes, dropping to values between –0.600 and –0.800 V at 15 weeks. These results suggest that the MC bars started the tests in a passive condition, becoming relatively more active as the simulated pore solutions, both with and without NaCl, penetrated the mortar. The zinc provided protection during the test for both types of damage to the coating.

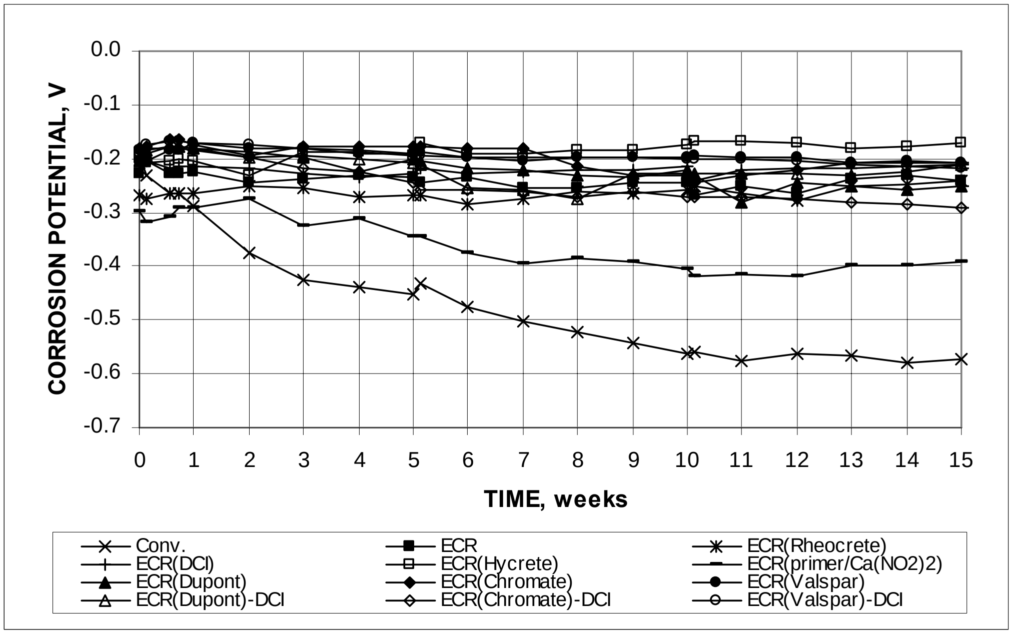

Figure 15a. Graph. Macrocell test—average corrosion potential, anode. Mortar-wrapped conventional, epoxy-coated reinforcement, epoxy-coated reinforcement with increased adhesion, epoxy-coated reinforcement cast with corrosion inhibitor, and ECR with calcium nitrite in simulated pore solution with 1.6 m ion NaCl.

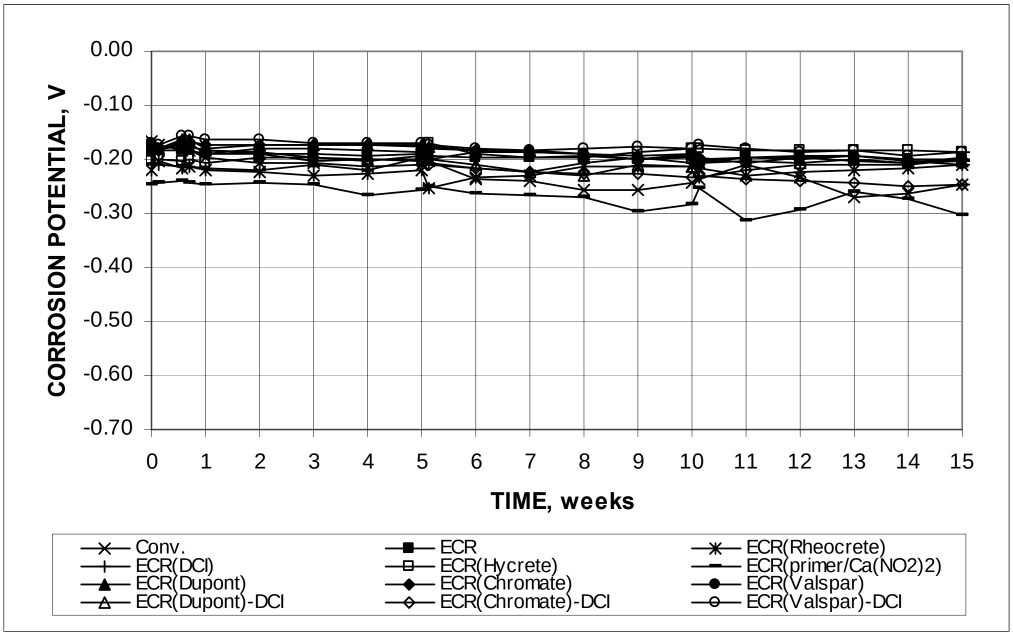

Figure 15b. Graph. Macrocell test—average corrosion potential, cathode. Mortar-wrapped conventional, epoxy-coated reinforcement, epoxy-coated reinforcement with increased adhesion, epoxy-coated reinforcement cast with corrosion inhibitor, and ECR with calcium nitrite in simulated pore solution with 1.6 m ion NaCl.

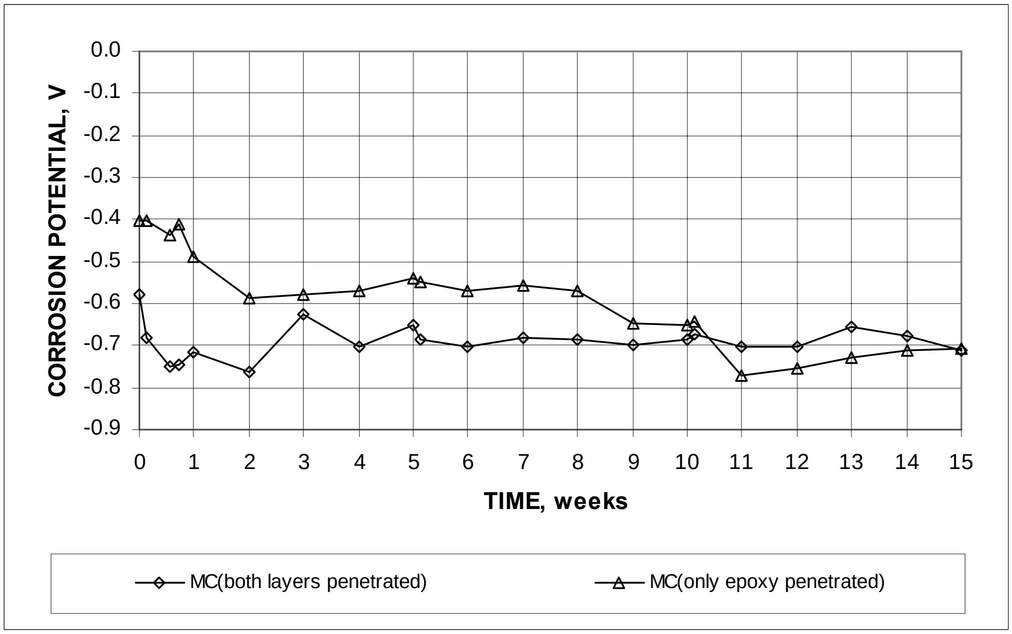

Figure 16a. Graph. Macrocell test—average corrosion potential, anode. Mortar-wrapped multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

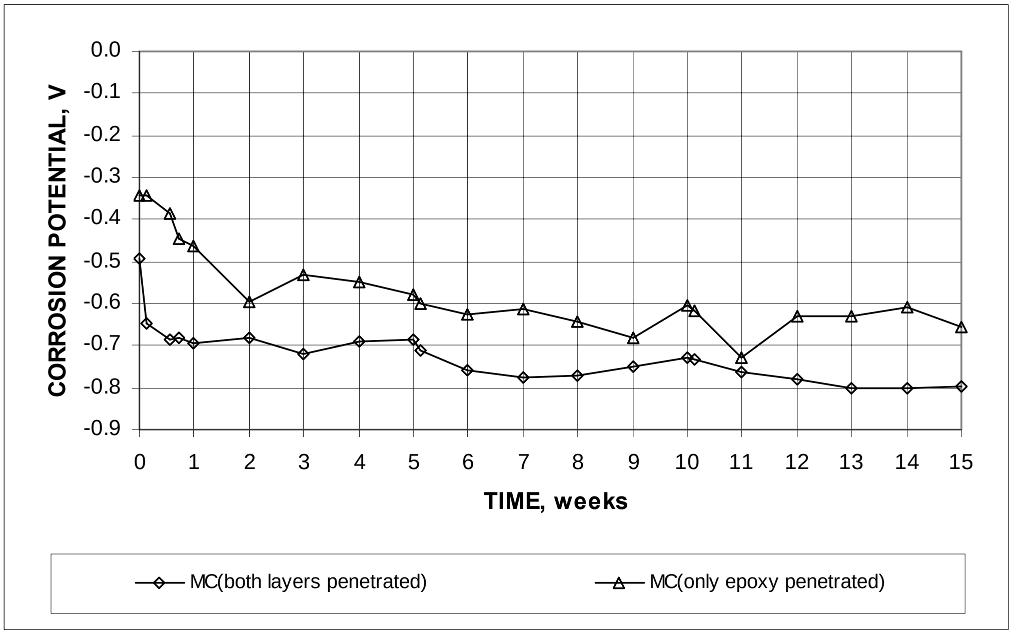

Figure 16b. Graph. Macrocell test—average corrosion potential, cathode. Mortar-wrapped multiple coated steel in simulated pore solution with 1.6 m ion NaCl.

At the conclusion of the tests, the mortar was removed and the bars were inspected for evidence of corrosion. The uncoated conventional steel bars exhibited corrosion, as shown in figure 17, while none of the epoxy-coated bars exhibited any corrosion products.

Figure 17. Photo. Conventional anode bar after removal of mortar, at 15 weeks.

The results shown table 7 and figures 13 through 17 indicate several things about the corrosion process for steel with a damaged epoxy coating. As mentioned for the bare bar tests, the epoxy coating significantly reduces total corrosion losses. But more than that, the tests demonstrate that, even with a relatively homogenous material like the mortar used in these tests, the chloride concentrations at the surface of the bar are likely to vary, providing concentrations high enough to initiate corrosion at some locations but not high enough at all locations. This is clearly the case for mortar-wrapped conventional steel, as shown in figure 17, where the corrosion products are distributed nonuniformly across the bar surface. The exposed steel at locations where epoxy is damaged should begin to corrode at the same chloride concentration as uncoated conventional steel. When this does not occur, as demonstrated in these tests, it is likely that the chloride concentration at the location of the damaged epoxy has not reached the critical chloride threshold. Thus, even damaged epoxy-coated reinforcement will have an advantage over conventional steel because all locations that are damaged may not be subjected to chloride concentrations high enough to cause corrosion, while under the same conditions for uncoated steel, the chloride concentration would be high enough to initiate corrosion somewhere on the bars.

The test results also suggest that if this test is to be used to evaluate the corrosion protection provided by damaged epoxy coating (as opposed to systems used with uncoated bars for which it provides a consistent measure of corrosion resistance(25)), the severity of the exposure conditions should be increased, such as would be provided by an increase in the number of penetrations in the epoxy or by an increase in the concentration of chloride in the solution at the anode. In the end, the test results for the mortar-wrapped rapid macrocell tests provide a general comparison of the performance of the systems under test.

BENCH-SCALE TESTS

The results of the Southern Exposure (SE) and cracked beam (CB) tests provide additional insight into the performance of the corrosion protection systems that are under evaluation in this study. The tests have not been completed, but all of the bench-scale tests have been underway for at least 56 weeks, a time period that is adequate to provide a useful comparison of the systems. The systems, as reported in the following sections, are compared based on average values for three specimens for each corrosion protection system. Six specimens are used for conventional reinforcing steel and conventional ECR cast in concrete with a *w/c* ratio of 0.45.

Southern Exposure Tests

The test results, expressed in terms of corrosion loss based on the total area of the bar in contact with concrete and on the exposed area at holes in the epoxy are presented in tables 8a and b, respectively. For these tests, the corrosion rates based on the exposed area for bars with four and 10 penetrations through the epoxy on each bar are, respectively, 480 and 192 times the corrosion rates based on total bar area. As noted in the tables, four of six specimens with conventional steel cast in concrete with *w/c* ratios of 0.45 (Conv.-45) and two of six specimens with conventional epoxy-coated reinforcement cast in concrete with *w/c* = 0.45 with four holes through the epoxy (ECR-4h-45) have not been included in the averages because the specimens have abnormally low chloride contents [below 7 kg/m^3 (12 pounds per cubic yard (lb/yd^3)) at 96 weeks] for the SE test. Further, even the corrosion rates exhibited by the remaining Conv.-45 specimens are only about half those exhibited by similar specimens in earlier investigations.(20,21) The difference in performance may be due to unplanned variations in concrete quality – in this case higher quality in the subject specimens. As a result, the Conv.-45 and ECR-4h-45 Southern Exposure tests are being repeated for use in the final report; the analyses that follow are based on the remaining two and four SE specimens, respectively, for Conv.-45 and ECR-4h-45. Chloride contents taken at 48 weeks and after indicate that all of the other specimens are on track to have chloride contents above 7 kg/m^3 (12 lb/yd^3) at 96 weeks. Full details of the chloride analyses will be presented in the final report.

The variation in chloride contents and corrosion performance observed in these tests provides some insight into the variability in corrosion performance observed in the field, where bridge decks reinforced with uncoated bars have provided service lives that range from 4 to 40 years for bridges in the same environment. That variability may be due to differences in concrete quality which can significantly affect the rate of chloride penetration.

Table 8a. Corrosion loss at 56 weeks (in µm) for Southern Exposure specimens based on total area.

Steel Designation[a]	Specimen						Average	Standard Deviation
	1	2	3	4	5	6		
Control								
Conv.-45	0.015[b]	1.630[b]	0.011[b]	0.546	-0.101[b]	0.409	0.478	0.097
Conv.-35	0.066	0.172	0.098	-	-	-	0.112	0.055
ECR-4h-45	0.002[b]	0.002[b]	0.003	0.001	0.004	0.005	0.004	0.002
ECR-10h-45	0.004	0.003	0.004	-	-	-	0.004	0.000
ECR-10h-35	0.003	0.003	0.002				0.003	0.000
Epoxies with increased adhesion								
ECR(Chromate)-4h-45	0.002	0.004	0.007				0.004	0.002
ECR(Chromate)-10h-45	0.004	0.014	0.054				0.024	0.007
ECR(DuPont)-4h-45	0.002	0.002	0.002				0.002	0.000
ECR(DuPont)-10h-45	0.006	0.010	0.006				0.007	0.003
ECR(Valspar)-4h-45	0.012	0.005	0.001				0.006	0.005
ECR(Valspar)-10h-45	0.003	0.014	0.007				0.008	0.007
Corrosion inhibitors in concrete								
ECR(DCI)-4h-45	0.001	0.001	0.002				0.001	0.000
ECR(DCI)-10h-45	0.001	0.003	0.008				0.004	0.004
ECR(DCI)-10h-35	0.009	0.001	0.000				0.003	0.005
ECR(RH)-4h-45	0.000	0.000	-0.001				0.000	0.000
ECR(RH)-10h-45	-0.002	-0.009	-0.001				-0.004	0.004
ECR(RH)-10h-35	0.001	0.004	0.003				0.003	0.002
ECR(HY)-4h-45	-0.001	0.000	0.000				-0.001	0.000
ECR(HY)-10h-45	0.004	0.000	0.003				0.002	0.002
ECR(HY)-10h-35	0.001	0.000	0.000				0.001	0.001
ECR(primer/$Ca(NO_2)_2$)-4h-45	0.002	0.006	0.002				0.003	0.003
ECR(primer/$Ca(NO_2)_2$)-10h-45	0.005	0.044	0.001				0.017	0.023
ECR(primer/$Ca(NO_2)_2$)-10h-35	0.004	0.000	0.001				0.002	0.002
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete								
ECR(Chromate)-DCI-4h-45	0.003	-0.001	-0.011				-0.003	0.007
ECR(DuPont)-DCI-4h-45	-0.001	-0.001	0.001				-0.001	0.001
ECR(Valspar)-DCI-4h-45	-0.001	0.000	0.007				0.002	0.004
Bars with multiple coatings								
MC(both layers penetrated)-4h-45	0.030	0.013	0.016				0.020	0.009
MC(both layers penetrated)-10h-45	0.055	0.229	0.153				0.146	0.088
MC(only epoxy penetrated)-4h-45	0.012	0.007	-0.001				0.006	0.006
MC(only epoxy penetrated)-10h-45	0.001	0.021	0.026				0.016	0.013

[a] Conv. = conventional steel. ECR = conventional epoxy-coated bars. ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(Rheocrete) = conventional ECR with Rheocrete inhibitor. ECR (Hycrete) = conventional ECR with Hycrete inhibitor.
MC(both layers penetrated) = multiple coating bars with both layers penetrated.
MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.
4h = bar with four holes through epoxy, 10h = bar with 10 holes through epoxy.
35 = concrete with w/c = 0.35, 45 = concrete with w/c = 0.45.

[b] Excluded from average because of low chloride content.

Table 8b. Corrosion loss at 56 weeks (in µm) for Southern Exposure specimens based on area exposed at holes through coating.

Steel Designation[a]	Specimen						Average	Standard Deviation
	1	2	3	4	5	6		
Control								
Conv.-45	-	-	-	-	-	-	-	-
Conv.-35	-	-	-	-	-	-	-	-
ECR-4h-45	0.77[b]	1.20[b]	1.55	0.53	2.08	2.60	1.69	0.88
ECR-10h-45	0.84	0.66	0.70	-	-	-	0.74	0.10
ECR-10h-35	0.51	0.55	0.46				0.51	0.04
Epoxies with increased adhesion								
ECR(Chromate)-4h-45	1.09	1.79	3.24				2.04	1.09
ECR(Chromate)-10h-45	0.80	2.72	10.33				4.62	1.35
ECR(DuPont)-4h-45	0.77	1.13	1.16				1.02	0.21
ECR(DuPont)-10h-45	1.11	1.86	1.08				1.35	0.53
ECR(Valspar)-4h-45	5.53	2.64	0.70				2.96	2.43
ECR(Valspar)-10h-45	0.62	2.60	1.32				1.52	1.40
Corrosion inhibitors in concrete								
ECR(DCI)-4h-45	0.63	0.53	0.92				0.69	0.20
ECR(DCI)-10h-45	0.25	0.56	1.62				0.81	0.72
ECR(DCI)-10h-35	1.69	0.11	-0.07				0.58	0.97
ECR(RH)-4h-45	-0.14	0.00	-0.35				-0.16	0.18
ECR(RH)-10h-45	-0.31	-1.69	-0.20				-0.73	0.83
ECR(RH)-10h-35	0.11	0.83	0.52				0.49	0.36
ECR(HY)-4h-45	-0.46	-0.21	-0.14				-0.27	0.17
ECR(HY)-10h-45	0.70	0.00	0.61				0.44	0.38
ECR(HY)-10h-35	0.27	0.00	0.04				0.10	0.14
ECR(primer/Ca(NO2)2)-4h-45	0.77	3.10	1.02				1.63	1.28
ECR(primer/Ca(NO2)2)-10h-45	0.97	8.36	0.25				3.19	4.49
ECR(primer/Ca(NO2)2)-10h-35	0.77	0.04	0.27				0.36	0.37
Epoxies with increased adhesion plus $Ca(NO_2)_2$ in mortar or concrete								
ECR(Chromate)-DCI-4h-45	1.30	-0.53	-5.21				-1.48	3.36
ECR(DuPont)-DCI-4h-45	-0.35	-0.67	0.28				-0.25	0.48
ECR(Valspar)-DCI-4h-45	-0.25	0.00	3.31				1.02	1.98
Bars with multiple coatings								
MC(both layers penetrated)-4h-45	14.57	6.19	7.52				9.43	4.50
MC(both layers penetrated)-10h-45	10.49	44.03	29.38				27.97	16.82
MC(only epoxy penetrated)-4h-45	5.64	3.41	-0.27				2.93	2.99
MC(only epoxy penetrated)-10h-45	0.25	4.09	4.93				3.09	2.49

[a] Conv. = conventional steel. ECR = conventional epoxy-coated bars. ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(Rheocrete) = conventional ECR with Rheocrete inhibitor. ECR (Hycrete) = conventional ECR with Hycrete inhibitor.

MC(both layers penetrated) = multiple coating bars with both layers penetrated.

MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.

4h = bar with four holes through epoxy, 10h = bar with 10 holes through epoxy.

35 = concrete with w/c = 0.35, 45 = concrete with w/c = 0.45.

[b] Excluded from average because of low chloride content.

Control Tests

The control tests for this study consist of conventional steel cast in concrete with *w/c* ratios of 0.45 (Conv.-45) and 0.35 (Conv.-35), conventional epoxy-coated reinforcement cast in concrete with *w/c* = 0.45 with four holes through the epoxy (ECR-4h-45) or 10 holes through the epoxy (ECR-10h-45), and conventional ECR cast in concrete with *w/c* = 0.35 and 10 holes through the epoxy (ECR-10h-35). The corrosion rates based on the total area of steel in contact with the concrete are shown in figure 18. The figure demonstrates that, as seen in the rapid macrocell tests, corrosion proceeds at a much higher rate for uncoated than for coated reinforcement, with the latter corroding at about one percent of the rate of the former, a rate that is equal to about twice the ratio of the area exposed at the holes to the total area of the bars. The lower *w/c* ratio provides additional protection for the uncoated steel, with significant corrosion starting at about 48 weeks for the concrete with a *w/c* ratio of 0.35, compared to 25 weeks for the concrete with a *w/c* ratio of 0.45. The corrosion rate for the Conv.-45 specimens reaches a maximum of 4.2 µm/yr, dropping to a value of about 2 µm/yr at 96 weeks. Over time, the corrosion rate of the Conv.-35 specimens reaches the same order of magnitude as that of the Conv.-45 specimens, and by week 72, the Conv.-35 specimens are actually corroding at a higher rate than the higher *w/c* ratio specimens, reaching a value of 3.8 µm/yr at 84 weeks.

The average total corrosion losses for the systems are shown in figures 19a and b, which, like figure 18, shows the effect of the lower *w/c* ratio in delaying corrosion initiation and lowering corrosion losses. Average total losses at 84 weeks equal 2.1 and 1.25 µm for the Conv.-45 and Conv.-35 specimens, respectively.

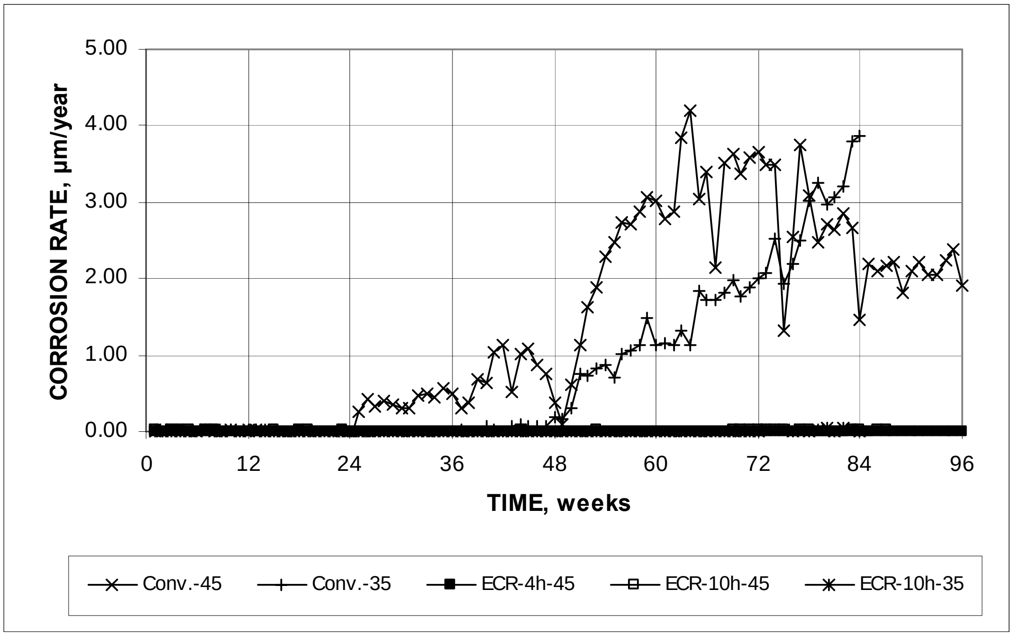

Figure 18. Graph. Southern Exposure test—average corrosion rates based on the total area for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

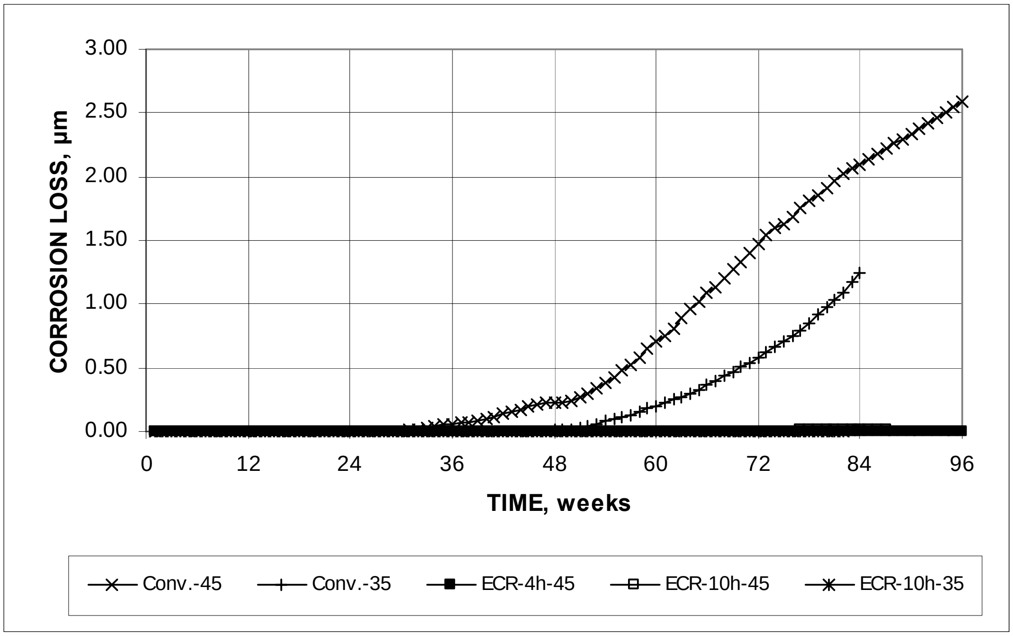

Figure 19a. Graph. Southern Exposure test—average corrosion loss based on total area for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

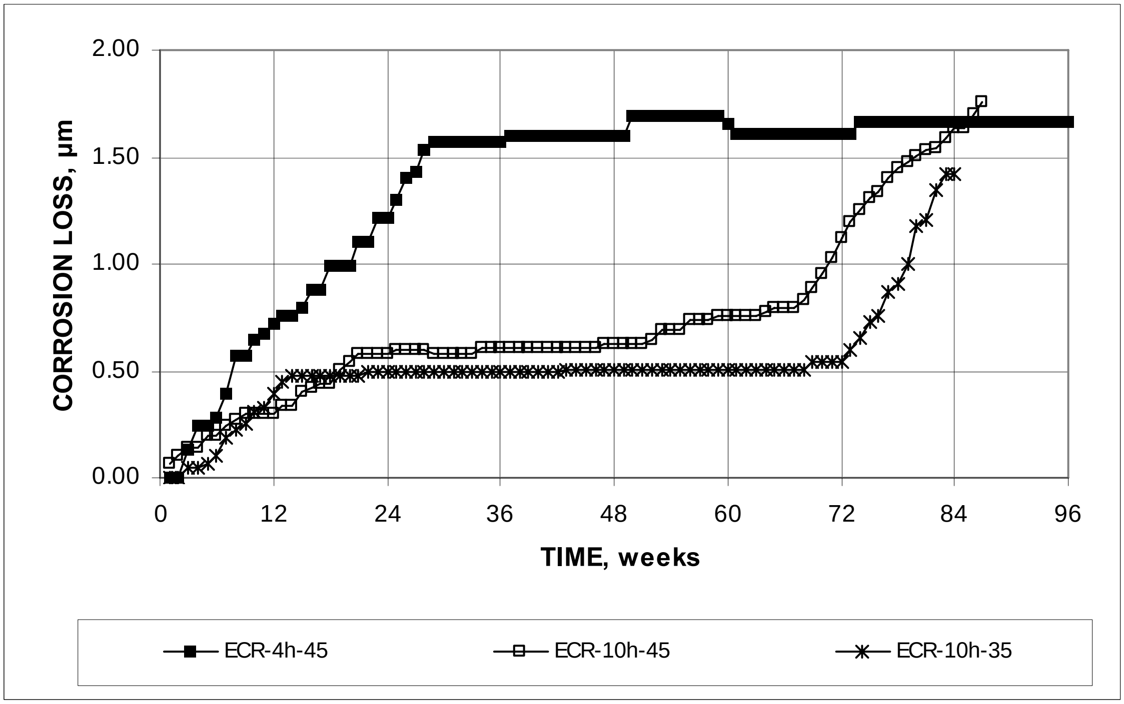

Figure 19b. Graph. Southern Exposure test—average corrosion loss based on area exposed at holes through coating for epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

The corrosion losses for the epoxy-coated bars based on area exposed at hole through the coating (referred to in the following as the “exposed area”) are shown in figure 19b. As for conventional steel, the lower *w/c* ratio provides additional corrosion protection, with losses at 56 weeks for ECR-10h-35 equal to about 70 percent of the value at 56 weeks for ECR-10h-45. The corrosion of the epoxy-coated bars appears to start earlier than it does on the uncoated bars. This may be a function of the very low corrosion currents and the precision of the microvoltmeter used in the tests. After the initiation of significant corrosion in the uncoated bar specimens, however, total losses on the exposed area of the epoxy-coated bars, 0.5 to 1.7 μm, are similar to total losses on the uncoated bars, as can be seen by comparing losses at 84 weeks in figures 19a and b. For the ECR bars, the average corrosion loss based on exposed area for epoxy-coated reinforcement with four holes in the concrete with a *w/c* of 0.45 **(**ECR-4h-45) is equal to about twice that of the same bars with 10 holes at 56 weeks. As demonstrated in tables 8a and b, however, the scatter in the test results for conventional ECR is quite high (as it is for a number of other systems). As a result, the difference in corrosion rate between ECR-4h-45 and ECR-10h-45 is not statistically significant. The difference is, however, statistically significant between ECR-10h-45 and ECR-10h-35. The flat regions on corrosion loss curves shown in figure 19b may be the result of corrosion products temporarily blocking the small exposed areas on the bars.

The corrosion potentials for the top and bottom mats of steel are shown in figures 20a and b. For the top mat, the average corrosion potential for ECR-10h-35 remains more positive than –0.350 V with respect to a copper-copper sulfate electrode (CSE) to date (84 weeks), indicating a low probability of corrosion. The corrosion potentials drop below –0.350 V at weeks 38, 51, 52, and 92 for Conv.-45, Conv.-35, ECR-10h-45, and ECR-4h-45, respectively.

The corrosion potentials for the bottom mats of reinforcement remain more positive than –0.350 V with respect to a copper-copper sulfate electrode (CSE) throughout the tests for Conv.-35, ECR-4h-45, and ECR-10h-35. The potential drops below –0.350 V at weeks 43 and 56 for Conv.-45 and ECR-10h-45, respectively, indicating that chlorides had penetrated to the level of the bottom mat for those specimens.

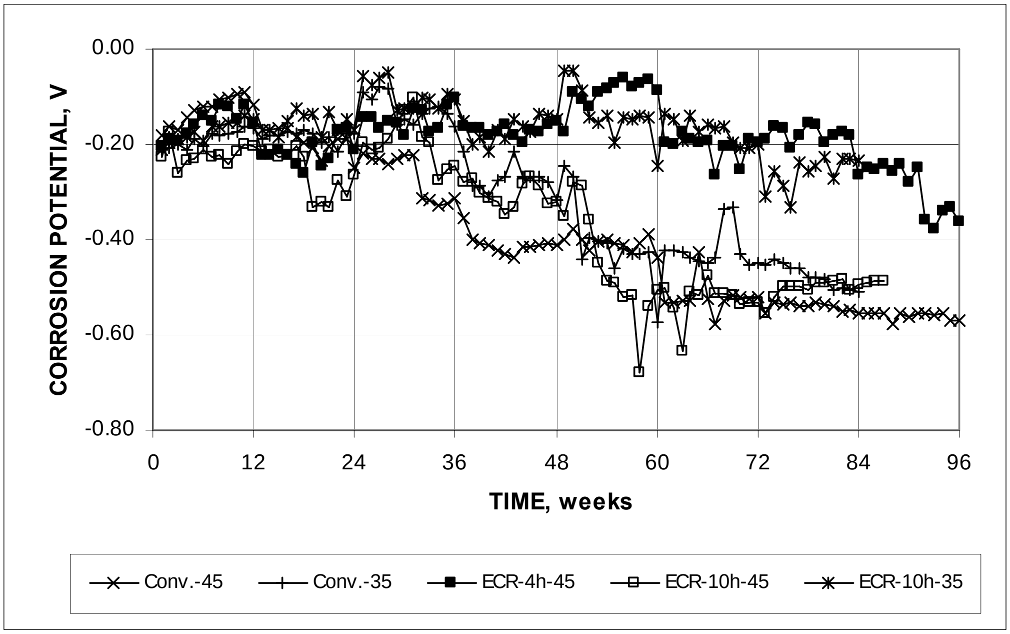

Figure 20a. Graph. Southern Exposure test—corrosion potential, top mat, for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

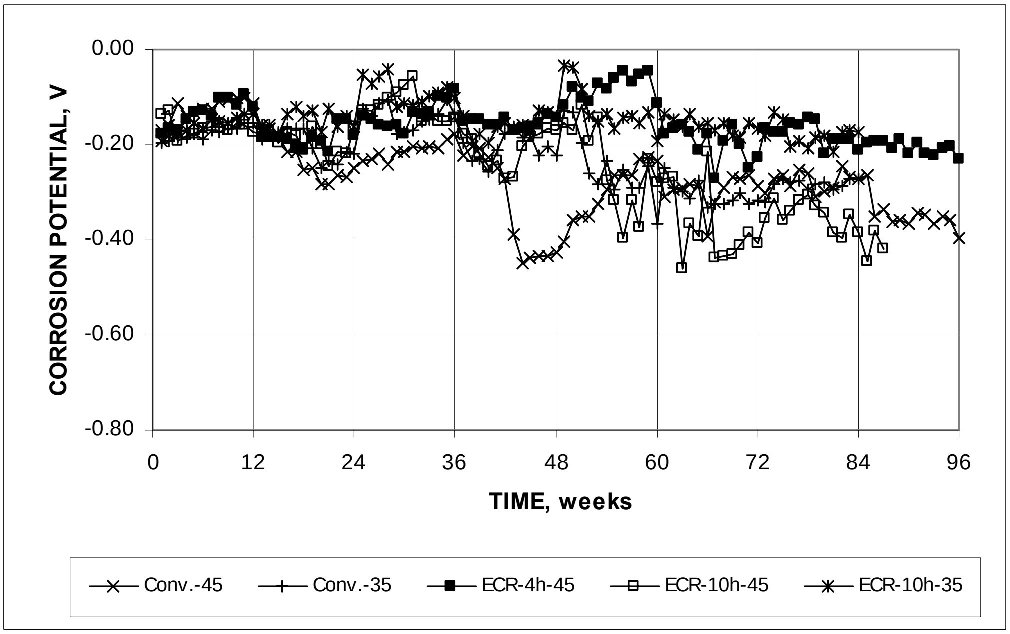

Figure 20b. Graph. Southern Exposure test—corrosion potential, bottom mat, for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

Epoxies With Improved Adhesion

The corrosion losses for conventional ECR-4h-45 and ECR-10h-45 are compared with the corresponding specimens of ECR(Chromate), ECR(DuPont), and ECR(Valspar) based on total and exposed area in figures 21a and b, respectively. The figures demonstrate that increased adhesion between the epoxy and reinforcing steel provides no benefits under the exposure conditions provided by these tests. In fact, by week 64, all of the bars with the higher adhesion epoxies exhibit greater average corrosion losses on the exposed area than the conventional ECR specimens, as losses reach values above 1 µm. The higher corrosion losses, most notably for the ECR(Valspar)-4h-45 and ECR(Chromate)-10h-45 specimens, may be due to variations in chloride content along the surface of the reinforcing bars. As shown in tables 8a and b, the variability in the test results can often be explained by very high readings on a single specimen. This is true in the two cases cited. As shown in the plot of corrosion potential for the top mats of steel (figure 22), the systems exhibit average corrosion potentials below –0.350 V by 45 weeks, with the exception of conventional ECR (ECR-4h-45), which, as noted earlier, remained above this value until week 92.

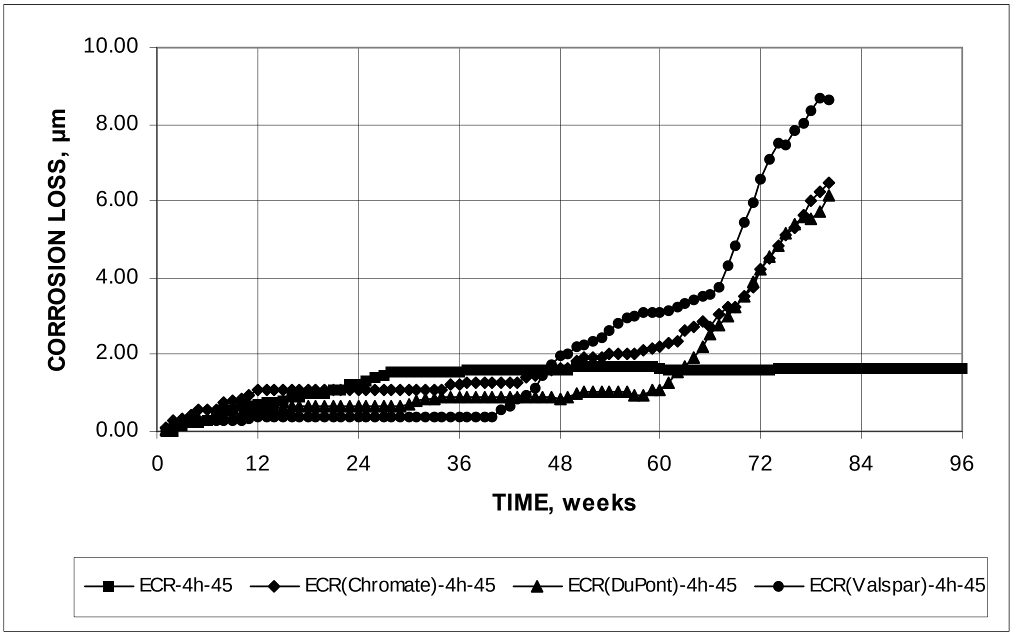

Figure 21a. Graph. Southern Exposure test—corrosion losses based on area exposed at holes through coating for conventional epoxy-coated and increased adhesion epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

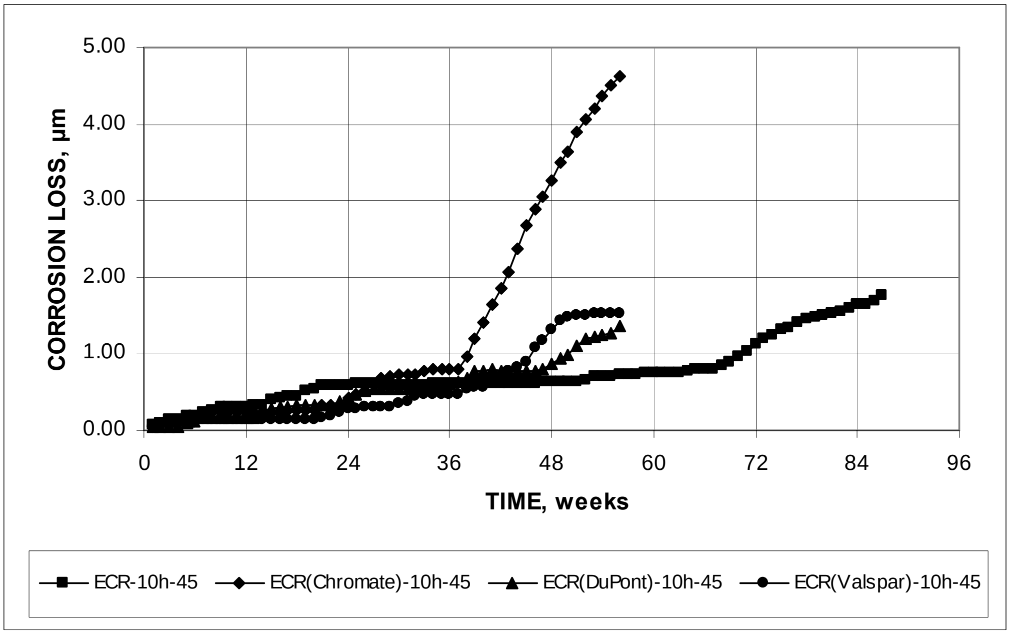

Figure 21b. Graph. Southern Exposure test—corrosion losses based on area exposed at holes through coating for conventional epoxy-coated and increased adhesion epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

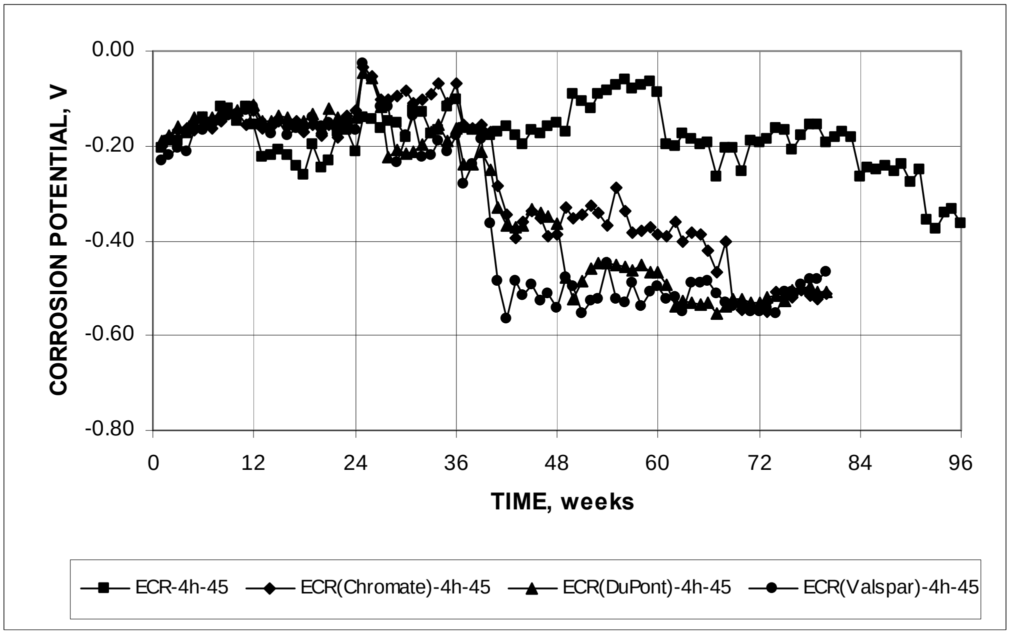

Figure 22. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated and increased adhesion epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

Epoxy-Coated Reinforcement Used in Conjunction With Corrosion Inhibitors

The corrosion losses based on exposed area for conventional epoxy-coated reinforcement cast in concrete without a corrosion inhibitor (ECR) and cast in concrete with calcium nitrite [ECR(DCI)], Rheocrete 222$^+$ [ECR(RH)], and Hycrete [ECR(HY)] are shown in figures 23a, b, and c for bars with four holes in the epoxy in concrete with $w/c = 0.45$, bars with 10 holes through the epoxy in concrete with $w/c = 0.45$, and bars with 10 holes cast in concrete with $w/c = 0.35$, respectively. The figures also include the results for conventional epoxy reinforcement with the primer containing microencapsulated calcium nitrite ECR(primer/$Ca(NO_2)_2$).

The figures 23a, b, and c show that the presence of a corrosion inhibitor delays the onset of corrosion and, in most of the cases shown, results in lower corrosion losses at 56 weeks. As can be seen in table 8 and by comparing figures 21a and b with figures 23a, b, and c, the corrosion losses in the presence of corrosion inhibitors are lower than those observed for the epoxies with the improved adhesion by a factor of at least 2. The variability in the test results, as represented by the standard deviation, is similar for the two sets of data. With the exception of ECR(primer/$Ca(NO_2)_2$), the corrosion losses, whether negative or positive, for the specimens with corrosion inhibitors, are less than 1 µm at the end of 56 weeks. Negative corrosion losses in this test are due to variability in test readings and should be viewed as zero corrosion.

Figures 23a, b, and c also show that a lower w/c ratio, which presumably results in a lower chloride level in the concrete due to reduced permeability, enhances the performance of the corrosion inhibitors. This observation is especially apparent for ECR(primer/$Ca(NO_2)_2$), as can be seen by comparing the corrosion losses shown in figures 23a and b ($w/c = 0.45$) with those

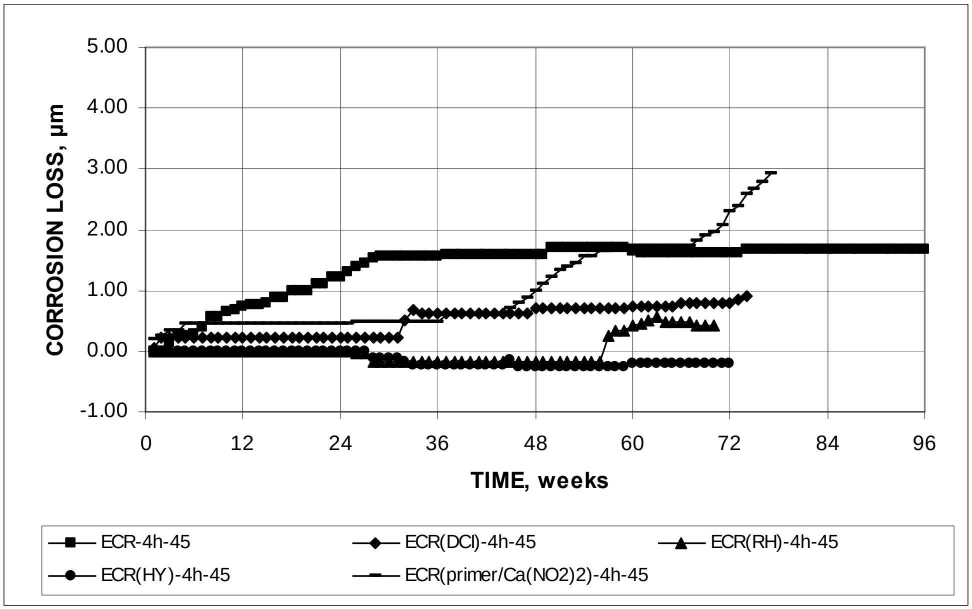

Figure 23a. Graph. Southern Exposure test—corrosion losses based on area exposed at holes through coating for conventional epoxy-coated reinforcement and with inhibitors, $w/c = 0.45$, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

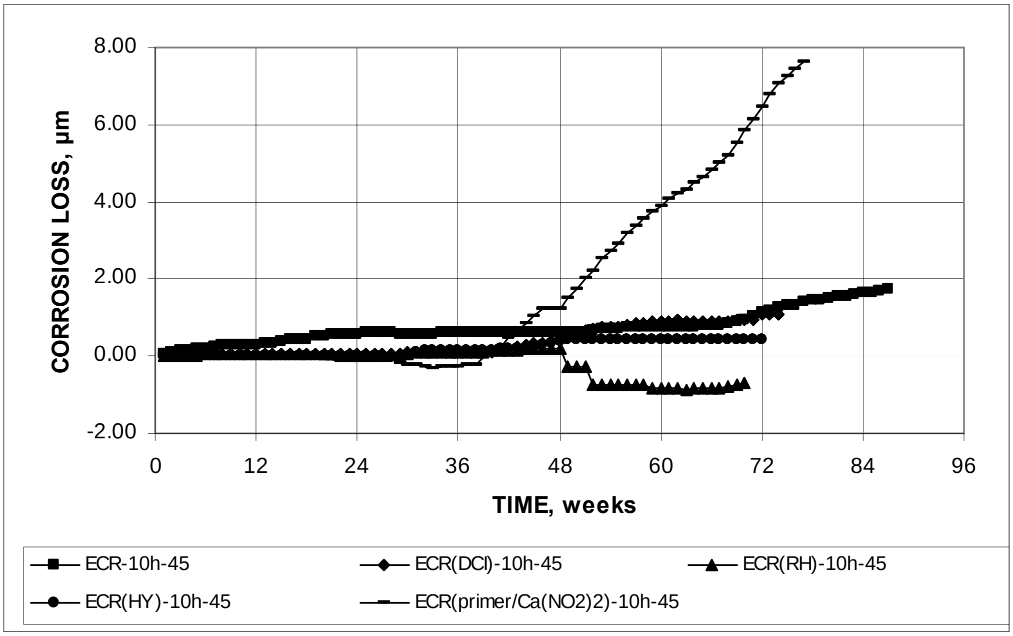

Figure 23b. Graph. Southern Exposure test—corrosion losses based on area exposed at holes through coating for conventional epoxy-coated reinforcement and with inhibitors, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

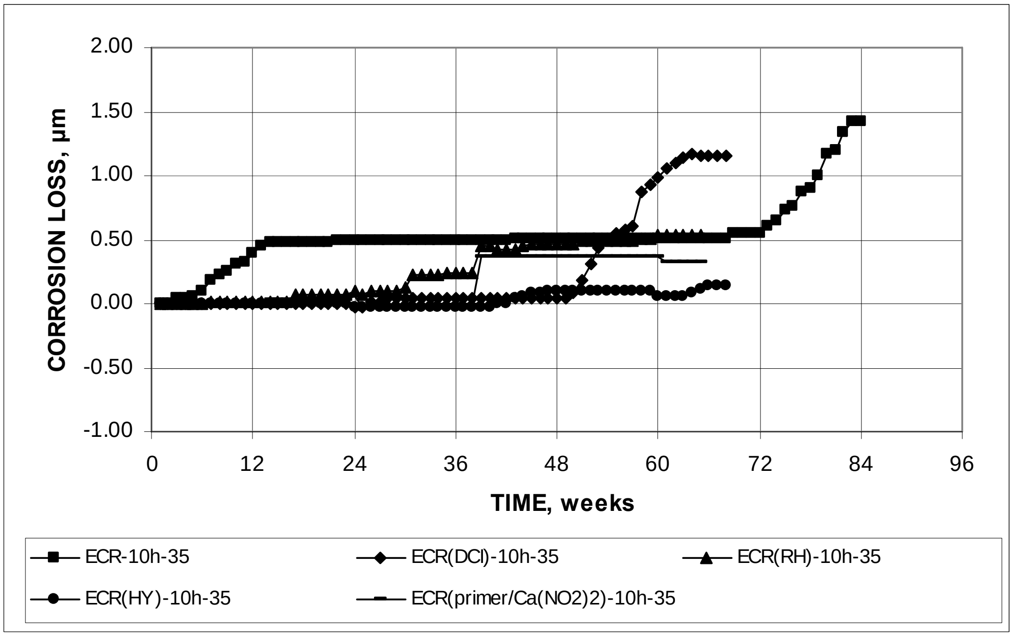

Figure 23c. Graph. Southern Exposure test—corrosion losses based on area exposed at holes through coating for conventional epoxy-coated reinforcement and with inhibitors, *w/c* = 0.35, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

shown in figure 23c (*w/c* = 0.35). The differences observed in this case are likely due to the limited quantity of nitrite, which is available only from the exposed primer where the epoxy is penetrated. For *w/c* = 0.45, this limited quantity of nitrite is consumed in a shorter period of time than for *w/c* =0.35 due to the higher chloride concentration at the bar surface for the higher water-cement ratio concrete. In contrast, the quantity of available nitrite is considerably higher for all of the ECR(DCI) specimens because the calcium nitrite is added to the concrete.

The corrosion potentials exhibited by the top mats in the test specimens are shown in figures 24a, b, and c. They indicate that most of the specimens experience corrosion potentials more negative than –0.350 V with respect to a CSE. The exceptions are ECR-10h-35, ECR(HY)-10h-45, and ECR(primer/$Ca(NO_2)_2$)-10h-35.

Epoxy Coating With Improved Adhesion Cast in Concrete Containing Calcium Nitrite

A limited number of specimens (four holes in the epoxy and concrete with *w/c* = 0.45) were tested for each of the three epoxies with improved adhesion cast in concrete containing calcium nitrite. As observed for the other tests with concrete containing a corrosion inhibitor, the bars with improved adhesion exhibit improved corrosion resistance in the presence of $Ca(NO_2)_2$, as shown in figure 25, and over the test periods shown, exhibit improved corrosion performance compared to conventional ECR in concrete with calcium nitrite. At 56 weeks, all losses are below 1 µm, although the losses for ECR(Valspar) appear to be increasing rapidly. The scatter in the data shown in table 8 indicates that these values do not differ in a statistically meaningful way from each other.

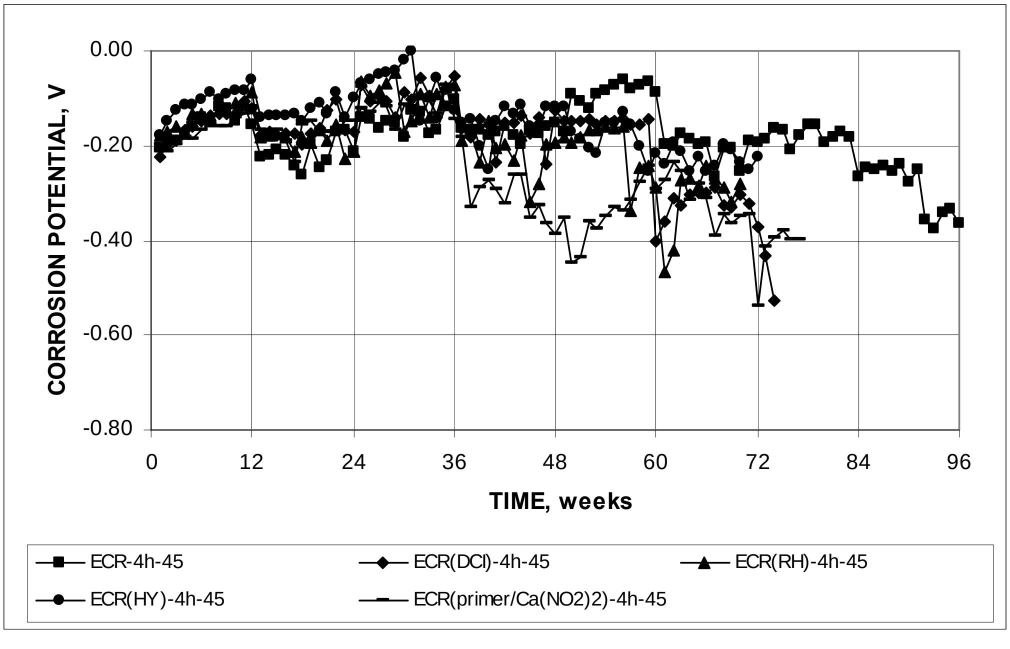

Figure 24a. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

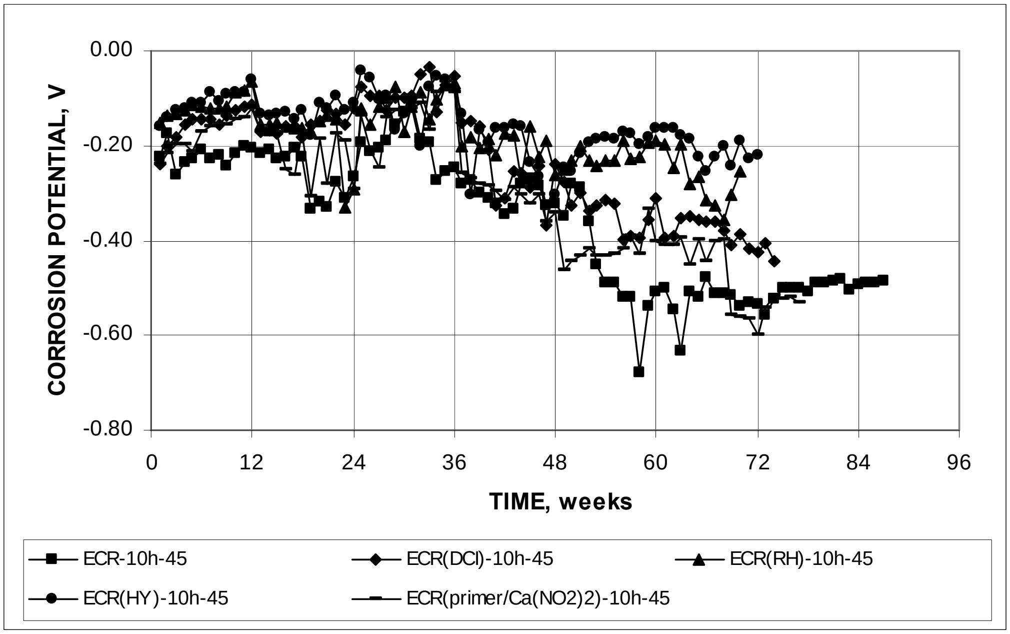

Figure 24b. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

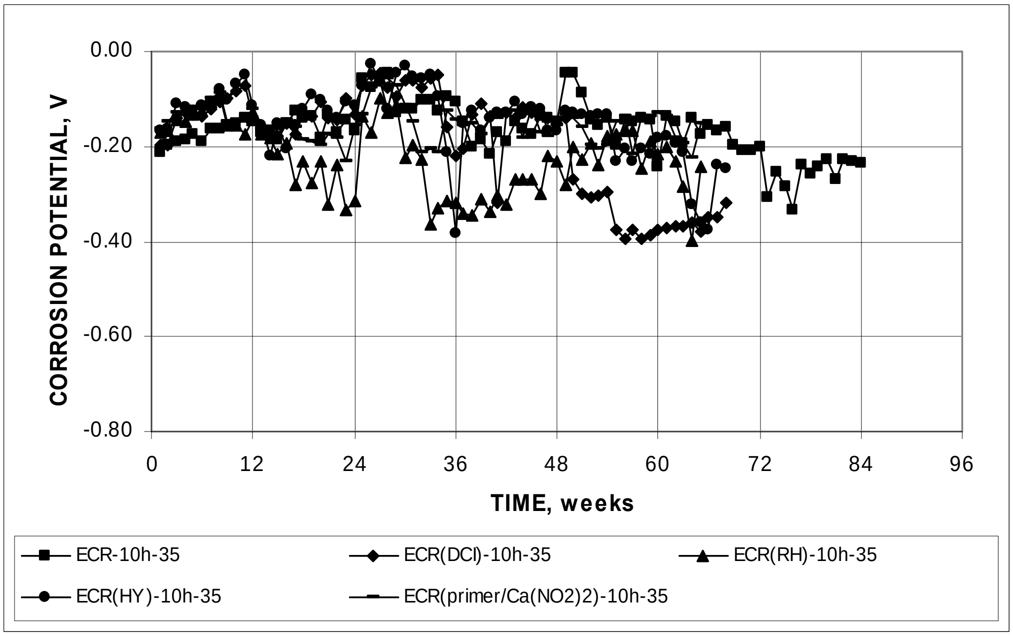

Figure 24c. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.35, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

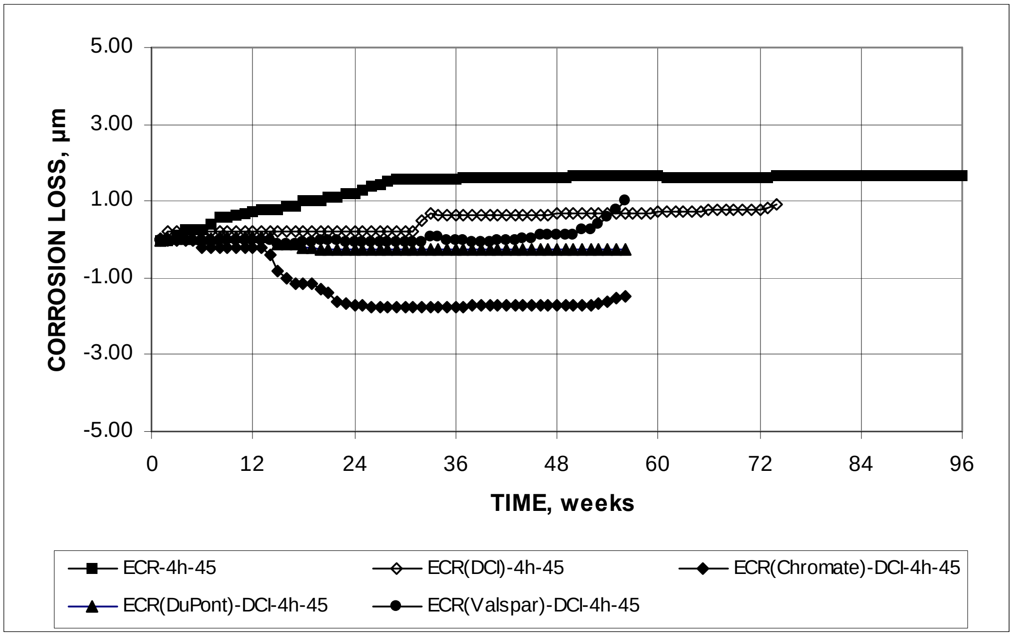

Figure 25. Graph. Southern Exposure test—average corrosion losses based on area exposed at holes through coating for conventional epoxy-coated and epoxy-coated rebar with and without increased adhesion and DCI-S corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four drilled holes.

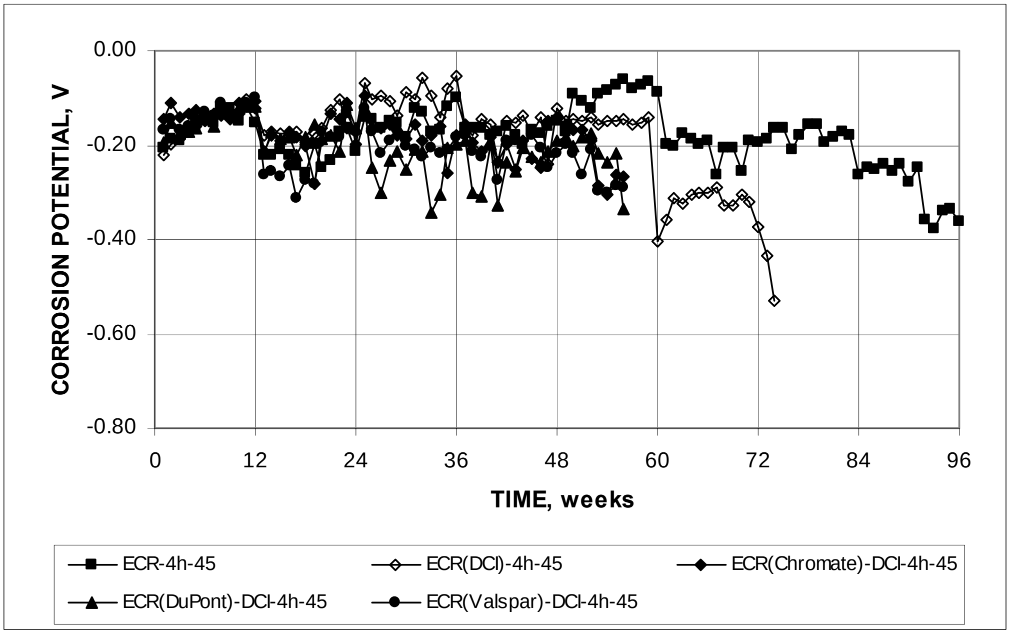

Figure 26. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated reinforcement with and without DCI-S corrosion inhibitor and increased epoxy-coated reinforcement with DCI-S corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

The corrosion potentials for the top mats in these tests are shown in figure 26. The average corrosion potential of the ECR(DCI)-4h-45 specimens drops below –0.350 V at 60 weeks. The potential of the other bars remain above that value to date (56 weeks).

Bars with Multiple Coatings

The corrosion losses for the multiple coated (MC) bars are compared with those for conventional ECR in figures 27a and b for bars with four and 10 holes, respectively. The specimens with the MC bars consistently exhibit greater corrosion losses than those with conventional ECR. The multiple coated bars with both layers penetrated exhibit average corrosion losses on the exposed area of 9.4 μm (for four holes) and 23.7 μm (for 10 holes) at 56 weeks compared to values of 1.45 and 0.74 μm for conventional ECR. The respective values with only the epoxy penetrated are 2.9 and 3.1 μm, as shown in figures 27a and b and table 8b.

The average corrosion potentials for the top and bottom mats are shown in figures 28 and 29 for bars with 4 and 10 holes to the epoxy, respectively. The top mat corrosion potentials (figures 28a and 29a) are similar for the cases in which both layers are penetrated and only the epoxy penetrated, differing most widely during the first 10 to 20 weeks of the test. For the top mats, the values are, in general, more negative than those for conventional ECR, which appears to remain passive (more positive than –0.350 V with respect to a CSE until week 92). The values for the MC bars range between –0.200 and –0.500 V between the beginning of the test and week 10, stabilizing between –0.500 and –0.600 V after week 20. It is not clear at this point if this means that the steel is actively corroding or if the zinc is providing protection. A better evaluation will be possible following the conclusion of the tests to determine if the zinc is intact.

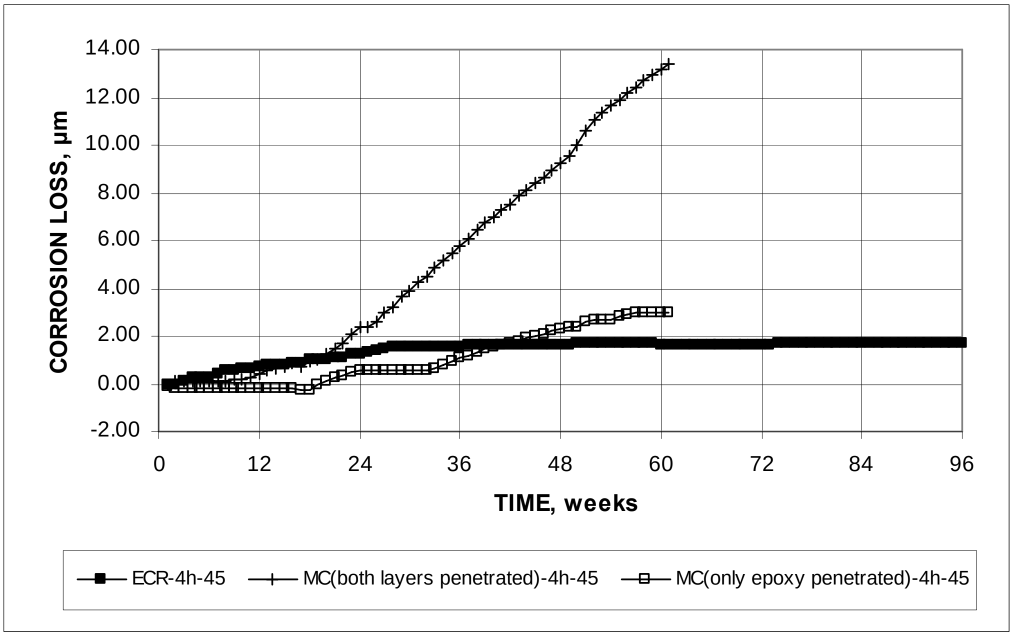

Figure 27a. Graph. Southern Exposure test—corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

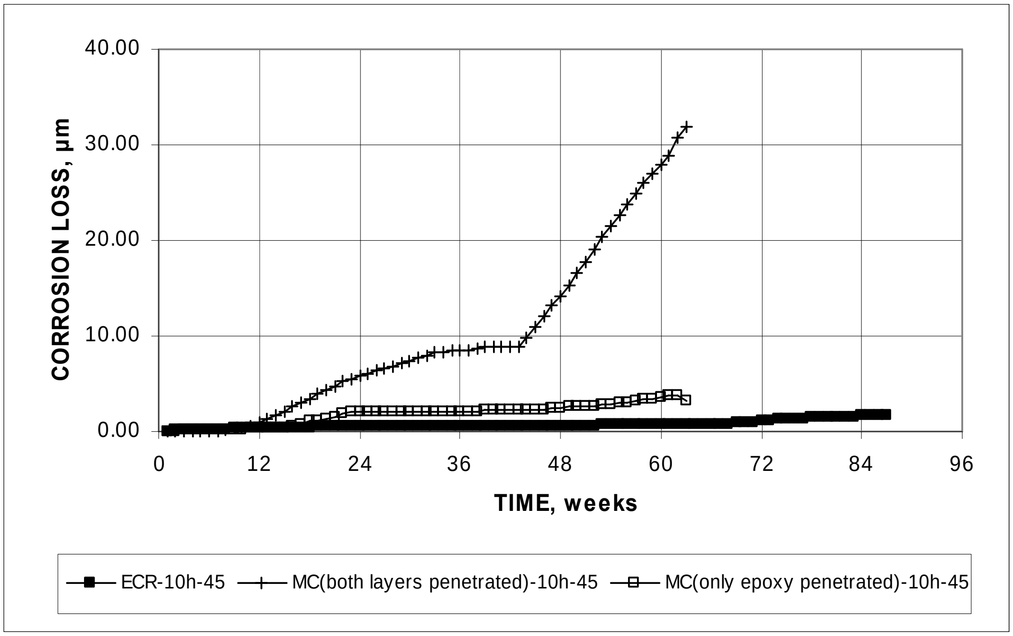

Figure 27b. Graph. Southern Exposure test—corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

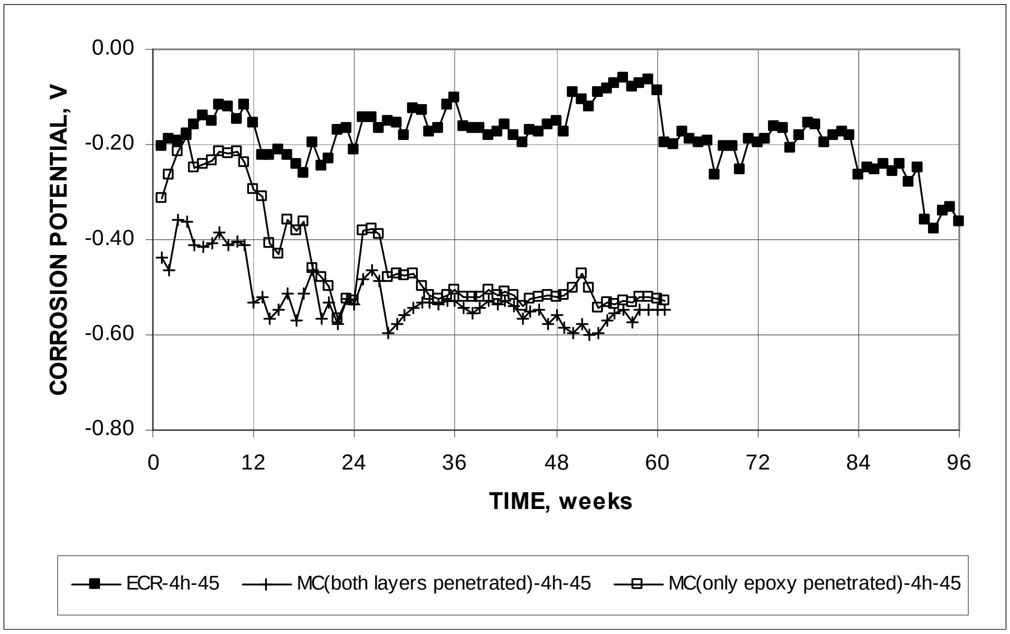

Figure 28a. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

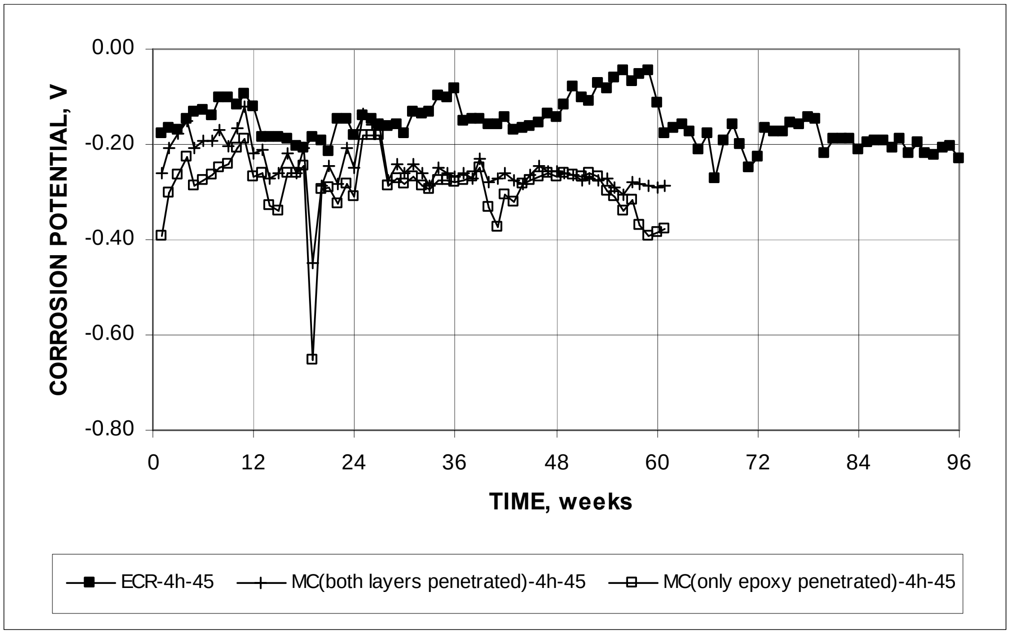

Figure 28b. Graph. Southern Exposure test—corrosion potential, bottom mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

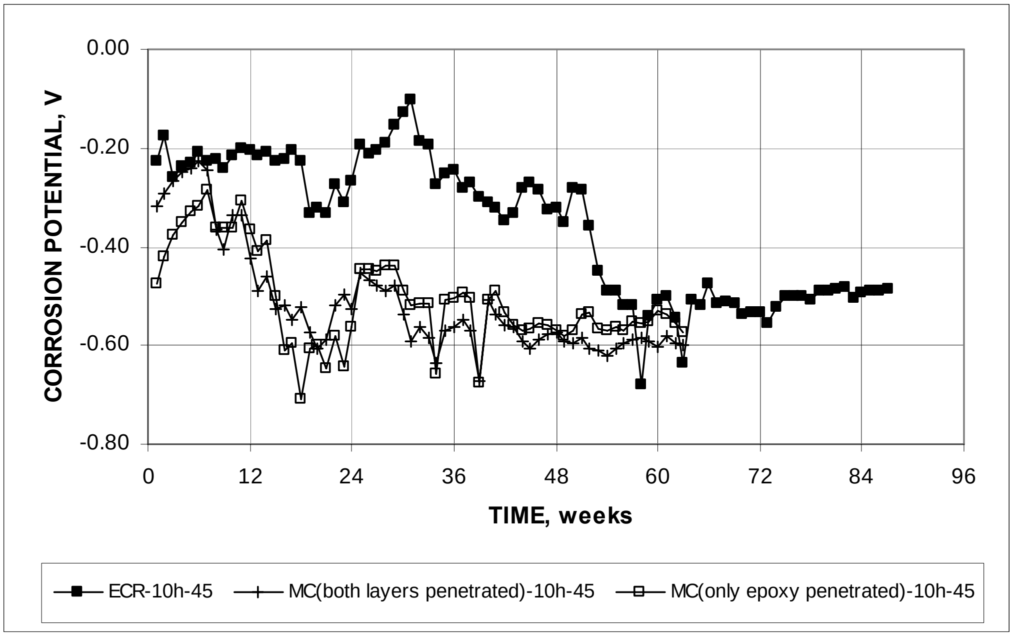

Figure 29a. Graph. Southern Exposure test—corrosion potential, top mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

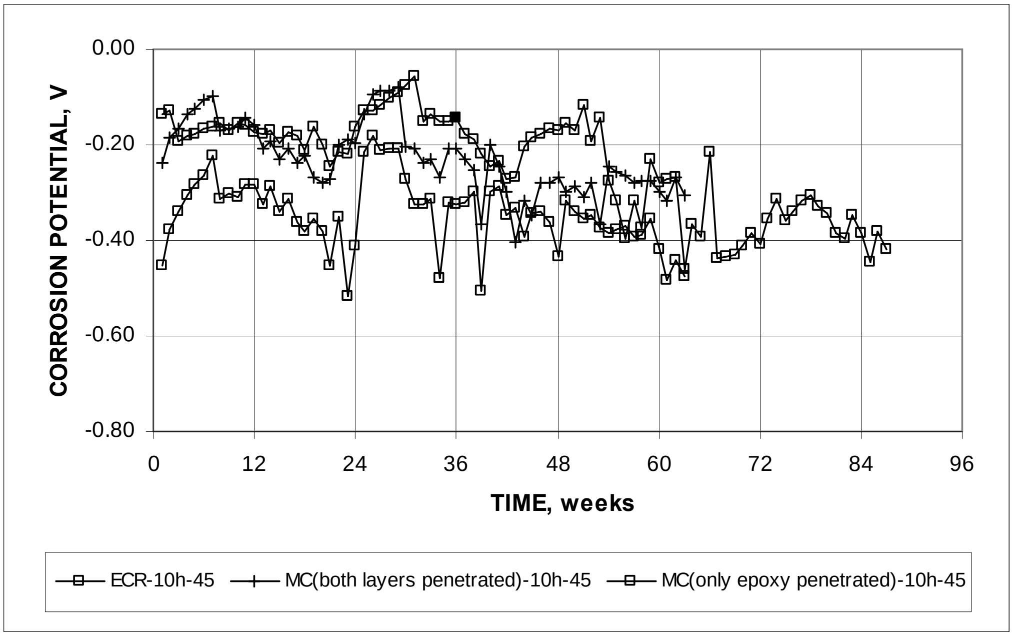

Figure 29b. Graph. Southern Exposure test—corrosion potential, bottom mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

Cracked Beam Tests

The performance of the corrosion protection systems based on the cracked beam test is presented in this section. The losses at 56 weeks based on total area and exposed area on the ECR bars are summarized in tables 9a and b.

Control Tests

The corrosion rates and corrosion losses based on the total area of the reinforcing bars are shown in figures 30 and 31a, respectively, for cracked beam specimens with conventional reinforcing steel and conventional epoxy-coated reinforcement steel. The specimens with epoxy-coated reinforcement have four or 10 holes through the epoxy for concrete with a *w/c* ratio of 0.45 and 10 holes through the epoxy for concrete with a *w/c* ratio of 0.35. Because the simulated crack provides direct access of the 15 percent NaCl solution to the top reinforcing bars, significant corrosion rates, on the order of 10 μm/yr, are observed early in the test for specimens containing conventional steel at both *w/c* ratios. Throughout the test period, the lower *w/c* ratio appears to provide some protection, likely the result of lower concrete permeability, which reduces access of oxygen and moisture to the cathode. At both *w/c* ratios, however, the corrosion rate is significant, with average rates on the order of 6 to 9 μm/yr for the *w/c* = 0.45 specimens and 2 to 5 μm/yr for the *w/c* = 0.35 specimens after week 10. The corrosion rates decrease from the high initial values as a result of the accumulation of corrosion products within the crack. Occasionally, individual specimens exhibit large increases in corrosion rate. This increase is due to the accumulated corrosion products exerting enough stress on the concrete to again open the crack, providing direct access of the NaCl solution to the top reinforcing bar. Overall, figures 30 and 31a indicate some advantage of a lower *w/c* ratio, even for cracked concrete, and a significant reduction in corrosion loss provided by epoxy coating.

Corrosion losses as a function of exposed area are plotted versus time for the epoxy-coated specimens in figure 31b. The bars with 10 holes cast in concrete with a *w/c* of 0.35 (ECR-10h-35) exhibit two to three times the losses of the same bars cast in concrete with a *w/c* ratio of 0.45 (ECR-10h-45). The bars with four holes in concrete with a *w/c* of 0.45 (ECR-4h-45) exhibit corrosion losses between those of the other two specimen types. The results represent the average of six specimens for ECR-4h-45 and three specimens for the others. For the epoxy-coated bars, there does not appear to be an advantage based on a reduced *w/c* ratio. The corrosion losses for the ECR bars based on exposed area are one to four times the average values observed for the uncoated conventional bars.

Table 9a. Corrosion loss at 56 weeks (in µm) for cracked beam specimens based on total area.

Steel Designation[a]	Specimen						Average	Standard Deviation
	1	2	3	4	5	6		
Control								
Conv.-45	11.32	4.98	5.75	9.54	6.97	6.47	7.51	2.43
Conv.-35	6.51	2.66	3.73	-	-	-	4.30	1.99
ECR-4h-45	0.03	0.03	0.01	0.05	0.03	0.01	0.03	0.01
ECR-10h-45	0.025	0.062	0.027	-	-	-	0.038	0.020
ECR-10h-35	0.082	0.086	0.113	-	-	-	0.094	0.017
Epoxies with increased adhesion								
ECR(Chromate)-4h-45	0.055	0.052	0.060	-	-	-	0.056	0.004
ECR(Chromate)-10h-45	0.018	0.085	0.250	-	-	-	0.118	0.047
ECR(DuPont)-4h-45	0.052	0.070	0.028	-	-	-	0.050	0.021
ECR(DuPont)-10h-45	0.073	0.050	0.135	-	-	-	0.086	0.017
ECR(Valspar)-4h-45	0.146	0.056	0.009	-	-	-	0.070	0.070
ECR(Valspar)-10h-45	0.063	0.016	0.162	-	-	-	0.080	0.033
Corrosion inhibitors in concrete								
ECR(DCI)-4h-45	0.013	0.017	0.000	-	-	-	0.010	0.009
ECR(DCI)-10h-45	0.027	0.057	0.029	-	-	-	0.037	0.017
ECR(DCI)-10h-35	0.090	0.059	0.351	-	-	-	0.167	0.160
ECR(RH)-4h-45	0.016	0.090	0.024	-	-	-	0.044	0.041
ECR(RH)-10h-45	0.113	0.097	0.091	-	-	-	0.100	0.012
ECR(RH)-10h-35	0.079	0.183	0.101	-	-	-	0.121	0.055
ECR(HY)-4h-45	0.010	0.011	0.062	-	-	-	0.028	0.030
ECR(HY)-10h-45	0.004	0.087	0.062	-	-	-	0.051	0.043
ECR(HY)-10h-35	0.124	0.110	0.262	-	-	-	0.165	0.084
ECR(primer/Ca(NO2)2)-4h-45	0.008	0.003	0.008	-	-	-	0.006	0.003
ECR(primer/Ca(NO2)2)-10h-45	0.103	0.048	0.063	-	-	-	0.071	0.029
ECR(primer/Ca(NO2)2)-10h-35	0.367	0.137	0.248	-	-	-	0.251	0.115
Bars with multiple coatings								
MC(both layers penetrated)-4h-45	0.190	0.101	0.159	-	-	-	0.150	0.045
MC(both layers penetrated)-10h-45	0.134	0.552	0.129	-	-	-	0.272	0.243
MC(only epoxy penetrated)-4h-45	0.063	0.047	0.236	-	-	-	0.116	0.105
MC(only epoxy penetrated)-10h-45	0.095	0.066	0.204	-	-	-	0.122	0.073

[a] Conv. = conventional steel. ECR = conventional epoxy-coated bars. ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(Rheocrete) = conventional ECR with Rheocrete inhibitor. ECR (Hycrete) = conventional ECR with Hycrete inhibitor.
MC(both layers penetrated) = multiple coating bars with both layers penetrated.
MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.
4h = bar with four holes through epoxy, 10h = bar with 10 holes through epoxy.
35 = concrete with w/c = 0.35, 45 = concrete with w/c = 0.45.

Table 9b. Corrosion loss at 56 weeks (in µm) for cracked beam specimens based on area exposed at holes through coating.

Steel Designation[a]	Specimen						Average	Standard Deviation
	1	2	3	4	5	6		
Control								
Conv.-45	-	-	-	-	-	-	-	-
Conv.-35	-	-	-	-	-	-	-	-
ECR-4h-45	12.5	13.5	6.1	22.5	13.7	5.8	12.4	6.1
ECR-10h-45	4.9	11.9	5.3	-	-	-	7.3	3.9
ECR-10h-35	15.7	16.6	21.6				18.0	3.2
Epoxies with increased adhesion								
ECR(Chromate)-4h-45	26.6	24.8	28.9	-	-	-	26.8	2.0
ECR(Chromate)-10h-45	3.5	16.2	48.0	-	-	-	22.6	9.0
ECR(DuPont)-4h-45	24.9	33.6	13.4	-	-	-	24.0	10.1
ECR(DuPont)-10h-45	14.1	9.6	25.9	-	-	-	16.5	3.2
ECR(Valspar)-4h-45	70.0	26.8	4.3	-	-	-	33.7	33.4
ECR(Valspar)-10h-45	12.1	3.2	31.1	-	-	-	15.4	6.3
Corrosion inhibitors in concrete								
ECR(DCI)-4h-45	6.5	8.2	-0.1	-	-	-	4.9	4.3
ECR(DCI)-10h-45	5.1	10.9	5.6	-	-	-	7.2	3.2
ECR(DCI)-10h-35	17.2	11.4	67.5	-	-	-	32.0	30.8
ECR(RH)-4h-45	7.7	43.3	11.8	-	-	-	20.9	19.5
ECR(RH)-10h-45	21.8	18.7	17.5	-	-	-	19.3	2.2
ECR(RH)-10h-35	15.2	35.2	19.4	-	-	-	23.3	10.6
ECR(HY)-4h-45	4.8	5.3	30.0	-	-	-	13.4	14.4
ECR(HY)-10h-45	0.7	16.8	12.0	-	-	-	9.8	8.2
ECR(HY)-10h-35	23.8	21.1	50.3	-	-	-	31.7	16.1
ECR(primer/Ca(NO2)2)-4h-45	3.8	1.5	3.8	-	-	-	3.1	1.3
ECR(primer/Ca(NO2)2)-10h-45	19.8	9.1	12.0	-	-	-	13.7	5.5
ECR(primer/Ca(NO2)2)-10h-35	70.5	26.4	47.7	-	-	-	48.2	22.0
Bars with multiple coatings								
MC(both layers penetrated)-4h-45	91.4	48.6	76.5	-	-	-	72.2	21.8
MC(both layers penetrated)-10h-45	25.8	106.1	24.7	-	-	-	52.2	46.7
MC(only epoxy penetrated)-4h-45	30.4	22.6	113.5	-	-	-	55.5	50.4
MC(only epoxy penetrated)-10h-45	18.3	12.8	39.3	-	-	-	23.5	14.0

[a] Conv. = conventional steel. ECR = conventional epoxy-coated bars. ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(Rheocrete) = conventional ECR with Rheocrete inhibitor. ECR (Hycrete) = conventional ECR with Hycrete inhibitor.
MC(both layers penetrated) = multiple coating bars with both layers penetrated.
MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.
4h = bar with four holes through epoxy, 10h = bar with 10 holes through epoxy.
35 = concrete with w/c = 0.35, 45 = concrete with w/c = 0.45.

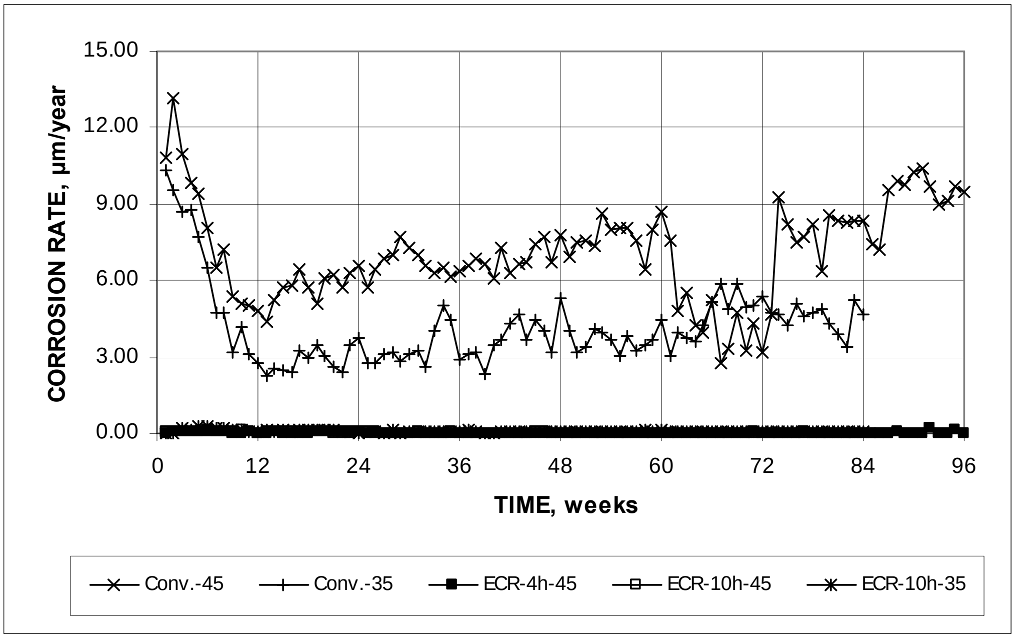

Figure 30. Graph. Cracked beam test—average corrosion rates based on the total area of control specimens for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

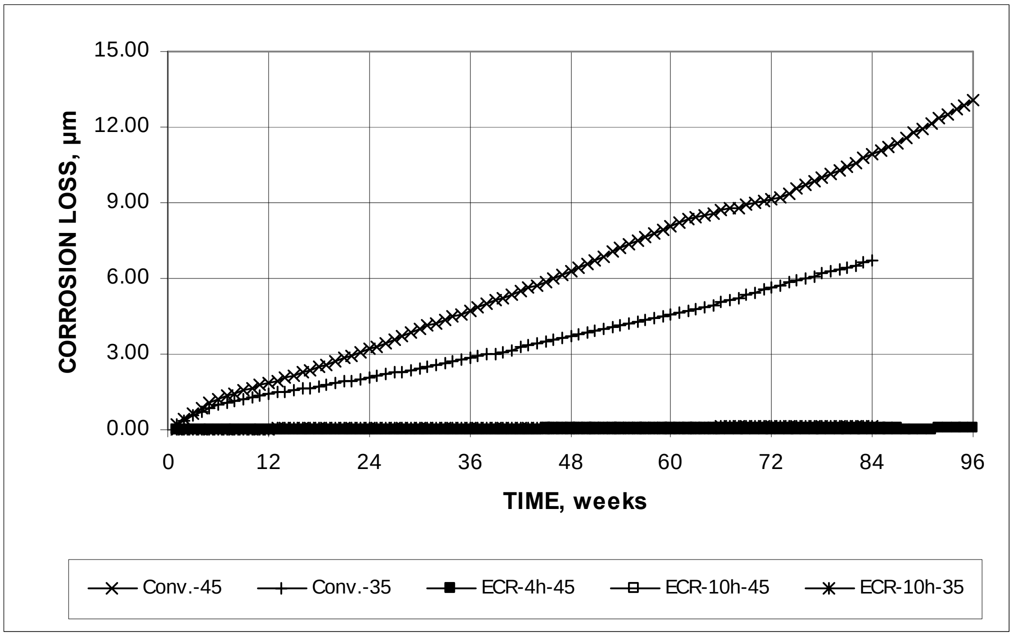

Figure 31a. Graph. Cracked Beam test—average corrosion loss based on total area of control specimens for conventional and epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

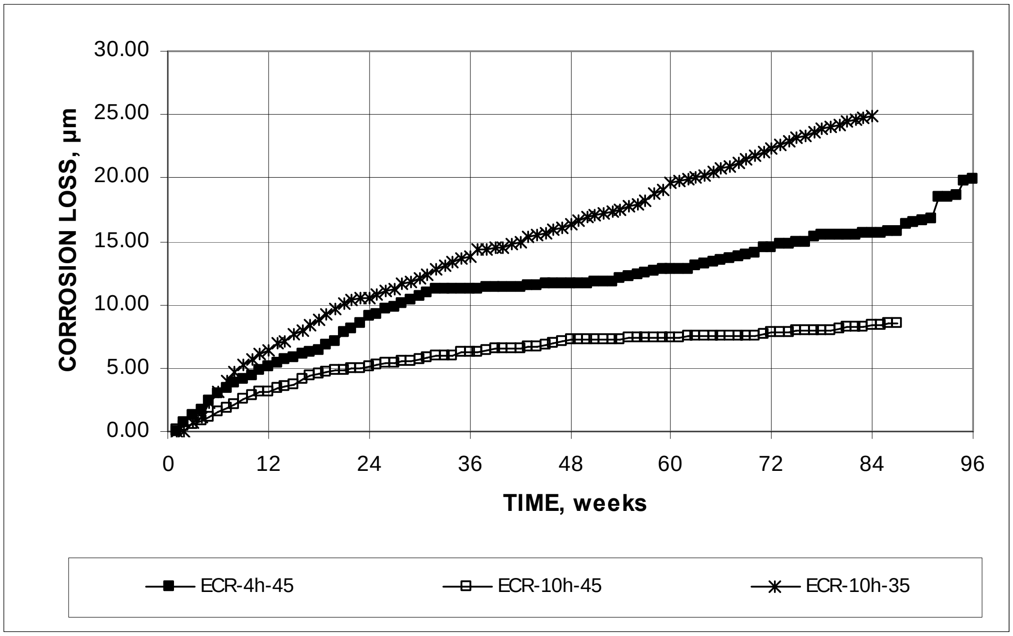

Figure 31b. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

Epoxies With Improved Adhesion

The total corrosion losses based on exposed area for the bars coated with the improved adhesion epoxies are compared with losses for conventional ECR in figures 32a and b for bars with four and 10 holes, respectively. As observed in the Southern Exposure test, these results indicate that the improved adhesion epoxies provide no advantage with respect to conventional ECR under these severe exposure conditions. In fact, the corrosion losses for the bars with the improved adhesion epoxy are at least twice those for the bars with conventional epoxy with both four (24.0 to 33.7 µm versus 12.4 µm) and 10 holes (15.4 to 22.6 µm versus 7.3 µm).

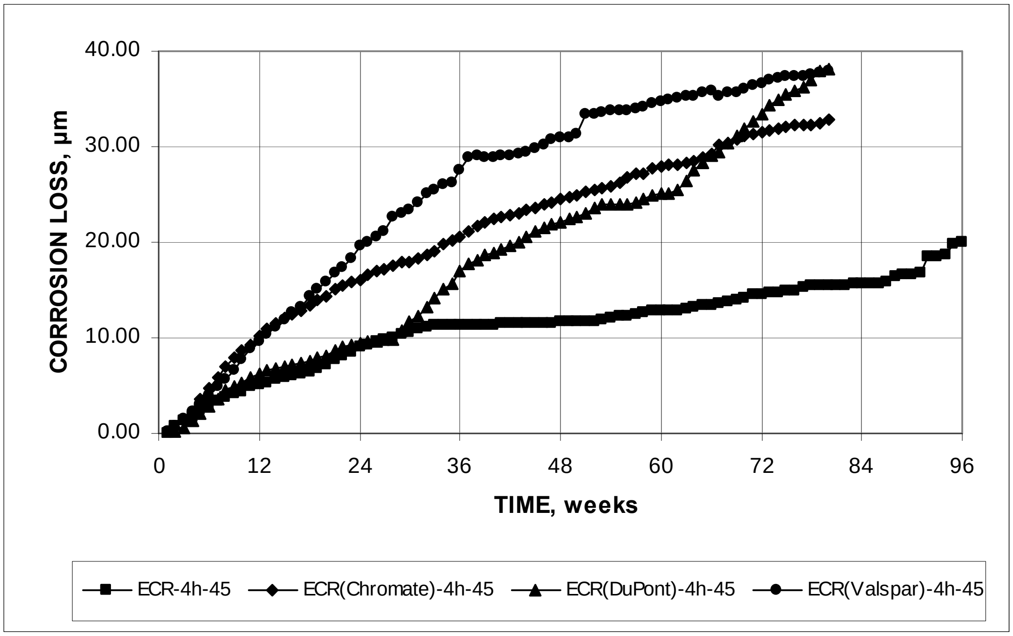

Figure 32a. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and increased adhesion epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

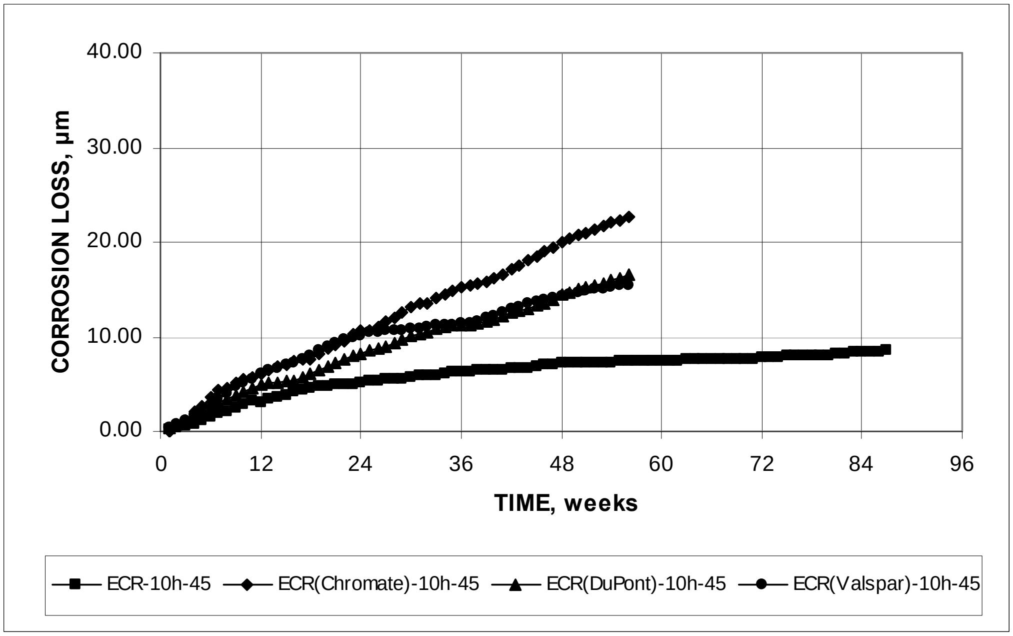

Figure 32b. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and increased adhesion epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

Corrosion losses for cracked beam specimens with conventional ECR cast in concrete with corrosion inhibitors or for ECR bars with the primer containing microencapsulated calcium nitrite are shown in figures 33a, b, and c for specimens with four and 10 holes through the epoxy on bars cast in concrete with *w/c* = 0.45 and bars with 10 holes through the epoxy cast in concrete with *w/c* = 0.35, respectively. Unlike the results for intact concrete in the Southern Exposure tests, the presence of a corrosion inhibitor does not provide an advantage in cracked concrete, where chlorides have direct access to the reinforcing steel. Except for the ECR (DCI)-4h-45 and ECR (primer/$Ca(NO_2)_2$)-4h-45), at 56 weeks, the corrosion losses are the same or greater for the specimens with a corrosion inhibitor in the concrete than for the conventional ECR specimens.

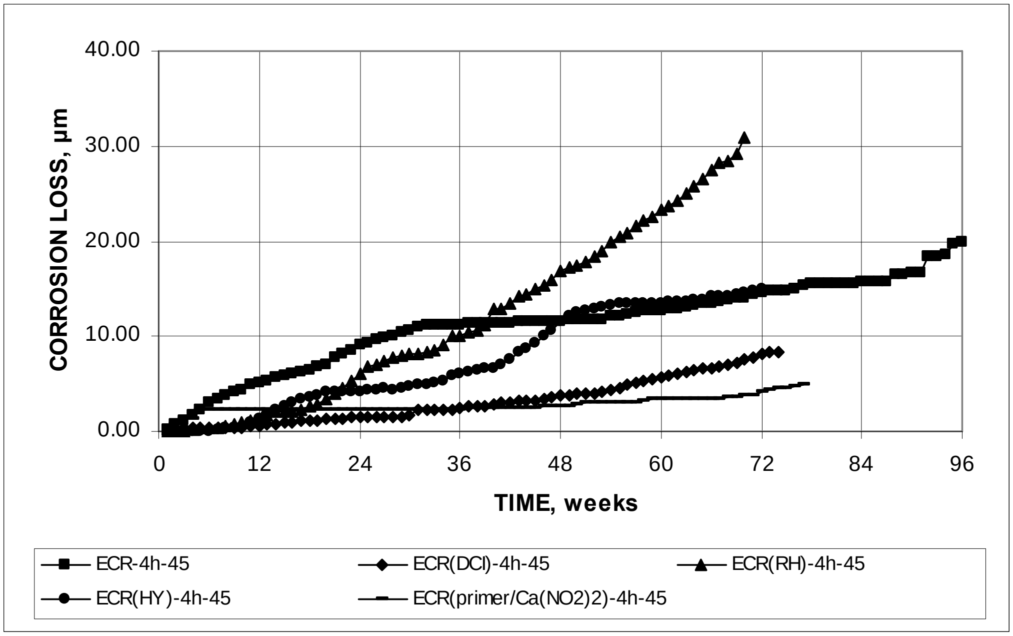

Figure 33a. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

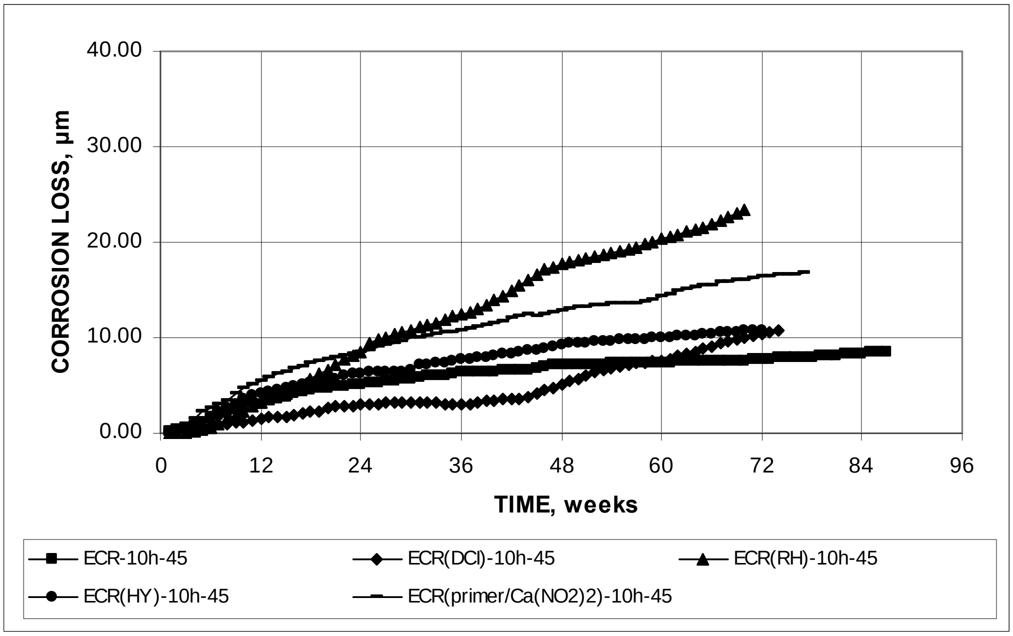

Figure 33b. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

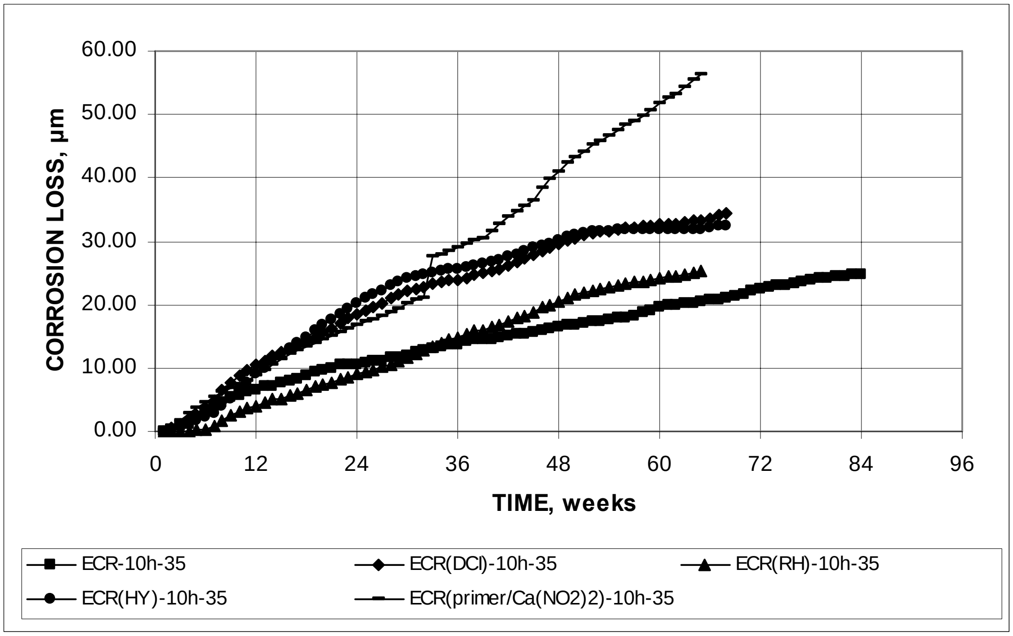

Figure 33c. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated reinforcement with and without corrosion inhibitor, *w/c* = 0.35, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

Bars With Multiple Coatings

The corrosion losses for the bars with multiple coatings are compared with those for conventional ECR in figures 34a and b for bars with 4 and 10 penetrations, respectively. Both figures show that the highest corrosion losses were attained by the MC bars with both layers penetrated followed by those with only the epoxy layer penetrated and, in turn, by conventional ECR. For the specimens with four holes in the epoxy coating, the respective losses based on exposed area are 72, 55, and 12 µm at 56 weeks. For specimens with ten holes, the respective values are 52, 24, and 7 µm at 56 weeks. Corrosion losses less than 50 µm, the thickness of the zinc coating, may indicate that the coating has not been penetrated, but as observed for the rapid macrocell specimens, the values shown here may not reflect the effects of microcell corrosion which could increase the metal loss. Losses greater than 50 µm, may indicate that the coating has been penetrated, but may also be indicative of zinc corrosion under the epoxy layer. Actual behavior will become apparent only after the tests have been completed and the specimens are autopsied. Under any circumstances, it is clear that the total losses for the MC bars exceed those observed for ECR and for most of the combinations of ECR with the other corrosion protection systems evaluated in this study.

The corrosion potentials for these specimens are shown in figures 35 and 36 for bars with four and 10 holes through the epoxy coating, respectively. In both cases, the top bars reach a potential of approximately –0.600 V and sustain that value throughout most of the test period, while the corrosion potential of the bottom bars remains between –0.200 and –0.400 V for most of the test (generally more positive than observed for the SE tests). The similarity in the potentials of the top bars seems to indicate that the zinc layer is consumed relatively rapidly and that the performance of the exposed regions of the MC bars is being dominated by exposed steel.

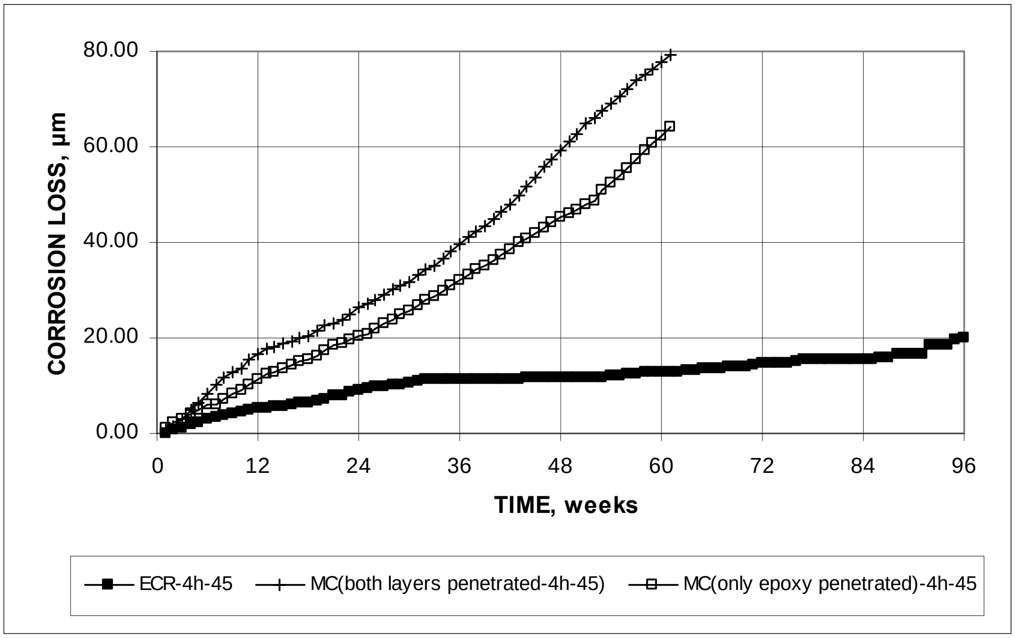

Figure 34a. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

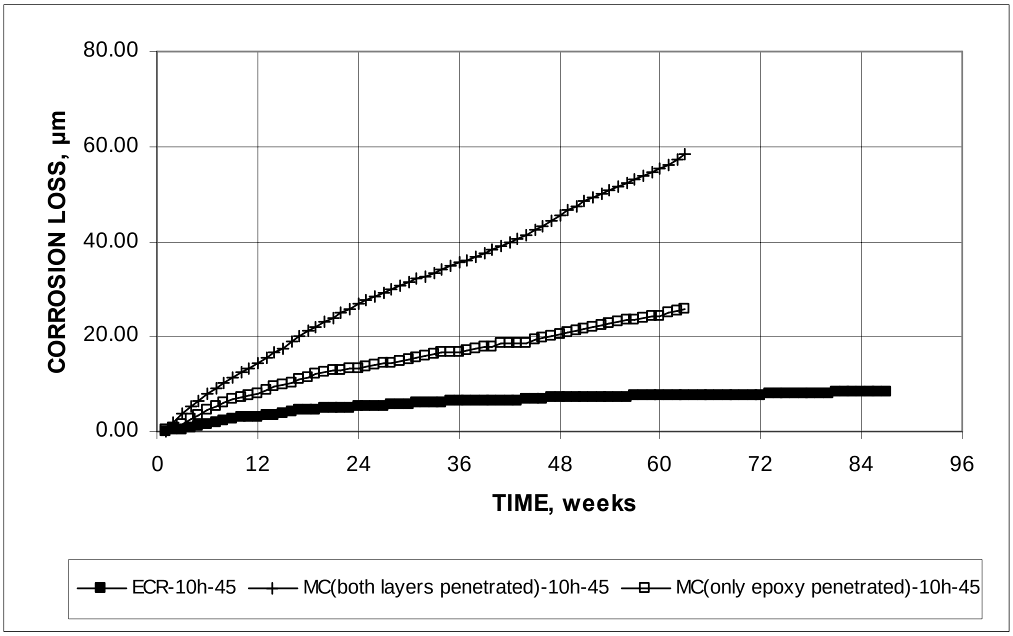

Figure 34b. Graph. Cracked Beam test—average corrosion loss based on area exposed at holes through coating for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

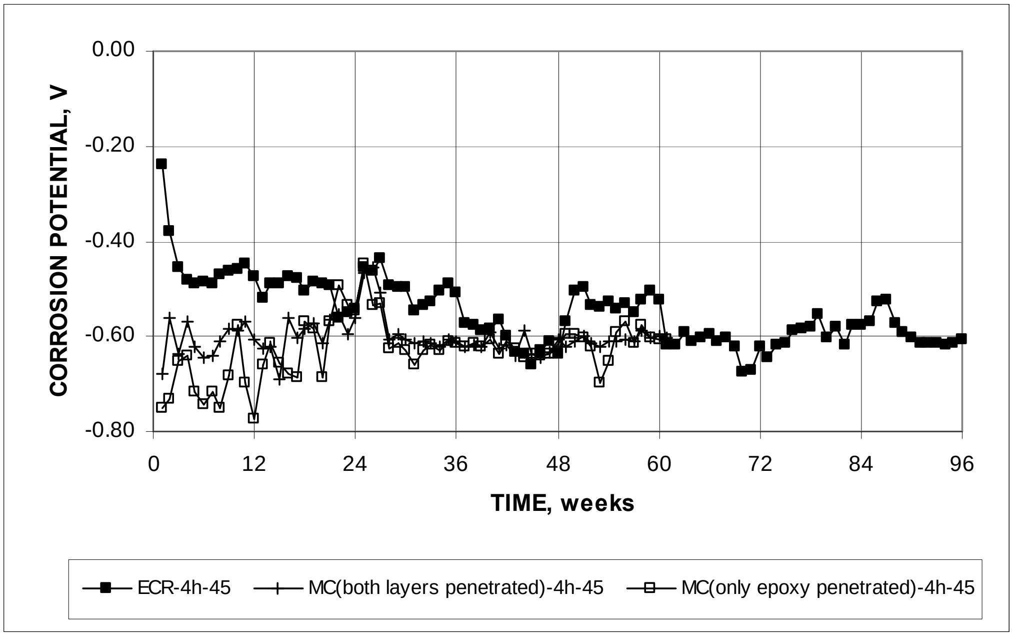

Figure 35a. Graph. Cracked beam test—corrosion potential, top mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

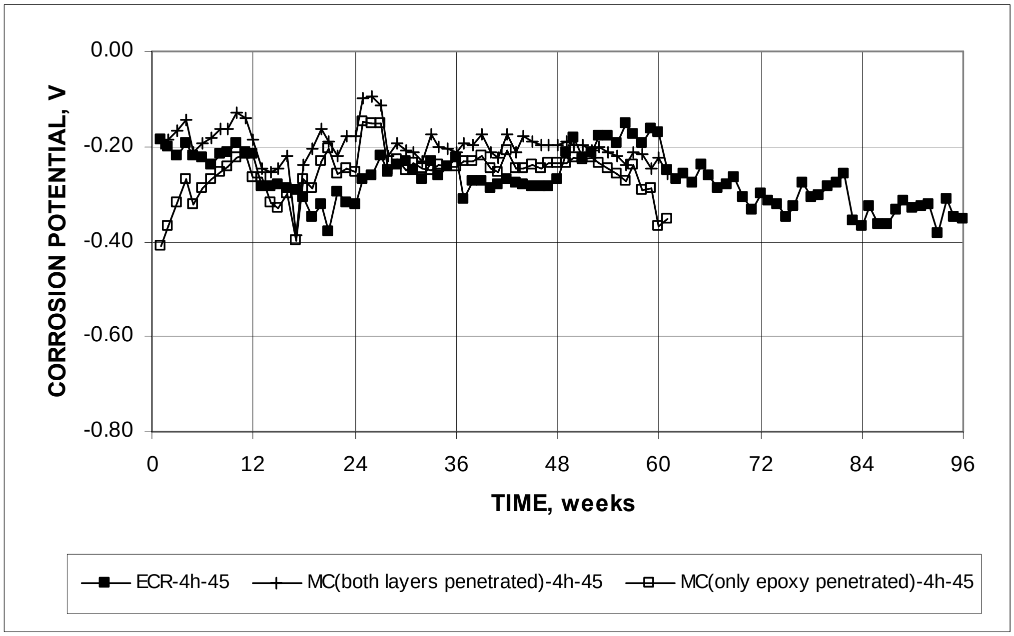

Figure 35b. Graph. Cracked beam test—corrosion potential, bottom mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four holes.

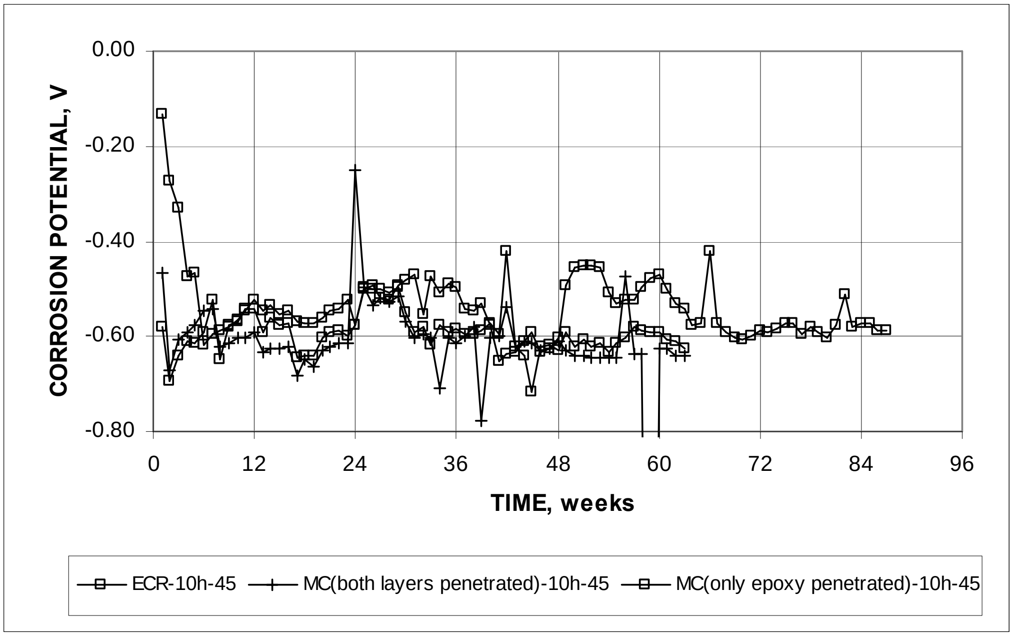

Figure 36a. Graph. Cracked beam test—corrosion potential, top mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

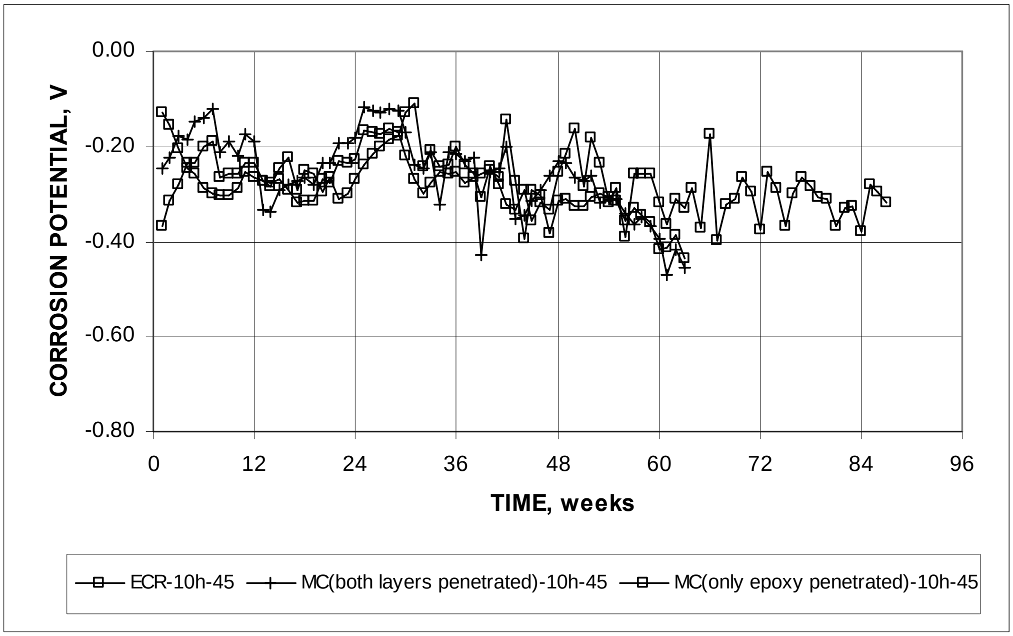

Figure 36b. Graph. Cracked beam test—corrosion potential, bottom mat, for conventional epoxy-coated and multiple-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain 10 holes.

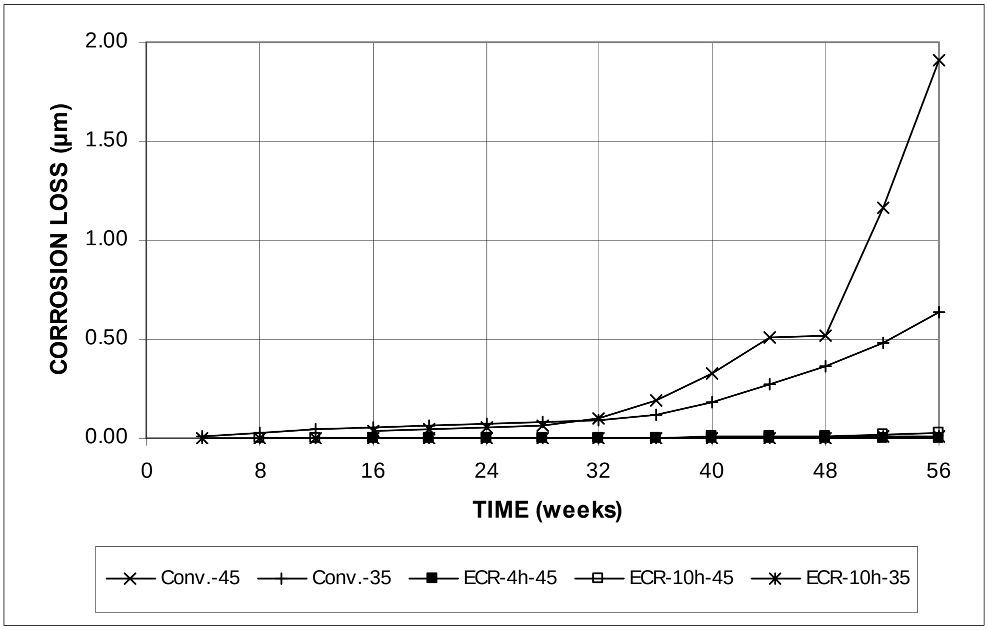

Figure 37a. Graph. Linear polarization test results for Southern Exposure specimens—average corrosion loss based on total area for conventional reinforcement and conventional epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

LINEAR POLARIZATION RESISTANCE TESTS

Linear polarization resistance tests provide values of microcell corrosion rates, usually expressed as microcell corrosion current density. For ease of comparison with the macrocell results presented earlier in this chapter, the corrosion current densities are converted to corrosion rates using Eq. (1) or (2) and integrated to obtain corrosion losses. As an example, the microcell corrosion losses for conventional steel (Conv.-45 and Conv.-35) and conventional epoxy-coated reinforcement (ECR-4h-45, ECR-10h-45, and ECR-10h-35) in the Southern Exposure tests are shown in figure 37a and b.

The macrocell losses at 56 weeks for the Southern Exposure and cracked beam tests are summarized in table 10 based on both total and exposed area. For comparison, the average macrocell losses at 56 weeks presented in tables 8 and 9 are shown side by side with the microcell losses. As would be expected, the losses based on the linear polarization results are, in most cases, higher than those obtained based on macrocell current. This is true in 23 out of 30 cases for the Southern Exposure test and in 26 out of 27 cases for the cracked beam test. As observed for macrocell losses, corrosion losses are noticeably higher for the cracked beam test than for the Southern Exposure test.

The combined results for microcell and macrocell corrosion are shown for the Southern Exposure tests in figures 38a and b (*w/c* = 0.45) and for the cracked beam tests in figure 39 (*w/c* = 0.45 and 0.35). Losses for conventional steel are based on total area, while the losses for

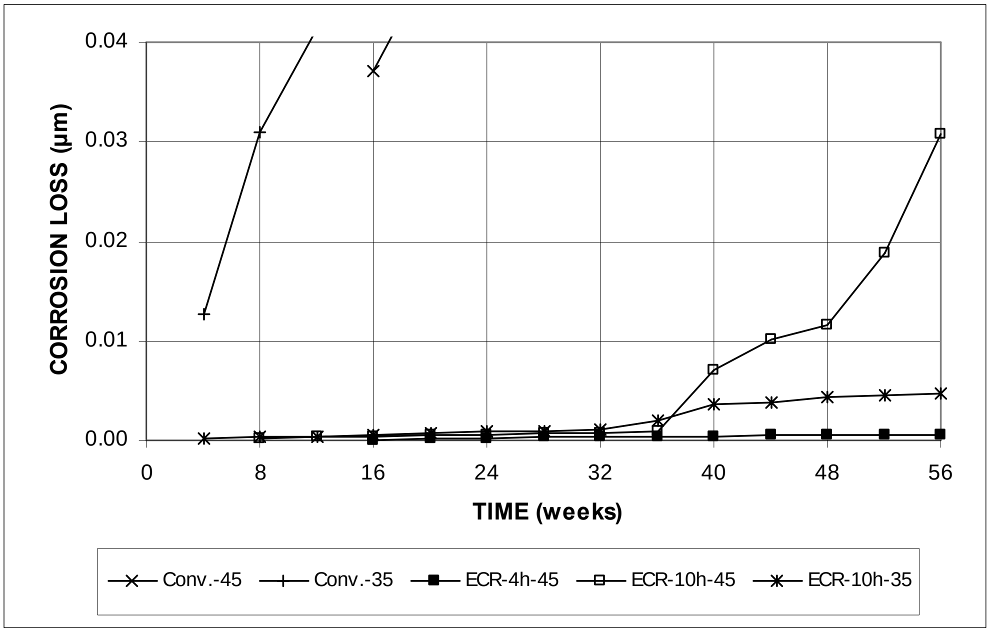

Figure 37b. Graph. Linear polarization test results for Southern Exposure specimens—average corrosion loss based on total area for conventional reinforcement and conventional epoxy-coated reinforcement, *w/c* = 0.35 or 0.45, ponded with 15 percent NaCl solution. Bars with coatings contain four or 10 holes.

epoxy-coated reinforcement are based on the area exposed at holes through the coating and represent the average of specimens with four and 10 holes. The figures demonstrate that the corrosion losses for conventional reinforcement based on total area are of the same order of magnitude as those for ECR based on exposed area, but as discussed for the bare bar rapid macrocell tests, the average corrosion losses based on total area for uncoated steel bars are generally lower than those based on exposed area for epoxy-coated bars. figures 38a and b and 39 also demonstrate that, overall, the relative performance of the systems is similar whether based on the microcell or macrocell corrosion current.

Total losses are highest for the multiple coated (MC) bars and significantly lower for the other systems in intact concrete, as shown in figures 38a and b. These figures do not show the results at 56 weeks for the Southern Exposure specimens with concrete with a *w/c* ratio of 0.35; if plotted, those results would appear in a tight grouping with macrocell losses between 0.0 and 0.6 µm and microcell losses between 0.2 and 2.2 µm.

Figures 38 and 39 illustrate the relative performance of the systems – with the more effective systems exhibiting data points closer to the origin. Based on corrosion losses, all of the systems under test appear to perform well in intact concrete, with the exception of the MC bars. The same statement cannot be made based on losses in cracked concrete, as demonstrated by wide scatter in both microcell and macrocell corrosion exhibited by the systems, as shown in figure 39. For the MC bars, a final judgment must await visual inspection of the bars at the conclusion of the 96-week test period. As will be discussed in chapter 4, however, the tests demonstrate that most of the systems under evaluation will serve well in practice.

Table 10. Microcell and macrocell corrosion loss at 56 weeks (in µm) for Southern Exposure and cracked beam specimens based on total area and area exposed at holes through coating.

Steel Designation[a]	Based on Total Area				Based on Exposed Area			
	Southern Exposure Test		Cracked Beam Test		Southern Exposure Test		Cracked Beam Test	
	Microcell	Macrocell	Microcell	Macrocell	Microcell	Macrocell	Microcell	Macrocell
Control								
Conv.-45	1.913	0.478	47.667	7.507	-	-	-	-
Conv.-35	0.641	0.112	57.520	4.298	-	-	-	-
ECR-4h-45	0.001	0.004	0.128	0.026	0.254	1.689	61.403	12.353
ECR-10h-45	0.031	0.004	0.209	0.038	5.906	0.737	40.105	7.337
ECR-10h-35	0.005	0.003	0.331	0.094	0.900	0.507	63.662	17.967
Corrosion inhibitors in concrete								
ECR(DCI)-4h-45	0.001	0.001	0.361	0.010	0.342	0.692	173.610	4.857
ECR(DCI)-10h-45	0.108	0.004	0.410	0.037	20.799	0.812	78.787	7.178
ECR(DCI)-10h-35	0.001	0.003	1.165	0.167	0.246	0.577	223.764	32.013
ECR(RH)-4h-45	0.001	0.000	0.662	0.044	0.618	-0.164	317.825	20.904
ECR(RH)-10h-45	0.009	-0.004	0.628	0.100	1.689	-0.732	120.717	19.300
ECR(RH)-10h-35	0.011	0.003	0.309	0.121	2.176	0.488	59.412	23.278
ECR(HY)-4h-45	0.002	-0.001	0.145	0.028	1.165	-0.270	69.472	13.373
ECR(HY)-10h-45	0.007	0.002	0.597	0.051	1.272	0.436	114.767	9.805
ECR(HY)-10h-35	0.003	0.001	0.471	0.165	0.603	0.103	90.554	31.731
ECR(primer/$Ca(NO_2)_2$)-4h-45	0.003	0.003	0.449	0.006	1.374	1.631	215.849	3.050
ECR(primer/$Ca(NO_2)_2$)-10h-45	0.003	0.017	0.263	0.071	0.646	3.195	50.609	13.664
ECR(primer/$Ca(NO_2)_2$)-10h-35	0.006	0.002	0.790	0.251	1.232	0.361	151.790	48.188
Bars with multiple coatings								
MC(both layers penetrated)-4h-45	0.246	0.025	0.725	0.150	118.102	12.186	348.036	72.168
MC(both layers penetrated)-10h-45	0.659	0.188	1.255	0.272	126.516	36.142	240.975	52.213
MC(only epoxy penetrated)-4h-45	0.268	0.006	1.381	0.116	128.664	2.926	663.229	55.499
MC(only epoxy penetrated)-10h-45	0.162	0.016	0.454	0.122	31.100	3.093	87.157	23.456
Epoxies with increased adhesion								
ECR(Chromate)-4h-45	0.006	0.004	0.759	0.056	3.065	2.041	364.657	26.770
ECR(Chromate)-10h-45	0.022	0.024	0.081	0.118	4.178	4.617	15.481	22.583
ECR(DuPont)-4h-45	0.021	0.002	0.209	0.050	9.862	1.021	100.353	24.001
ECR(DuPont)-10h-45	0.034	0.007	0.417	0.086	6.480	1.351	80.140	16.522
ECR(Valspar)-4h-45	0.021	0.006	0.936	0.070	10.100	2.956	449.485	33.714
ECR(Valspar)-10h-45	0.022	0.008	0.628	0.080	4.230	1.516	120.638	15.443
Epoxies with increased adhesion plus Ca(NO2)2 in concrete								
ECR(Chromate)-DCI-4h-45	0.013	-0.003			2.413	-1.478		
ECR(DuPont)-DCI-4h-45	0.001	-0.001			0.223	-0.246		
ECR(Valspar)-DCI-4h-45	0.002	0.002			0.387	1.021		

[a] Conv. = conventional steel. ECR = conventional epoxy-coated bars. ECR(Chromate) = ECR with chromate pretreatment. ECR(DuPont) = high adhesion DuPont bars. ECR(Valspar) = high adhesion. Valspar bars. ECR(DCI) = conventional ECR with DCI inhibitor. ECR(Rheocrete) = conventional ECR with Rheocrete inhibitor. ECR (Hycrete) = conventional ECR with Hycrete inhibitor.

MC(both layers penetrated) = multiple coating bars with both layers penetrated.

MC(only epoxy penetrated) = multiple coating bars with only epoxy penetrated.

4h = bar with four holes through epoxy, 10h = bar with 10 holes through epoxy.

35 = concrete with w/c = 0.35, 45 = concrete with w/c = 0.45.

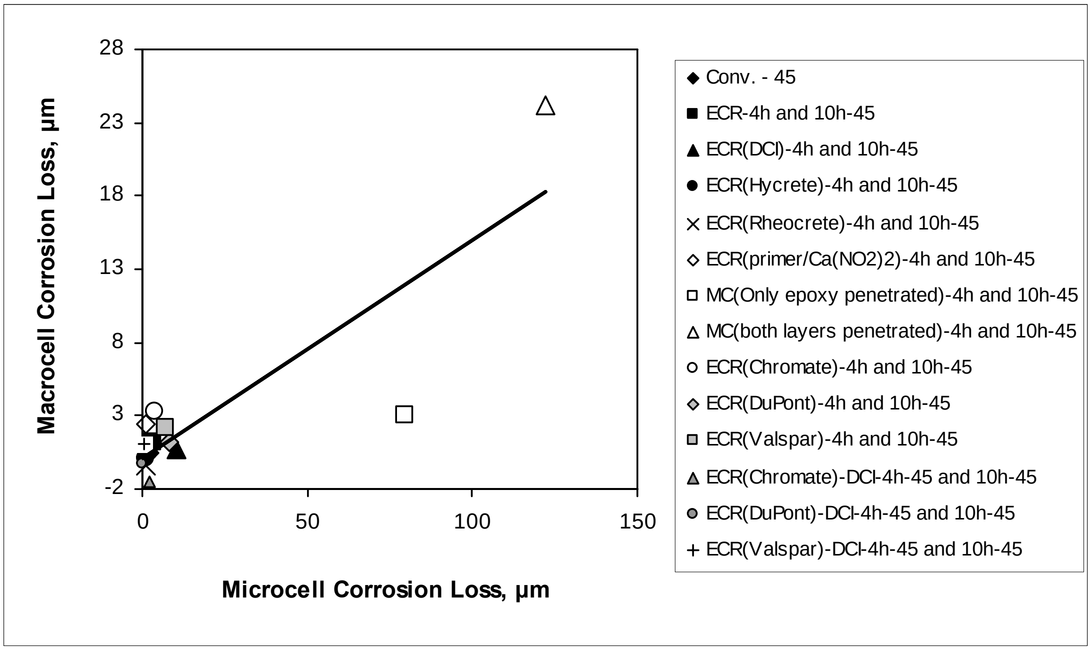

Figure 38a. Graph. Southern Exposure specimens—microcell versus macrocell corrosion loss based on total area for conventional reinforcement and area exposed at holes through coating for epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution. Results for epoxy-coated bar specimens based on average results for bars with coatings containing four and 10 holes.

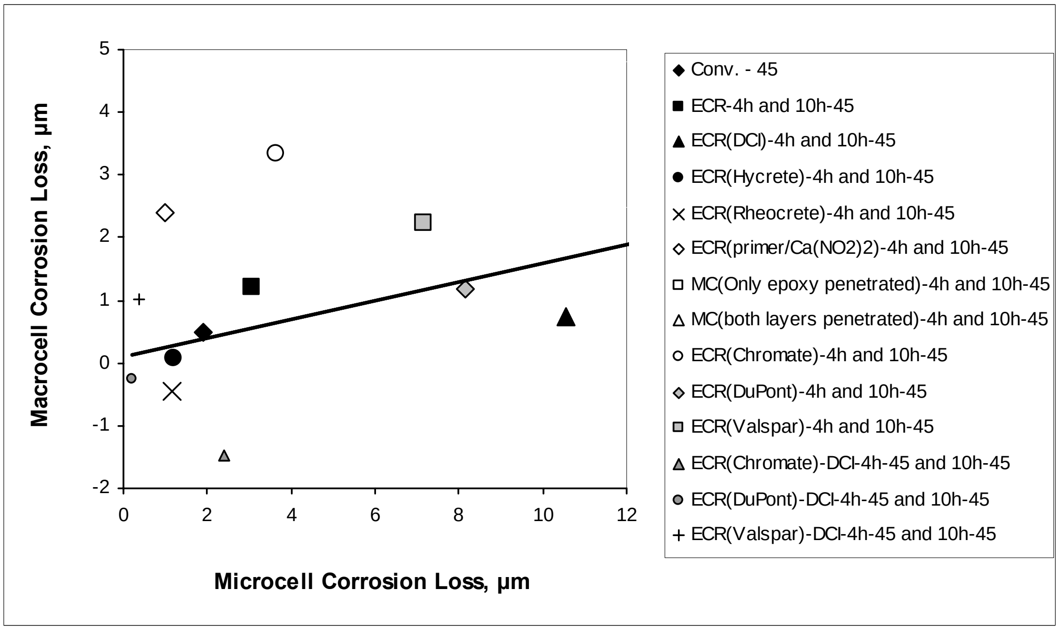

Figure 38b. Graph. Southern Exposure specimens—microcell versus macrocell corrosion loss based on total area for conventional reinforcement and area exposed at holes through coating for epoxy-coated reinforcement, *w/c* = 0.45, ponded with 15 percent NaCl solution.

Results for epoxy-coated bar specimens based on average results for bars with coatings containing four and 10 holes.

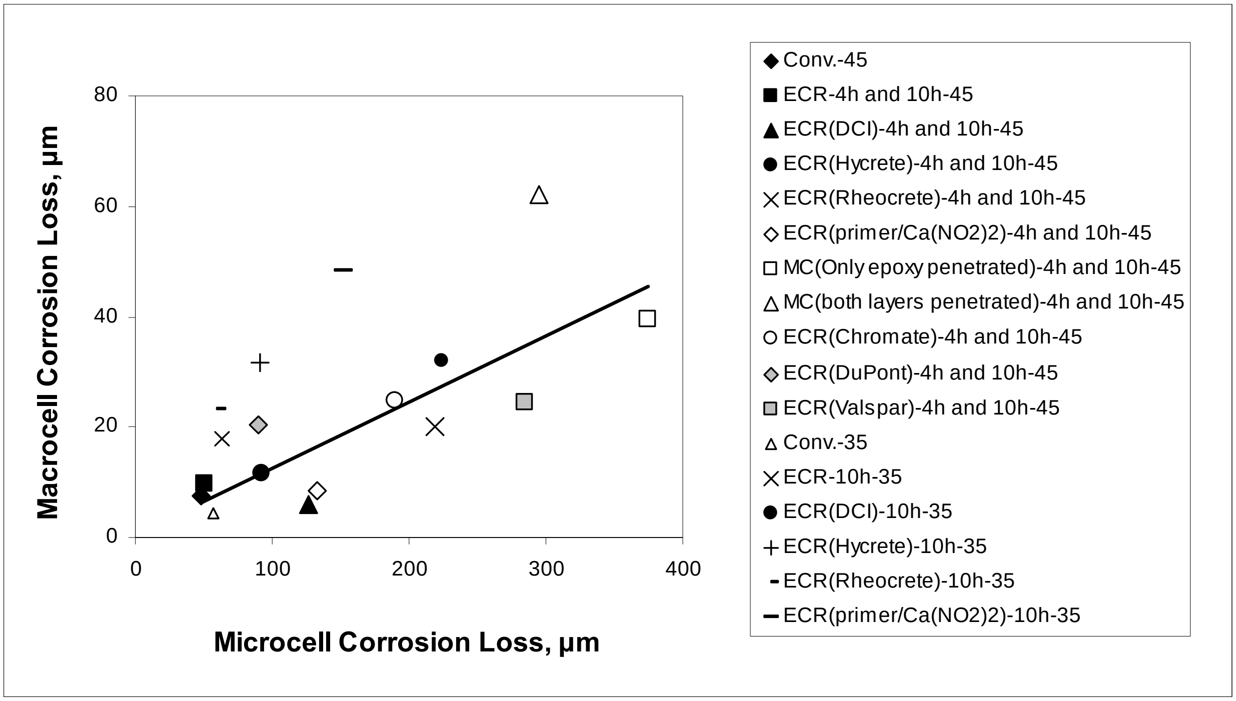

Figure 39. Graph. Cracked beam specimens—microcell versus macrocell corrosion loss based on total area for conventional reinforcement and area exposed at holes through coating for epoxy-coated reinforcement, *w/c* = 0.45 or 0.35, ponded with 15 percent NaCl solution. Results for epoxy-coated bar specimens with w/c = 0.45 based on average results for bars with coatings containing four and 10 holes.

CHAPTER 4. EVALUATION

The results presented in this report represent the initial findings of the study. More detailed information will be available at the conclusion of the 96-week test period for the bench-scale tests, especially the chloride content and the degree of corrosion on the bars at the conclusion of the tests, and with the incorporation of the results of on-going ASTM G 109(29) and field tests. The results obtained to date, however, provide a useful comparison of the relative performance of the systems and of the overall performance of the epoxy-coated reinforcement.

As illustrated in figures 38a, 38b, and 39, the corrosion losses on damaged (exposed) areas on epoxy-coated reinforcement are, for the most part, higher but of a similar magnitude to the average corrosion losses exhibited by uncoated conventional reinforcing steel. As discussed earlier, in reference to the bare bar macrocell test results, the relatively higher losses on the damaged areas may result because the losses recorded for uncoated conventional steel represent values that are averaged over the full contact surface, all of which may not be corroding. The superior performance (over the 15-week test period) by the mortar-wrapped macrocell specimens containing epoxy-coated reinforcement bodes well for epoxy-coated bars in the field. The tests indicate that due to the natural variation in chloride concentration within concrete, all damaged areas on epoxy-coated reinforcement will not come in contact with high chloride contents at the same time. If uncoated steel were used in its place, however, a portion of the unprotected steel would be expected to undergo corrosion.

In terms of overall performance, the use of concrete with a lower water-cement ratio provides an advantage for both uncoated and coated reinforcement in uncracked concrete due to its role in delaying penetration of chlorides. The same advantage does not appear to be available in all cases for cracked concrete; in the current study, concrete with a lower water-cement ratio resulted in a lower corrosion rate for uncoated steel, but not for damaged epoxy-coated reinforcement.

As has been observed in other studies,(11) increasing the adhesion between the epoxy coating and the reinforcing steel does not appear to provide an advantage over conventional ECR.

In uncracked concrete, the use of corrosion inhibitors and the use of the primer coating containing calcium nitrite appears to provide added protection for damaged epoxy-coated reinforcement, and in general, the lower the water-cement ratio, the better the protection. The epoxy-coated reinforcement with the primer coating appears to be the most sensitive of the systems incorporating a corrosion inhibitor to the water-cement ratio, performing better when used in concrete with the lower water-cement ratio. The advantages of corrosion inhibitors, however, were lost to varying degrees in cracked concrete, that is, in cases in which chlorides had direct access to the reinforcing steel. To date, conventional epoxy-coated reinforcement (ECR) has performed better than the other systems in cracked concrete.

The test results for the multiple coated (MC) bars indicate that, in cases in which either both layers are penetrated or just the epoxy is penetrated, the zinc coating provides some protection to the underlying steel. This protection, however, is obtained through the sacrificial loss of zinc.

Key points, as yet unknown, but which, ideally, will be determined prior to the conclusion of this study, are the corrosion threshold of the zinc coating relative to that of exposed steel and the ability of the 50-µm (2-mil) coating to substantially delay corrosion loss of the underlying steel reinforcement.

It is useful to consider one other aspect of the corrosion of reinforcing steel when assessing the relative performance of the different systems that are under study. For conventional steel, an average total corrosion loss of 25 µm (0.001 inch) results in the production of a volume of corrosion products that is adequate to cause concrete to crack.(35) This level of corrosion will be attained in 10 to 15 years at the corrosion rates shown in figure 18. In contrast, work by Torres-Acosta and Sagües(36) and analysis by Ji et al.(21) and Gong et al.(37) demonstrates that, for typical damaged areas on epoxy-coated bars, the corrosion loss on the damaged area must be 100 times higher or 2500 µm (0.10 inch) to cause concrete to crack. This 100 to 1 ratio, coupled with the observation that corrosion rates are similar on conventional steel and exposed portions of damaged epoxy-coated reinforcement, indicates that epoxy-coated steel should provide a service life significantly longer than the desirable range of 75 to 100 years, if the service life of a structure is judged based on concrete cracking, as it typically is. In that case, all of the systems tested that incorporate epoxy-coated reinforcement will provide a service life in excess of 75 years. The appropriateness of this conclusion, however, will be further tested as this study is completed and must be tempered by concerns with the potential effects of reductions in the bond strength between the coating and the steel for bars embedded in concrete, which have not, as yet, been addressed in this study.

CHAPTER 5. INTERIM CONCLUSIONS

The following interim conclusions are based on the results and analyses presented in this report.

1. In the short-term tests used in this study, the epoxy-coatings evaluated provide superior corrosion protection to the reinforcing steel. The results also indicate that the bars will continue to perform well in the longer term, although the tests performed to date do not evaluate the effects of long-term reductions in the bond between the epoxy and the reinforcing steel.

2. The corrosion rate on the exposed regions of damaged epoxy-coated reinforcement is somewhat higher than the average corrosion rate on the surface of uncoated reinforcement subjected to similar exposure conditions.

3. The use of concrete with a reduced water-cement ratio improves the corrosion performance of both conventional and epoxy-coated reinforcement in uncracked concrete but has little effect in cracked concrete.

4. Increased adhesion between the epoxy coating and reinforcing steel provides no significant improvement in the corrosion resistance of epoxy-coated reinforcement.

5. The use of corrosion inhibitors in concrete improves the corrosion resistance of the epoxy-coated steel in uncracked concrete, but not in cracked concrete.

6. The bars with the primer coating containing microencapsulated calcium nitrite provide improved corrosion performance in uncracked concrete, but not in cracked concrete.

7. The corrosion performance of epoxy-coated reinforcement in concrete containing a corrosion inhibitor generally improves as the water-cement ratio decreases.

8. The zinc coating on the multiple coated bars acts as a sacrificial barrier and provides some corrosion protection to the underlying steel in both uncracked and cracked concrete. The degree of protection, however, cannot be evaluated based on the results available to date and must await the conclusion of the Southern Exposure and cracked beam tests when the reinforcing bars will be inspected for the presence and type of corrosion products.

9. The superior performance of conventional epoxy-coated reinforcement in the current study may be improved with the addition of a corrosion inhibitor to the concrete. This conclusion may be modified as additional data are obtained.

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