Corrosion Evaluation of Epoxy-Coated, Metallic-Clad and Solid Metallic Reinforcing Bars in Concrete

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FOREWORD

This report describes results obtained from a 5-year test program to develop cost-effective "new breeds" of organic, inorganic, ceramic and metallic coatings, as well as metallic alloys that can be utilized on or as steel reinforcement for embedment in portland cement concrete. It was required that the corrosion-free design life shall be 75 to 100 yrs. Screening tests were conducted on 33 organic-coated; 14 ceramic-, inorganic-, and metallic-clad; and 10 solid metallic bar types. Based upon these screening tests, 12 bar types were selected for the severe 96-week in-concrete tests. The study concluded that the conventional black bars exhibited very poor corrosion performance. For the epoxy-coated bars, the presence of cracks in the concrete and the amount of damage to the bars played a significant role in the performance of the reinforcing. When an epoxy-coated cathode was utilized, these epoxy-coated bars exhibited a corrosion rate over 100 times less than that of black bars. The type of epoxy played a role in the performance of the epoxy-coated bars; however, such performance differences were significantly reduced when an epoxy-coated cathode was present. At best, the epoxy-coated bars with pretreatment gave a similar performance to that of the products without the pretreatment. The bars coated with the nonbendable epoxy coatings provided better performance than the bendable epoxy coatings when evaluated on bent bars. The performance of galvanized bars was found to be significantly better than black bars when the entire structure utilized galvanized bars. The newer zinc alloy-clad bar did not perform better than the galvanized bars. The corrosion rates of copper-clad reinforcing bars were 95.0 percent lower than that of the black bars; however, retardation of the concrete surrounding the bar was observed. The corrosion of Type 304 stainless steel bars was 99.8 percent lower than that of the black bar specimens when the stainless bars were attached to a stainless steel cathode. However, when a black cathode was present, several instances of significant corrosion were observed and the corrosion reduction was only 90.0 to 95.0 percent lower than that for black bars. Under all test conditions, the Type 316 stainless steel bars did not exhibit any visible corrosion. Type 316 stainless steel reinforcing should be considered in critical and hard to repair structures for maximum protection against corrosion-induced damage. Epoxy-coated reinforcement is a good corrosion protection system; however, these should be used throughout the structure and cracks in the concrete should be repaired. Damage in the rebar coatings should be minimized. This research supports the use of epoxy-coated reinforcing bars as a corrosion protection system for bridge decks.

This report will be of interest to materials and bridge engineers, reinforcing-concrete corrosion specialists, reinforcing bar manufacturers, producers of organic coatings and manufacturers of stainless steel.

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Director, Office of Engineering
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16. Abstract

This report describes the work conducted from 1993 to 1998 to develop *cost-effective* "new breeds" of organic, inorganic, ceramic and metallic coatings, as well as metallic alloys that can be utilized on or as reinforcement for embedment in portland cement concrete. As part of the study, 12 different bar types were tested in concrete: black bars, 3 bendable and 3 nonbendable epoxies, Type 304 and Type 316 stainless steel, copper-clad, galvanized and spray metallic-clad reinforcing. Measurements of macrocell voltages, half-cell potentials, electrical impedance spectroscopy, linear polarization and mat-to-mat resistances were used in conjunction with visual observations to determine the effectiveness of each system.

It was concluded that Type 316 stainless steel reinforcing bars should be considered at the design stage as a potential method for obtaining a 75- to 100-year design life. These bars had corrosion rates 800 times lower than that of the black bars, even when tested in precracked concrete. Costs associated with the bars limit their widespread use in concrete structures; however, for structures where repair to corrosion-induced damage is difficult, the additional costs associated with the stainless steel bars may be justified. Potential use includes marine substructures, tunnels, and bridges that carry significant traffic where costs associated with road closures are very high.

The research supports the continued use of epoxy-coated reinforcing bars as a corrosion-protection system; as in all cases, the corrosion rates of the epoxy-coated bars were less than that observed for the black bars. However, when epoxy-coated bars are to be used, it is appropriate to: use epoxy-coated reinforcing for both top and bottom mats of slabs, minimize damage to the reinforcing bars during shipment and placement, and repair cracks in the concrete. Decks constructed using epoxy-coated bars on the top mat only are not expected to have the same durability as those constructed with two layers of epoxy-coated bars; however, even these structures will show improved durability compared with companion structures that used black bars alone.

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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 yards	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)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°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	35.71	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)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°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 September 1993)

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CHAPTER 1. INTRODUCTION

FOREWORD

In May 1992, the Federal Highway Administration (FHWA) issued a Request for Proposal for a 5-yr research project on "Corrosion Resistant Reinforcing for Concrete Components." The objective of the proposed study was to develop *cost-effective* "new breeds" of organic, inorganic, ceramic and metallic coatings, as well as metallic alloys that could be utilized on or as reinforcement for embedment in portland cement concrete. It was required that new coatings and alloys "should provide reinforcement that is significantly more corrosion-resistant than the fusion-bonded, epoxy-coated reinforcement that has been used in the United States since 1975." It was also required that the "corrosion-free design life shall be 75 to 100 yrs for the proposed study when exposed to adverse environments."

The research was to be aimed at developing new reinforcement materials and systems that have minimum damage to the coating system during the coating application, the fabrication bending operations, shipment to the jobsite, and the installation at the jobsite. It was required that alloys should have superior characteristics, and thin-clad conventional steel should resist damage. The coating systems should also have superior physical and chemical properties that remain undamaged by long-term exposure to ultraviolet radiation, high temperatures, salt-laden atmosphere, and other environmental conditions during long-term storage prior to casting them in concrete.

PROJECT HISTORY

Based upon acceptance of a proposal, work commenced on February 18, 1993. On March 5, 1993, a letter was sent to about 80 interested parties announcing the initiation of the research. The letter announced informational meetings that were held in Northbrook, Illinois on March 22, 23, and 24, 1993.

On March 3, 1993, 3M informed the researchers that Scotchkote 213 would no longer be manufactured. The 3M 213 epoxy-coated bars had been used almost exclusively in the bridges in the United States from about 1980 to 1990. This unforeseen situation was caused by rulings from the United States Environmental Protection Agency (EPA). Based upon this change, it was impossible for the initial work plan to be initiated, and it became crucial to secure bars coated with the 3M 213 for the in-concrete tests that were to begin in 1995.

In early 1993, it was anticipated that numerous new candidate organic coatings would be submitted for testing, since the 3M 213 epoxy coating material was no longer available and new steel surface pretreatments used prior to coating the bars were being considered. As a result, a 30-d prescreening test program was planned to screen these numerous candidate bar systems, with and without special steel surface pretreatments. At that time, it was the consensus of the organic coaters that pretreatment would help the coating adhesion strength and long-term serviceability.

An invitational letter for submitting candidate bars was sent to 46 companies on May 17 and 18, 1993. It was expected that submittal of these bars would be obtained by July 1, 1993. Plans were also made with the Michigan and New Jersey departments of transportation to remove solid stainless steel bars, epoxy-coated bars, and stainless-clad bars from two identified 10-yr-old bridge decks. Prescreening tests on organic-coated bars were conducted during 1993 to 1995. Based upon this work, additional screening tests were conducted in 1995. Screening tests were conducted from 1993 to 1995 on metallic-clad and solid metallic-clad bars.

Based upon a revised work plan, bars for the 96-week in-concrete testing were requested from selected manufacturers in 1995 and 141 reinforced concrete slab specimens were made and prepared for long-term monitoring. These tests were completed in late 1997. This report describes in detail the fabrication and testing of the concrete specimens.

Epoxy-Coating Plant Certification and Quality Control

Over the past 10 years, there have been many papers, reports and theses written on the performance of epoxy-coated reinforcing bars. This report does not contain a detailed bibliography of the work conducted to date; however, the performance of epoxy-coated bars has been summarized by others[1].

Epoxy-coated reinforcing has typically been manufactured by coating straight 20-m (60-ft) lengths of reinforcing according to ASTM A 775 *Standard Specification for Epoxy-Coated Reinforcing Steel Bars*[2]. After coating, the bars are then bent to shape. Concern was expressed regarding the effect of this bending on the long-term performance of the coatings. More recently, epoxy-coating manufacturers have suggested the idea of putting less flexible coatings on bars that have been cut and bent to shape. In 1995, ASTM A 934 *Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars* was written and adopted for nonbendable epoxy-coated reinforcing bars.[3] A description of the manufacture of epoxy-coated bars and certification of epoxy-coated bar plants are described below.

The predominate straight reinforcing bar fusion-bonded epoxy-coating process includes abrasive blast cleaning of the steel, heating the steel to over 220°C (425°F), electrostatic application of charged epoxy powder, and forced cooling once the coating has cured. Abrasive cleaning is normally performed using steel grit or grit combined with steel shot. Since the early 1990s, considerable research and manufacturing effort has been expended into improving quality and the corrosion performance of epoxy-coated bars. This effort includes improved manufacturing quality control procedures, increased quality control testing, and the use of bond-promoting steel pretreatments.

In 1991, the Concrete Reinforcing Steel Institute (CRSI) implemented a program for voluntary certification of epoxy-coated reinforcing bar plants. By 1998, 32 plants within the United States were certified. The program requires written Quality Assurance/Quality Control (QA/QC) policies and procedures. Tests are conducted on the bars prior to coating to ensure that they are satisfactorily prepared and include: determination of the suitability of the bars to be coated, checking for contaminants on the bar surfaces, measurement of the anchor profile of the blasted bars and ensuring that the abrasive is not contaminated. Prior to coating, the bar temperatures are checked to verify that the bars are at a suitable temperature for coating. The powder is also checked to determine if it is stored at correct temperatures, used within its recommended shelf life, and has met the required American Society of Testing and Materials (ASTM) prequalification tests.

During the coating process, the bars are checked to determine if they are coated properly and that there is an adequate gel and cure time. After coating, holiday, thickness, and bend tests are conducted. Recently, cathodic debonding (CD) testing was also added as a requirement to evaluate adhesion. The program also limits the amount of time epoxy-coated bars are left exposed to moisture and the sun. The program mandates what happens to the coated bars that do not meet the rigorous quality standards. This program has resulted in advancement in holiday detection equipment and calibration of thickness gages, the development of target blast media working gradations, installation of alarms and recorders in powder storage rooms, the use of wetting agents for hand-held holiday testing and significant improvements in the daily inspection checklists and record keeping. Plants have also implemented employee training programs and education in response to the certification program. Several state agencies will now only purchase bars from plants that have QA/QC procedures such as those outlined in the CRSI Plant Certification Program. Prior to implementation of the certification programs, inadequately prepared bars were apparently being coated. These bars could have steel surface contamination levels of 40 to 60 percent. The reduction of this problem has significantly improved the adhesion of the epoxy coating to the reinforcing bars.

Improved handling and installation procedures are also being developed to reduce coating damage in the field. Some recent specifications require that all visible coating damage be repaired in the field. Training is also being performed on the handling, installation, and repair of field damage. Bars stored outdoors for a period of more than 2 months should be covered. Rubber-headed concrete vibrators are recommended to prevent coating damage during concreting operations.

Other corrosion-resistant bars

The performance of various inorganic-, ceramic-, and metallic-clad bars and solid corrosion-resistant bars is discussed in the 1996 FHWA report titled *The Corrosion Performance of Inorganic-, Ceramic-, and Metallic-Clad Reinforcing Bars and Solid Metallic Reinforcing Bars in Accelerated Screening Tests*(4). This new research studied 10 types of clad bars and 10 types of solid bars.

The use of bars clad with nickel, copper, and zinc blends has been suggested. To date, the long-term field performance data for these metallic products are not sufficient to conclude their effectiveness. As part of this FHWA project, a paper titled *Testing the Performance of Copper-Clad Reinforcing Bars* was written and published(5).

British Standard BS 6744 covers requirements for austenitic stainless steel reinforcement.(6) ASTM has developed a parallel standard specification as ASTM A 955(7). As part of this FHWA project, a paper titled *Stainless Steel Reinforcing as Corrosion Protection* was written and published(8). This 1996 paper discusses extensive field and laboratory studies on stainless steel-reinforced bridges and marine studies from the United States and England, and the seven stainless steel bars researched in this present FHWA study(4).

INDUSTRY CONTACTS AND REPRESENTATION

One of the tasks of the research was to develop test methods and procedures for evaluating the integrity of the existing and the newly developed coatings and alloyed materials as a quality control measure in addition to presently available test methods. The research was also required to develop a detailed plan for the commercial production of corrosion-resistant reinforcement developed under this project that is capable of competing with the fusion-bonded epoxy-coated reinforcement. It was envisioned that this task required coordination with coating/alloy producers, fabricators, coaters and manufacturers.

During these 5 yrs of research, the authors believed that the best methods to achieve the two goals outlined above were to become actively involved in the industry discussions regarding the performance of corrosion-resistant reinforcing bars and to provide an arena for open discussions on the evaluation and performance of the various systems. It was further believed that a closer working relationship between industry, research and government would result in significantly better research, and that this relationship is often poorly regarded in the research arena. The results of 5 yrs of extensive communication have been clearly evident in this research program and the distribution of information to the FHWA and numerous other government agencies, including the U.S. Navy, the Department of Energy, and numerous state departments of transportation. During the period 1993 to 1998, over 50 oral presentations on the research were made, and 9 papers(5, 8-15) and 3 FHWA reports(4, 16-17) were published.

CHAPTER 2. PRELIMINARY TESTING AND SELECTION OF BARS FOR IN-CONCRETE TESTS

INTRODUCTION

The research project was to develop new, cost-effective breeds of coating or cladding with performance when exposed to adverse environments that exceeded that of the currently utilized fusion-bonded epoxy coatings. The project also was required to develop or procure (if available) new cost-effective reinforcement alloys that had all the inherent properties of black steel, but whose corrosion-resistant characteristics when exposed to adverse environments exceeded those of fusion-bonded epoxy coating.

As part of the first 3 yrs of research, considerable work was conducted in evaluation of various coating and solid alloy systems. This work included:

- Prescreening tests on 33 organic-coated bar types
- Screening tests on 10 organic-coated bar types
- Tests on 14 ceramic-, inorganic-, and metallic-clad bar types
- Tests on 10 solid metallic bar types

These tests will be briefly described below. At the end of this work, bars were selected for in-concrete evaluation, described later in this chapter.

PRESCREENING TESTS ON ORGANIC-COATED BARS

Introduction

Prescreening tests were conducted from 1993 to 1994 on 33 different organic-coated bars. Results from these tests are fully discussed in reference 16. Bars were submitted from organizations in the United States, Canada, England, Japan, and Germany. Twenty-two bendable and 11 nonbendable organic-coated reinforcing bar types were submitted by 15 organizations. New steel surface cleaning and/or chemical treatments were utilized with 17 of these 33 coating systems. Prior to testing, straight sections of holiday-free bars coated with bendable coatings were bent 180° around a mandrel with a diameter four times that of the bar (4D) and examined for holidays, cracks, and crushing or cold flow of the coating. Prepared bars were evaluated using solution immersion and cathodic debonding tests, described below.

Solution Tests

The prescreening solution tests were selected to represent the four exposure conditions, representing rain, seawater, chloride-free concrete and chloride-contaminated concrete. Straight coated bars that were holiday-free and bent (4D) were prepared, each with one 6-mm- (0.25-in-) hole in the coating. These were then soaked at 55°C (131°F) for 28 d in the following solutions:

- Deionized water
- 3 percent NaCl
- 0.3N KOH + 0.05N NaOH
- 0.3N KOH + 0.05N NaOH and 3 percent NaCl

After 1, 3, 7, and 28 d of solution immersion, the coated bars were visually examined for blisters, cracks, holes, corrosion, and debonding. The adhesion of the organic coatings was evaluated on the straight and bent sections of the bar using knife-peel adhesion tests discussed in ASTM G 1[18]. In these tests, the coating was cut with a knife and the coating was peeled from the steel surface.

Coatings that resisted this peeling were sought. The knife-peel adhesion tests were made in the wet condition and again after 1 and 7 d of air drying. The rating system used is shown in figure 1.

Cathodic Disbondment Tests

Cathodic disbondment (CD) tests, such as those described in AASHTO M 284,[19] ASTM A 775[2], ASTM D 3963,[20] ASTM G 8,[21] and ASTM G 42[22] have been used on straight bars by the coating industry to assess coating quality. Present tests were conducted on organic-coated reinforcing bars that were bent to 4D. The use of a bent bar for the tests was a major change to previously conducted tests as it introduced bending stresses into the coatings. The tests were conducted at a potential of -1000 mV versus the rest potential over a period of 28 d at 23°C (73°F) in a 0.3N KOH + 0.05N NaOH solution at pH 13.3. The 0.3N KOH + 0.05N NaOH test solution was chosen since this solution had been previously shown to produce more disbondment to organic coatings than pH 7 solutions. During the testing, the specimens were monitored using ac impedance techniques after 1 h, 7 and 28 d of CD testing. After the 28-d period, adhesion tests were performed as described above. The apparatus used for the CD tests is shown in figure 2.

Results

Numerous observations and conclusions were made during the prescreening tests. These included:

1. Coating adhesion was reduced after the immersion tests.

2. The lowest adhesion was generally measured at the hole drilled through the organic coating.

3. Of the 88 straight bars tested in the 4 solutions, 67 did not suffer adhesion loss in holiday-free areas away from the hole.

4. The best adhesion was generally achieved on straight bars.

5. After bending to 4D, the adhesion of the bendable coatings after immersion tests was generally poor.

6. Only 2 of the 33 coated bent bars achieved excellent to marginal adhesion ratings in all 4 solutions following the immersion tests. Both of these bars used nonbendable coatings.

7. The bending of the bendable coating systems produced stresses that undoubtedly overshadowed the CD electrical debonding effects. All of the 21 bendable coating systems produced poor adhesion when tested immediately after removal from the solution.

8. The bars using nonbendable coatings had much better adhesion after CD testing than the bendable coatings; however, essentially none of these six nonbendable coatings provided excellent to good adhesion ratings at the hole under wet conditions. These same six nonbendable coatings produced excellent to good adhesion performance when tested away from the hole under wet or air-dry conditions. The significant difference in adhesion for the prebent bars after CD testing at the hole versus away from the hole under wet conditions showed that the hole created the conditions for adhesion loss.

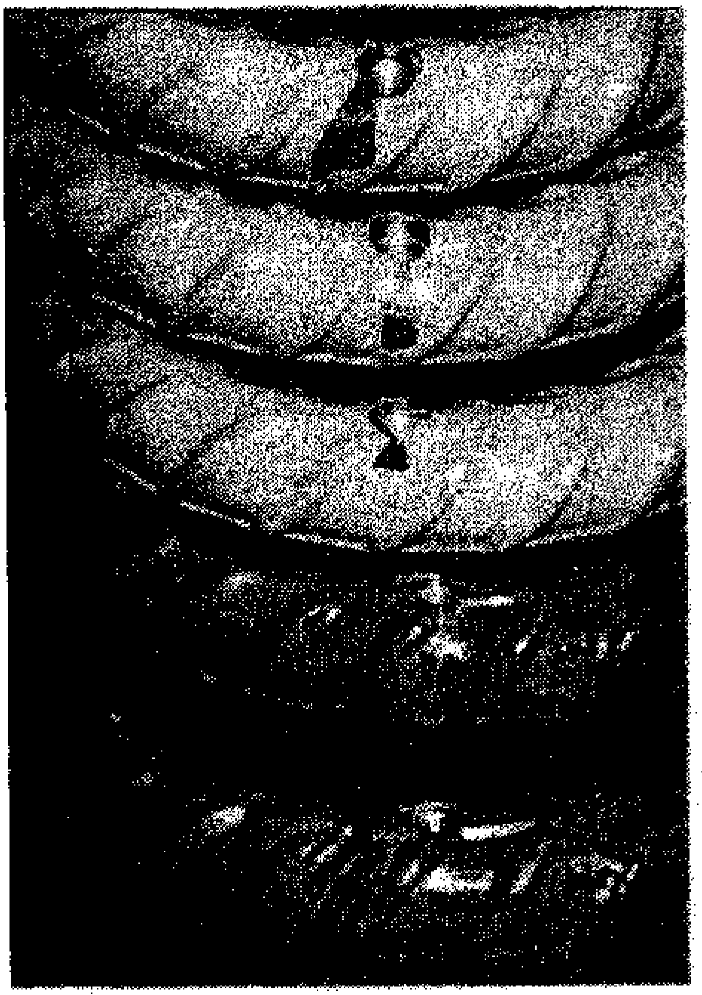

Figure 1. Adhesion of organic coatings.
Top: Poor - Rating = 5
Bottom: Excellent - Rating = 1

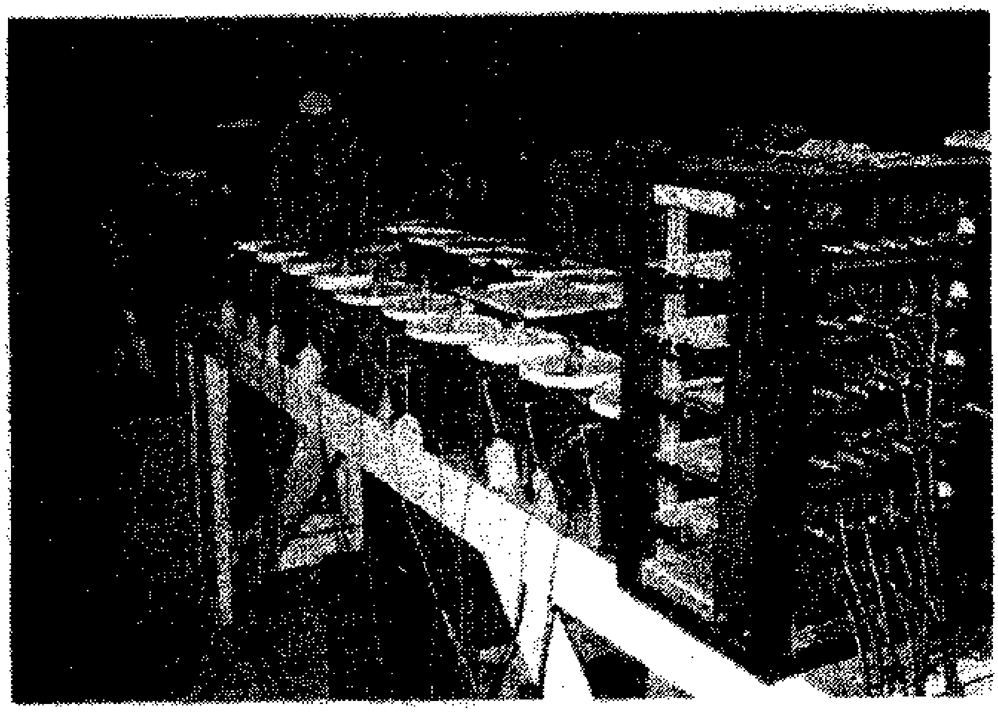

Figure 2. Apparatus used for cathodic debonding (CD) tests.

SCREENING TESTS ON ORGANIC-COATED BARS

In the prescreening tests, excellent adhesion was observed for both bendable and nonbendable coatings on straight bars following the severe immersion tests. Excellent adhesion was also obtained for the prebent bars using nonbendable coatings. As poor adhesion was obtained on bent bars using bendable coatings, it was necessary to initiate a screening test to determine the extent of bendability of bendable coatings. CD tests on straight bars and bars bent to different bend diameters using bendable and nonbendable coating systems were conducted. This testing is described in detail in reference 17, and that work is summarized below.

Seven of the best-performing coating systems from the prescreening tests were selected for testing. Four were bendable epoxy coatings and three were nonbendable epoxy coatings. 3M Scotchkote 213 bendable epoxy coating was also tested as this coating was the dominant coating used for many years. Two additional nonbendable coatings, one epoxy and one vinyl, were also selected and tested. These five bendable and five nonbendable coating systems were tested on straight bars and bars bent to 8D, 6D, and 4D shapes using solution immersion and CD tests.

While the prescreening tests utilized four different solutions to simulate four different environments, the screening tests utilized the two solutions that produced the best and worst adhesion performance. These were pH 7 deionized water and a high-pH (13.3) solution with a Cl^-/OH^- ratio of 4.5 (0.3N KOH + 0.05N NaOH + 9 percent NaCl).

Three straight, three 8D, three 6D, and three 4D bars were tested in each of the two solutions. In each specimen, two 6-mm- (0.25-in-) drill holes were made in each bar specimen through the coating. The bars were stored in the solutions at 55°C (131°F) for 28 d, removed from solution, inspected and the coating was tested for adhesion to the bar at the hole and away from the hole. These adhesion tests were made when the bars were still wet and again after 7 d of air drying at these locations. CD tests were also conducted, followed by adhesion tests. Observations and conclusions included:

1. In the solution immersion tests, corrosion did not extend under the film, even if a coating was poorly bonded and the bar was tested in the pH 7, deionized water.

2. The nonbendable coatings exhibited significantly better adhesion than the bendable coatings.

3. Significantly better adhesion was observed for bars tested in the straight condition than those tested in the bent condition.

4. Significant differences exist between the adhesion ratings for straight and bent bars for the bendable coating systems.

5. The differences in adhesion rating for the prebent bars in the 4D, 6D, and 8D shapes coated with the nonbendable coatings are considered to be minimal.

6. The five bendable coating systems exhibited consistently poor adhesion in the 4D, 6D, and 8D shapes.

7. Adhesion on straight bars is significantly enhanced through the use of the nonbendable coating systems.

8. Significantly better adhesion was found away from the drill hole than at the drill hole after testing. Adhesion away from the drill hole on straight bars based on

either test method is excellent on 7 of the 10 coatings. Thus, adhesion reduction was apparently not a serious problem at locations that do not have defects in the coating.

9. Significantly better adhesion occurred when the coating was dry than when the coating was tested wet.

10. If adhesion is lost in CD tests, it is unlikely to be regained upon drying.

11. For the at-the-hole location, poor correlation was obtained between the solution immersion and the CD tests, indicating that different adhesion deterioration mechanisms are occurring in each test.

SCREENING TESTS ON CERAMIC-, INORGANIC-, AND METALLIC-CLAD BARS AND SOLID METALLIC BARS

Introduction

A screening test program was conducted on 14 different ceramic-, inorganic-, and metallic-clad bar types. Results from this work are fully discussed in reference 4 and the work is summarized below. Submitted clad bars included:

- Hot-dipped galvanized
- Bars coated with zinc using the Delot process
- Nickel-clad
- Inorganic zinc silicate-clad
- Ceramic-clad bars using a micro-infiltrated macro-laminated coating
- Several proprietary zinc-rich claddings
- Copper-clad
- Type 304 stainless steel-clad
- Copper-based alloy-clad
- Reactive copper in an organic coating
- Galvalum (aluminum and zinc) coated bars

A screening program was also conducted on 10 different solid metallic bar types. These included:

- Black
- Titanium
- Type 304 stainless steel
- Type 304 stainless steel (European)
- Type 316 stainless steel
- Type 317 stainless steel
- Type XM-19 stainless steel
- Nitronic 33 stainless steel
- Corrosion-resistant steel alloy
- Type C613000 aluminum bronze

Bars were submitted from the United States, Canada, England, and France. The tests were developed to screen the various products and to indicate which were most likely to exhibit superior corrosion resistance in concrete.

Testing of Clad Bars

For each type of clad bar, four companion bars in three different conditions were tested in two solutions. The bars were tested in the following conditions: as-received, with a drill hole through the cladding and after abrasion. Both straight and bent bars were tested, amounting to 24 bars of each shape. Prior to testing, eight of the bent and eight of the straight bars of each bar type had a 6-mm- (0.25-in-) hole drilled through the cladding to simulate field damage and unprotected cut ends. Eight of the straight and eight of the bent bars of each type were also prepared by blasting with a fixed amount of clean blasting slag to simulate field damage due to abrasion. Eight of the straight and eight of the bent bars of each type were tested as-received. In addition, two of the bent as-received bars, two of the bent with drill hole, and two of the bent abraded bars of each coating type were prepared for polarization resistance (PR) measurements. These measurements were used to determine corrosion rates.

Two solutions were used for the tests, a 3 percent NaCl solution and a 0.3N KOH + 0.05N NaOH + 3 percent NaCl solution. Testing was conducted for 28 d in specially constructed machines that dipped the bent and straight specimens in solution for a period of 1¼ h, and then totally removed the specimens to allow air drying for a period of 4¾ h. This 6-h cycle was then repeated continuously, providing 112 cycles in 28 d. Apparatus used for these tests are shown in figure 3. Quantitative analysis of the amount of corrosion occurring was performed using PR. Half-cell potential measurements were also made. The bars were visually assessed, and a ranking of 0 to 4 was assigned to each bar type. The clad bars that performed well in the screening tests were the zinc alloy-clad, the Type 304 stainless-clad, the copper-clad and the ceramic-clad bars. These four clad bar types were selected for further testing in longer, more aggressive corrosion tests alongside the solid metallic bars, described below.

Testing of Selected Clad and Solid Metallic Bars

Bars were prepared for these screening tests in a similar manner to that described above for the clad bars. As it was generally found that the bent bars exhibited significantly more corrosion than the straight bars, only bent bars were tested. None of the solid bar types were subjected to abrasion; however, the selected four clad bar types were subjected to abrasion prior to testing. All of the bars were also tested in the as-received and drilled hole conditions. Four solutions were used in the screening tests. These were:

- 3 percent NaCl solution
- 0.3N KOH + 0.05N NaOH + 3 percent NaCl
- 0.3N KOH + 0.05N NaOH + 9 percent NaCl
- 0.3N KOH + 0.05N NaOH + 15 percent NaCl

This testing was designed to be more severe than that used to screen the clad bars. Testing was conducted in the pH 7, 3 percent NaCl solution for a period of 90 d or 360 cycles. Companion tests were conducted in pH 13 solutions for a period of 56 d in the 0.3N KOH + 0.05N NaOH + 3 percent NaCl solution, followed by 56 d of testing in the 0.3N KOH + 0.05N NaOH + 9 percent NaCl solution and then 56 d of testing in the 0.3N KOH + 0.05N NaOH + 15 percent NaCl solution. These high pH tests were conducted over a period of 168 d or 672 cycles.

For the black bar, the PR values in the various NaCl solutions at pH 13 averaged about 0.90, 0.51, and 0.26 ohm.m^2, equivalent to corrosion current densities of approximately 29, 51 and 99 mA/m^2 (2.69, 4.74 and 9.29 mA/ft^2), respectively. These very high corrosion current densities are typical of those measured in 1- to 2-yr-long accelerated corrosion tests within reinforced-concrete test slabs, and are indicative of rapid corrosion.

The numerous zinc-containing clad bar types had performances similar to the black bar. The copper-clad bar had PR values of about 16 times that of black bar in the longer term, 168-d test series with the 3 different and progressively stronger NaCl solution strengths indicating proportionally lower corrosion rates. The stainless-clad, solid stainless and titanium bars had PR values that were 50 to 750 times that of the black bar. The data from the stainless-clad, solid stainless steels and solid titanium bars suggest that a significant corrosion-free life can be obtained. The Nitronic 33, Type 304, Type 316 stainless steels and the titanium bars had consistently high PR values of about 100 to 700 ohm.m^2 during the 168-d tests, equivalent to corrosion current densities of approximately 0.26 to 0.04 mA/m^2 (0.02 to 0.004 mA/ft^2).

Figure 3. Wetting and drying tests used for evaluation of ceramic-,inorganic-, and metallic-clad and solid metallic bars.

SELECTION OF BARS FOR IN-CONCRETE TESTING

The two best bendable and the two best nonbendable epoxies from the screening tests were selected for the in-concrete tests. As Scotchkote 213 was used almost exclusively in concrete structures until 1993, it was also selected. A post-baked epoxy was also chosen based upon the prescreening tests. Three metallic-clad and two solid metallic bar types were selected, based upon the screening testing. From review of the PR data, it was found that of the 10 best-performing clad and solid metallic bars, 7 were solid stainless steels, 1 was the stainless-clad steel, 1 was aluminum bronze, and 1 was titanium. Type 304 and Type 316 stainless steel bars were chosen for the in-concrete tests as they also exhibited excellent durability in previous long-term concrete test programs[8]. Due to inconsistent corrosion performance in some research tests, galvanized bars were also selected[4]. This selection would allow the performance of galvanized bars to be directly compared to other corrosion-resistant reinforcement systems in both cracked and non-cracked concrete. It was found in the screening tests that the newer zinc alloy-clad bar was significantly better than the galvanized bars. It was of interest to determine whether the advances shown through the use of a newer zinc alloy-cladding would be exhibited during the in-concrete tests. For this reason, a zinc alloy-clad bar was also selected. Copper-clad bars were also found to have good performance and a limited study was included. The 12 bar types selected for the in-concrete tests were:

- ASTM A 615 black reinforcing bar (BL)
- Epoxy-coated bars coated with 3M Scotchkote 213 (Epoxy-A)
- Two bendable epoxy-coated bar types (Epoxy-B, Epoxy-C)
- Two nonbendable epoxy-coated bar types (Epoxy-D, Epoxy-E)
- One post-baked nonbendable epoxy coating (Epoxy-F)
- ASTM A 767 galvanized bar (GL)[23]
- Zinc alloy-clad bar (SM)
- ASTM A 955 Type 304 and Type 316* solid stainless steel bar (304, 316)[7]
- Copper-clad bar (CU)

Of the six epoxies selected, three utilized steel pretreatments prior to coating (Epoxy-B, Epoxy-C, and Epoxy-E), and three did not (Epoxy-A, Epoxy-D, and Epoxy-F). Epoxy-C and Epoxy-E used a chromate pretreatment, while the pretreatment material used for Epoxy-B was not revealed by the manufacturer. Epoxy-F has not been commercially utilized for the coating of reinforcing bars, but it is used for the protection of steel pipes in severe environments. All other epoxy-coating systems were available commercially.

The hot-dip galvanized reinforcing bars were prepared according to ASTM A 767 *Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*. The supplied coating thickness was determined to be 0.10 mm (0.004 in). Several types of zinc alloy-clad steel bars were submitted for testing by P.C. Campana Inc., Lorain, Ohio. These bars were coated using a proprietary process, currently undergoing a patent application. The cladding consists primarily of zinc; however, other metals were added to the zinc to improve the coating corrosion resistance when evaluated in salt-spray tests. The average cladding thickness was determined to be 0.05 mm (0.002 in). The Type 304 stainless steel bars had a tensile strength of 592.9 MPa (86.0 ksi), a 2 percent yield strength of 317.8 MPa (41.6 ksi) and a 60.0 percent elongation in 50 mm (2 in). The Type 316 stainless steel bars had a tensile strength of 604.6 MPa (87.7 ksi), a 2 percent yield strength of 354.3 MPa (51.4 ksi) and a 53.6 percent elongation in 50 mm (2 in).

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* Funding of the in-concrete tests using Type 316 stainless bars was provided by the Nickel Development Institute.

CHAPTER 3. IN-CONCRETE TESTS

CONCRETE TEST SPECIMENS

Introduction

During the last 15 yrs, different reinforced-concrete test specimens and test methods have been used to evaluate corrosion protection systems and materials. Common to most is the use of the macrocell current measuring system as reported in the 1983 FHWA report *Time to Corrosion of Reinforcing Steel in Concrete Slabs, Vol 5.*[24] A majority of the specimens have been similar to or identical to the slab specimens as reported in the 1987 FHWA report *Protective Systems for New Prestressed and Substructure Concrete.*[25] Similar slab specimens were also tested with straight and bent bars in the top mat and straight bars in the bottom mat during the 3-yr study in 1988 to 1991 on 3M 213 epoxy-coated bars from eight bar-coating factories.[26]

The concrete slabs used in the tests measured 300 x 300 x 175 mm (12 x 12 x 7 in) and contained two layers of 16-mm- (⅝-in-) diameter reinforcing, as shown in figure 4. The top mat contained either two straight or bent reinforcing bars, while the bottom mat contained four straight reinforcing bars. Each top-mat bar was connected to two bottom-mat bars using a 10-ohm resistor. A clear cover of 25 mm (1 in) was utilized in all concrete specimens. This represented either the American Association of State Highway Transportation Officials (AASHTO) bottom-of-slab specified 25-mm- (1-in-) clear cover, or the expected minimum in-place clear cover allowing for construction tolerances when 38- to 50-mm (1½- to 2-in) requirements are used.

While most previously published corrosion studies were on crack-free concrete slabs, numerous unpublished tests by the authors in conjunction with manufacturers of various products have been recently undertaken on flexurally cracked concrete beams. In these previous studies on cracked beam specimens, the crack was perpendicular to the reinforcing bar. In bridge deck structures, just the opposite occurs, and the cracks are almost always parallel to and directly over a top-mat transverse bar or longitudinal bar. Thus, in bridge decks, the crack follows the bar. Cracks in selected concrete slabs were formed in the concrete specimens using a 12-mil (0.30-mm) stainless steel shim, cast into the concrete down to the bar level and removed 1 d after the concrete was cast. These shims have a thickness typical of cracks observed in concrete decks. The cracks were oriented such that they were directly above and followed the reinforcing bars for a length of 150 mm (6 in), as shown in figure 4.

The eight specimen configurations used for the tests on epoxy-coated bars are shown in table 1. For each of the 6-bar types, 16 concrete slabs were cast, each containing an anodic bar with 0.5 percent damage and an anodic bar with 0.004 percent damage.

Table 1. In-concrete test specimens for epoxy-coated bars.

Top mat	Bottom mat	Precracked slab	Percent damage to coating
Straight	Black	No	0.5
Straight	Black	No	0.004
Straight	Same as anode	No	0.5
Straight	Same as anode	No	0.004
Straight	Black	Yes	0.5
Straight	Black	Yes	0.004
Bent	Black	No	0.5
Bent	Black	No	0.004

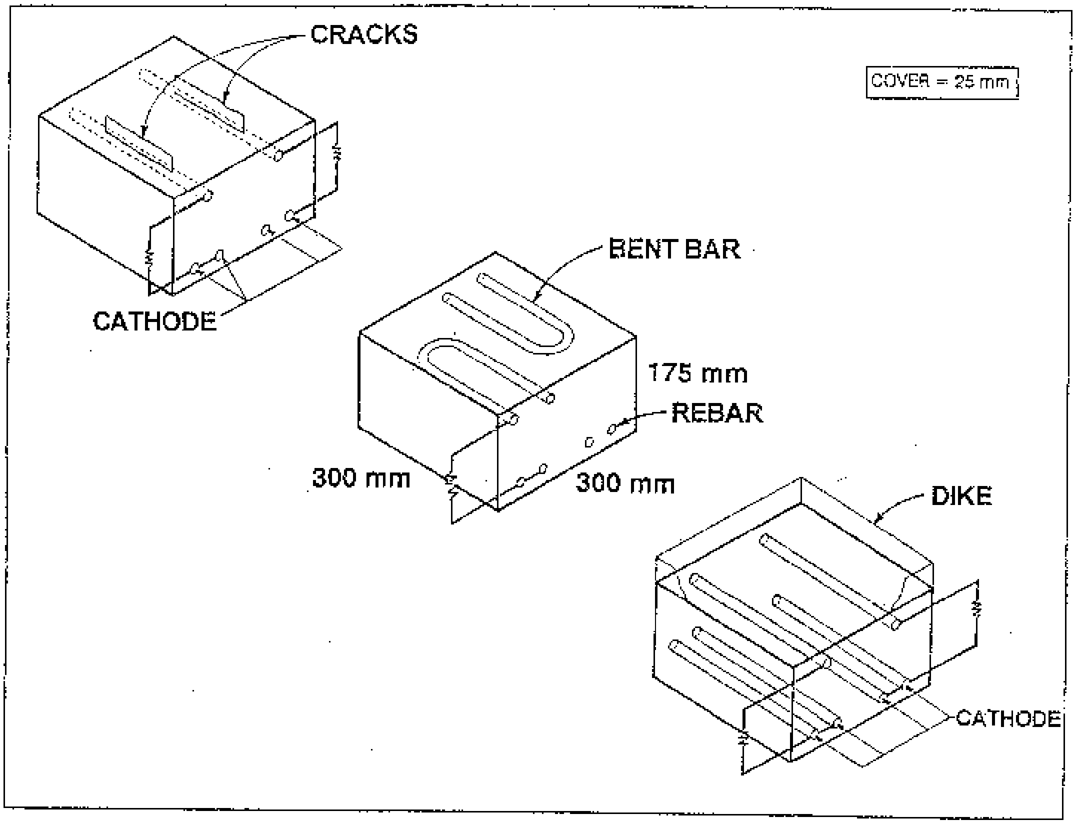

Figure 4. Test specimens used for in-concrete corrosion tests.

The five specimen configurations used for the tests on clad and solid metallic are shown in table 2. For each of the clad or metallic-clad bar types, six concrete specimens were cast with straight bars and three were cast with bent bars. No specimens containing bent copper-clad bars were cast, as discussed later in this chapter.

Table 2. In-concrete test specimens for clad and solid-metallic bars.

Top mat	Bottom mat	Precracked slab	Percent damage to coating or bar surface
Straight	Black	No	0.5
Straight	Black	Yes	0.5
Straight	Same as anode	No	0.5
Straight	Same as anode	Yes	0.5
Bent	Black	No	0.5

Type of Cathode

In 1983, the FHWA reported the electrical resistance measurements between epoxy-coated top-mat bars and uncoated bottom-mat bars in 17 bridge decks in Kentucky and Virginia.[27] A total of 275 readings were taken on these 15 decks in Kentucky. For these decks, 4 of the 15 decks exhibited no electrical contact between the top and bottom mats. The percentage of resistance readings on each deck with very high resistance values ranged from 0 to 100 percent, with an average of 75 percent and a coefficient of variation (CV) of 43 percent.

In Virginia, the two decks had more electrical contact between the two mats than those in Kentucky. The percentage of readings with very high resistance values ranged from 15 to 25 percent, with an average of 20 percent.

These cumulative data show that electrical isolation is often achieved between the top and bottom mats in many decks, even when the bottom mat is bare black steel bars; however, in many cases, this electrical isolation does not exit. It was believed and was shown in this current study, that this isolation can certainly play a dominant role in providing the long-term corrosion performance for epoxy-coated bars.

Most of the test conditions used in the in-concrete studies used a straight black bar bottom mat. This simulated a design where the top mat was the corrosion-resistant bar and the bottom mat was black, or where steel-headed studs that are electrically continuous with the top mat were present in steel girder structures. In other test conditions, the same corrosion-resistant bars were used in both the top and bottom mats.

Damage to Epoxy-Coated Bars During Bending

Initially, holiday-free epoxy-coated bars were chosen for the in-concrete tests. After bending to 4D, the holidays and cracks formed during bending of Epoxy-A, Epoxy-B, and Epoxy-C were determined, as shown below.

Epoxy-A — 36 to 56 per m (11 to 17 per ft)
Epoxy-B — nil
Epoxy-C — 26 to 46 per m (8 to 14 per ft)

Reasons for cracking may include poor elongation of the coating, insufficient adhesion, or poor surface preparation. The cracking of the coating during bending is not believed to be related to the extensibility or cracking of the steel. Bent bars with Epoxy-D, Epoxy-E, and Epoxy-F did not have bending-induced holidays, as these were coated after bending.

Bar Damage

It is appropriate to believe that bars at the jobsite are always damaged when placed into concrete. Therefore, all bars were deliberately damaged prior to placing into concrete. The epoxy-coated bars were subjected to two damage levels, 0.5 and 0.004 percent of the bar surface area; while the solid metallic and metallic-clad bars were damaged to a level of 0.5 percent prior to placement in concrete. These damaged levels were formed by drilling through the holiday-free coating into the black steel using either two 6-mm (¼-in) or four 0.40-mm ($\frac{1}{64}$-in) drill holes. The solid and metallic-clad bars were drilled with two 6-mm (¼-in) drill holes through the cladding or into the solid bar. When bars used for the bottom-mat cathode were made from the same material as the top-mat bars, these bottom-mat bars received the same damage levels as that of the top-mat bar.

Epoxy-Coating Thickness

Prior to casting the epoxy-coated bars in concrete, the thickness of the coating was determined using a magnetic coating thickness gage.[28]. Values obtained for the six coatings are shown in table 3.

Table 3. Epoxy thickness on straight and bent bars, mm (mil).

Epoxy Type	A	B	C	D	E	F
			Straight Bars			
Average	0.23 (9.2)	0.36 (14.0)	0.24 (9.5)	0.37 (14.4)	0.28 (11.0)	0.31 (12.3)
Maximum	0.27 (10.5)	0.41 (16.0)	0.20 (8.0)	0.41 (16.0)	0.36 (14.0)	0.42 (16.5)
Minimum	0.20 (8.0)	0.32 (12.5)	0.28 (11.0)	0.33 (13.0)	0.23 (9.0)	0.25 (10.0)
			Prebent Bars			
Average				0.38 (14.8)	0.19 (7.6)	
Maximum				0.34 (13.5)	0.23 (9.0)	
Minimum				0.39 (15.5)	0.17 (6.5)	

Current specifications for epoxy-coated bars limit coating thicknesses since coatings that are too thin may lead to areas with insufficient coating to protect the bar against corrosion, while coatings that are too thick may lead to loss of mechanical bond in concrete. Typical specifications limit coating thicknesses from 0.18 to 0.30 mm (0.007 to 0.012 in); however, it has been found that coatings thicker than this may not exhibit significantly lower bond in concrete.[29] Only Epoxy-A and Epoxy-C would meet this typical specification, while all other coatings had thicknesses exceeding that currently specified.

Resistor Size

For many years, the authors have recognized that the size of resistor used between the upper and lower reinforcing bar mats may significantly affect the measured macrocell corrosion rates. The authors of this report recommend the use of a 10-ohm resistor, while ASTM G 109 *Standard Test Method for Determining the Effects of Chemical Admixtures on the Corrosion Rate of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments* specifies a 100-ohm resistor.[30] Others have recommended that the macrocell be measured using a zero-resistance ammeter.

As part of the present studies, the authors placed different size resistors between the mats of an actively corroding black bar slab. Initially, with the 10-ohm resistor, a voltage drop of 4970 μV was measured, or a macrocell current of 497 μA. When a 1-ohm resistor was placed into the system instead of the 10-ohm resistor, the macrocell current increased slightly to 513 μA. Various other resistors ranging from 1 to 1000 ohm were systematically placed into the system and the macrocell corrosion currents were determined. Values of voltage and calculated currents are shown in table 4. During these studies, it was found that placing larger resistors into the system significantly increased the time period before the system stabilized. This factor is probably due to polarization of the concrete between the reinforcing bars.

When a 1-ohm resistor is used, the macrocell current increased by only 3 percent compared with the current determined using a 10-ohm resistor; however, when a 100-ohm resistor is used, the macrocell current was only 87 percent of that measured using the 10-ohm resistor. When a resistor of 1000 ohm was placed into the system between the reinforcing bar mats, the corrosion rate was only 41 percent of that measured using the 10-ohm resistor. These studies show that the resistor size is significant when considering macrocell measurements.

The mat-to-mat resistance measured for black reinforcing bar slabs was approximately 300 ohm. It can be considered that the current flows from the top to the bottom mat of reinforcing bars and that the concrete resistance works in parallel with the 10-ohm external measuring resistor.

Using basic circuit equations, with resistors in parallel, the ratio of current flowing through the concrete to that flowing through the exterior resistor can be determined. For a 10-ohm resistor, the current flowing through the concrete is only 3.2 percent of the total current, while for a 100-ohm resistor the current flowing through the concrete is 25 percent of the total current measured. These estimations of current flow, using basic circuit analogies, are similar to that measured on the actual concrete slabs.

Table 4. Measured voltages and calculated macrocell currents for various resistor sizes.

Resistor size, ohms	Voltage, µV	Current, µA	Percent of value at 10 ohm
10	4970	497	100.00
1	513	513	103.22
10	4943	494	99.46
100	43233	432	86.99
500	141500	283	56.94
1000	204800	205	41.21
10	4996	500	100.52

Based upon the above studies, it is clear that the 10-ohm resistor used in this study is significantly better than the 100-ohm resistor recommended by ASTM G 109. It further suggests that results obtained using the 10-ohm resistor would be comparable with those obtained using a zero-resistance ammeter (ZRA).

Concrete Properties

Concretes used by state transportation agencies typically are of high quality. A nominal water-cement (w/c) ratio of 0.47 was used in construction of the concrete slabs, as it is within the expected range for normal 0.45 w/c AASHTO Class A(AE) concrete for bridge construction. Tests using very low w/c ratios were considered; however, such tests would require more time than was available for the 2-yr in-concrete tests.

The concrete properties used for the test slabs, based upon the 30 concrete batches used to produce the 141 reinforced concrete slabs, are shown in table 5. After casting, the concrete specimens were cured under wetted burlap and polyethylene film for a period of 3 d, representing realistic field curing of bridge structures, but less than the 7-d AASHTO requirement.

Table 5. Concrete properties.

	Average (30 batches)	Standard deviation
Cement, kg/m^3 (lb/yd^3)	370 (623)	3.3 (5.56)
Air, %	5.6	0.51
Slump, mm (in)	167 (6.58)	31.7 (1.25)
Unit wt, kg/m^3 (lb/ft^3)	2315 (144.5)	21.0 (1.31)
w/c	0.47	0.01
28-d compressive strength, MPa (psi)	39.3 (5700)	2.7 (403.00)

Replicates

Typically, for the slabs containing black or epoxy-coated bars, four replicate specimens for each test condition were used. For the metallic-clad and solid metallic bars, three replicate specimens were used. This number of specimens enabled a single specimen to be autopsied after 48 weeks of testing, two specimens to be autopsied at the end of the 96-week test program and one to be retained for future investigations.

Ponding Procedures

Several wetting and drying procedures have been utilized by researchers trying to accelerate the corrosion process of steel in concrete. The following wetting and drying test cycle was used for this study.

- 3 d of drying at 38°C (100°F) and 60 to 80 percent relative humidity followed by 4 d under a 15 percent NaCl solution at 16 to 27°C (60 to 80°F) and 60 to 80 percent relative humidity for a period of 12 week.
- 12 weeks of continuous ponding under a 15 percent NaCl solution at 16 to 27°C (60 to 80°F) and 60 to 80 percent relative humidity.

The test area is shown in figure 5.

The long ponding period was utilized to simulate a sustained period of submersion or long periods of high humidity. Long wetting periods are also known to reduce coating adhesion. This 24-week cycle was repeated four times over a total test period of 96 weeks. Initial ponding commenced about 59 d after casting of the concrete slabs. The 15 percent salt solution has a concentration about five times that of normal seawater. It was chosen to represent high salt concentrations occurring on in-land bridge structures from deicing salts.

MEASUREMENT TECHNIQUES

Various measurements were made to enable the corrosion rates of the reinforcing bars to be determined. These included macrocell currents, linear polarization and ac impedance. All of these measurements provide a value that relates to the corrosion rate occurring at the instant of measurement.

Half-cell potentials, electrochemical impedance spectroscopy (EIS), and polarization resistance (PR) techniques have been used to investigate the corrosion performance of metals embedded in concrete and other potentially corrosive environments. Half-cell potential surveys are commonly conducted on bridges, garages, water tanks, precast concrete tunnel liners, building cladding systems, and many other structures. Polarization methods are being more frequently used in concrete inspections to estimate corrosion rates. EIS technology has only recently become available due to the complexity of the measurement devices. This method has many advantages over the PR methods as it enables not only the corrosion rates to be determined, but coating deterioration to be observed. EIS and PR testing were used in a study of epoxy-coated reinforcing in four decks for the Minnesota Department of Transportation to nondestructively locate areas of damaged coating prior to core sampling[13]. Further discussion of the test methods is presented in reference 16.

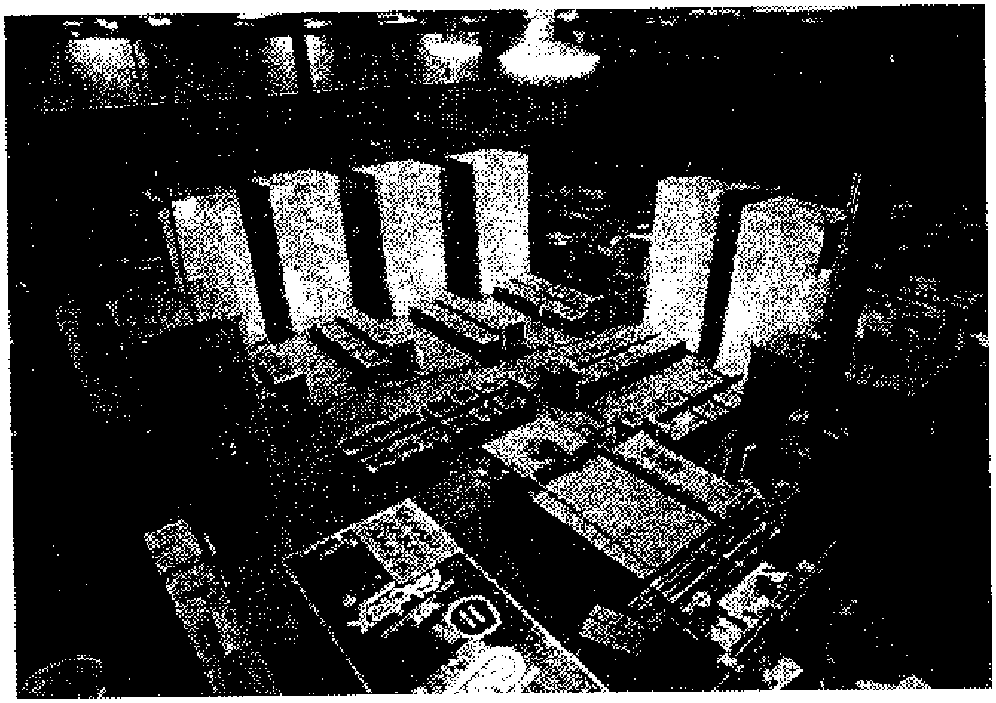

Figure 5. Test area for in-concrete cyclic testing program.

Macrocell Currents

The macrocell current is the current determined from measuring the voltage drop across the 10-ohm resistor that is placed between the top-mat bar and the two lower mat reinforcing bars. It should be noted that the anode-cathode ratio will change the measured macrocell currents in these concrete tests.

The relationship between the voltage drop across the resistor and the macrocell current is shown below:

Macrocell current, amp = voltage measured across resistor, ohm ÷ size of resistor, ohm

For black bars after initiation of corrosion, the voltage drop was approximately 4000 μV. Thus, the macrocell current was 400 μA.

A bar that is 16 mm (5/8 in) in diameter and has a length of 254 mm (10 in) has an area of ($\pi \times 16 \times 254$) = 12767 mm^2 (19.8 in^2). From use of the macrocell current (400 μA), the unit area (12767 mm^2), the atomic weight of iron (55.8 g/mol), Faraday's constant (96489 coulombs/mol), the density of iron (7.68 mg/mm^3) and the electron charge change during corrosion (two electrons), the steel loss per year per unit area can be determined, as shown below:

Metal loss per year

= (time period x atomic weight x current)
÷ (Faraday's constant x charge change x steel density x area)

= (365 x 24 x 60 x 60 s/yr x 55.8 g/mol x 400 x 10^{-6} amp)
÷ (96489 amp.seconds/mol x 2 x 7.68 x 10^{-3} g/mm^3 x 12767 mm^2)

= 0.037 mm/yr (1.5 mil/yr)

If it is assumed that 1 mil of corrosion metal loss will cause cracking of concrete, slabs containing black reinforcing bars would be expected to crack within approximately 35 weeks of testing. All slabs containing black bars were cracked within 48 weeks of testing, indicating that the time-to-cracking calculations using macrocell values are appropriate.

Using similar calculations, it may be shown that a macrocell voltage of 27 μV would result in corrosion of 0.025 mm/100 years (1 mil/100 years). Using a conservative assumption, it may be assumed that stable macrocell voltages of less than 10 μV do not pose a corrosion risk.

Copper-Copper Sulfate Half-Cell Testing

Copper-copper sulfate half-cell testing uses basic electrochemical techniques to give an indication of the corrosion state of reinforcing steel in concrete. The test is performed by measuring the voltage difference between the reinforcing steel and a reference cell, called a "half-cell." A piece of copper immersed in a saturated solution of copper sulfate is used as a reference cell. The test methodology is described in detail in ASTM C 876, *Standard Test Method of Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete*[31].

The test is performed by connecting the positive terminal of a high-impedance voltmeter to the top reinforcing bar, and the negative terminal to the copper/copper-sulfate reference cell. Once the connections are made, the readings are taken by holding the junction sponge of the reference cell in contact with the concrete and recording the observed voltage.

Previous FHWA-funded work on laboratory slabs containing black steel has found the threshold of corrosion to be indicated by readings more negative than -0.230 V[25]. Typically, readings more negative than this on bridge decks with black uncoated reinforcing steel indicate active corrosion, while those less negative indicate no corrosion.

EIS Testing

EIS testing is performed by applying a low-amplitude alternating current (ac) potential between the reinforcing bar and a counter electrode on the surface of the concrete and measuring the response of the system.

In the standard EIS technique, the system impedance (in this case, the bar, coating, and concrete) is measured over a large range of applied frequencies and the electrical properties of the test specimen are measured. The data are often presented in the form of a Bode plot, which shows the measured phase shift (θ), and the absolute impedance ($|Z|$) as a function of the frequency of the applied ac potential. The corrosion characteristics are then interpreted from the plots using the measured phase shifts, system impedances, and frequencies. The main information gained from the Bode plots are the impedances and the phase shifts. Depending on the system characteristics and the frequencies tested, the impedances represent the sum of one or more of the concrete resistance, the resistance of the coating, and the polarization resistance (PR) of the reinforcing steel. Except in very isolated cases, the measured impedances decrease with increasing frequency, as the effects of PR and coating resistance are effectively bypassed at high frequencies. The phase shift data also can inform about the capacitive behavior of the system as coatings on steel tend to act as capacitors during EIS testing.

EIS tests were performed on the bars over a frequency range of 0.1 to 100,000 Hz. The tests were performed with a PARC EG&G Model 273A potentiostat and a PARC EG&G 5210 Lock-In Amplifier, both computer-controlled. The measurements taken in the frequency ranges of 0.1 to 10 Hz were performed using a multi-sine technique in which the coated bar and concrete are subjected to a pseudo-white noise, and the discrete frequency response of the concrete/bar coating system is back-calculated using a fast-Fourier-transform technique. Measurements were made using a 178- by 76-mm (7- by 3-in) copper mesh counter electrode, as shown in figure 6.

Most of the EIS work was performed at an applied ac potential of ±10 mV, centered around the equilibrium potential measured using the copper-copper sulfate electrode of the reinforcing bar under test. A 10-mV amplitude was chosen to improve data quality without using excessively high potentials. Equipment and time limitations prevented scanning at frequencies higher than 100,000 Hz or lower than 0.1 Hz.

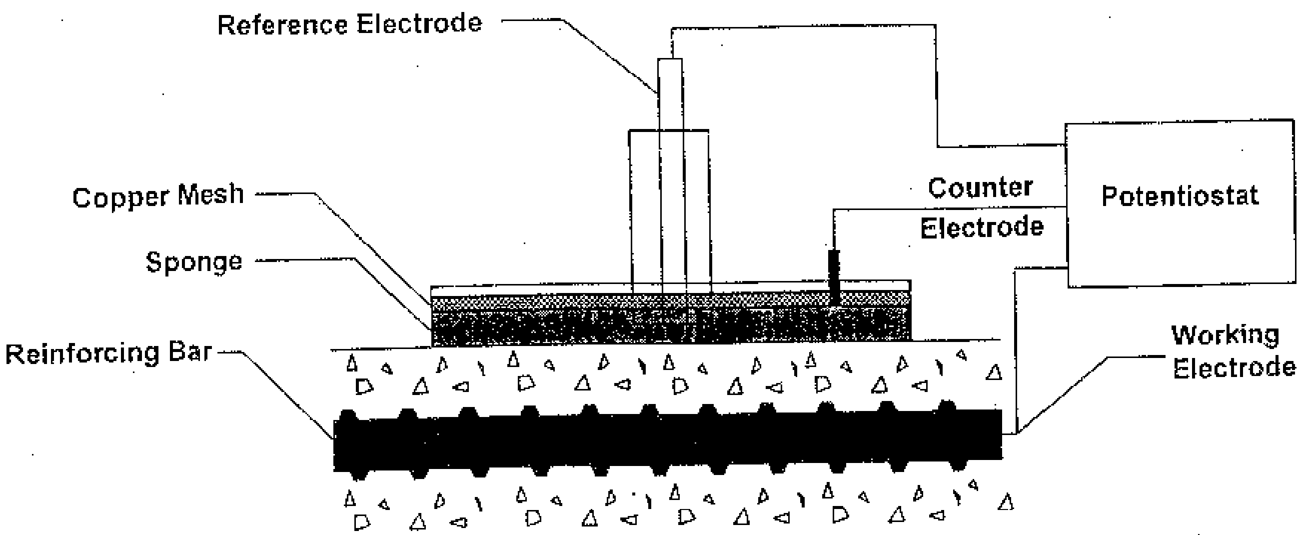

Figure 6. Setup of cell for PR testing.

Polarization Resistance Testing

The PR technique for the determination of corrosion rates has been used by corrosion engineers for a relatively long period of time. However, it has recently become more commonly utilized in the field for inspection of corroding concrete structures. PR uses simplified electrochemical corrosion theory to estimate corrosion rates of metals in corroding systems. Measurements are made using a potentiostat to force the area under test to deviate slightly (±10 mV) from its equilibrium corrosion potential using an externally applied electrical current. Because the specimen potential and the corrosion current are approximately linear over the small potential range measured, the measured changes in potential (ΔE) and applied current ($\Delta i_{applied}$) can be used to determine the corrosion rate (i_{corr}) of the system using the equation shown below.

$$\frac{\Delta E}{\Delta i_{applied}} = \frac{\beta_a \beta_c}{2.3(i_{corr})(\beta_a + \beta_c)}$$

In order to use the above equation, the Tafel slopes of the anodic and cathodic portions of the current versus potential relationship for the system, β_a and β_c, must be known or assumed. Although the equation is relatively insensitive to the β values, it is typical to assume a value of 0.12 V/decade for β_a and β_c for carbon-steel-based systems such as black or epoxy-coated reinforcing bars. Because of the Tafel slope assumptions, and the approximate relationship on which the test is based, the technique is limited in accuracy and calculated corrosion rates are only accurate to within a factor of 3 or 4. The test is very useful, however, in showing order-of-magnitude differences in the reinforcement behavior.

The greatest limitation of PR testing is its poor performance in high-resistance media, such as dry concrete. Under those conditions, the high electrical losses due to the concrete between the counter electrode supplying current and the bar under test may prevent the potentiostat from supplying sufficient current to shift the potential of the specimen from its equilibrium potential. This problem was avoided in the present study by testing the concrete in a moist condition soon after the chloride solution was removed. If the slab surfaces had visibly dried, they were lightly misted with water before testing.

The PR test was performed by making a connection to the reinforcing steel and monitoring its potential while an external current is applied, as shown schematically in figure 6. The current applied between the counter electrode and the reinforcing bars is automatically changed to produce a ±10-mV potential shift (ΔE) between the reinforcing steel and the reference cell. The current ($i_{applied}$) flowing between the counter electrode and the reinforcing steel is measured by the potentiostat and used to compute the corrosion rate using the equation shown above. For these tests, the exposed bar was 254 mm (10 in) in length with a diameter of 16 mm (⅝ in). Thus, an exposed area of 12,667 mm^2 (19.6 in^2) was polarized. Using this assumed polarized area, a PR measurement of 3500 ohm is equivalent to a corrosion density of 0.58 mA/m^2 (0.05 mA/ft^2) and a PR of 100 ohm is equivalent to a corrosion density of 20.5 mA/m^2 (1.90 mA/ft^2).

A difficulty arises in this test in that, like the EIS testing, an appropriate area for the normalization of the calculated currents must be estimated. This is done by dividing the raw polarization resistance value (in ohms) by the area under test. Although this is easily done for the bare bars, it is not as clear-cut for the coated bars because although the area of the entire bar is the same as that of the black bars, the bare area actually disturbed by the external current is very small. If the nominal exposed metal area for the intentionally damaged epoxy-coated bars is used, the calculated corrosion rates per unit area of exposed steel will be very large. The large computed value, however, is very deceiving because there is very little total corrosion (computed as the corrosion rate per unit area multiplied by the affected area) taking place. Because of this deceiving and overpowering effect of the area correction, it is more appropriate to treat the corrosion as taking place over the entire length of the bars under test.

PR tests were performed on pairs of test bars for each test condition at the start and conclusion of testing. Also, selected bars were monitored at intervals during the testing. The tests were performed using a computer-controlled PARC EG&G Model 273A potentiostat. At each test slab, the connection to the test bar was made using the same external connections used for the manual monitoring. The bottom-mat bars were electrically disconnected from the top-mat bars during the tests. A 178- x 76-mm (7- x 3-in) counter electrode was aligned on the concrete surface directly over the reinforcing bar under test as shown in figure 6. The corrosion potentials were monitored using a copper-copper sulfate reference electrode. The tests were performed over a potential range of the initial potential ±10 mV, used no internal current/resistance (IR) compensation, no filtering, and a scan rate of 0.167 mV/s.

Mat-to-Mat Resistance Testing

Mat-to-mat resistance measurements were made using a Neilson soil resistance meter. This ac resistance meter uses a bridge-type measurement to determine ac impedance. Measurements of the impedance between the top and bottom mats of steel were made using this equipment. In order to measure the mat-to-mat resistance, the electrical connections between the top and bottom mats were separated and the meter was placed in series between the two mats. After measurement, the electrical connection between the two layers of steel using a 10-ohm resistor was re-established.

CHAPTER 4. MACROCELL, MAT-TO-MAT RESISTANCE AND CONDITION OF SLABS AT END OF TEST PERIOD

INTRODUCTION

As discussed in chapter 2, bars selected for the in-concrete tests were:

- ASTM A 615 black reinforcing bar (BL)
- Epoxy-coated bars coated with 3M Scotchkote 213 (Epoxy-A)
- Two bendable epoxy-coated bar types (Epoxy-B, Epoxy-C)
- Two nonbendable epoxy-coated bar types (Epoxy-D, Epoxy-E)
- One post-baked nonbendable epoxy-coated bar type (Epoxy-F)
- ASTM A 767 galvanized reinforcing bars (GL)
- Zinc alloy-clad reinforcing bars (SM)
- Copper-clad bars (CU)
- ASTM A 955 Type 304 solid stainless steel reinforcing bars (304)
- ASTM A 955 Type 316 solid stainless steel reinforcing bars (316)

Of the six epoxies chosen, three utilized steel pretreatments prior to coating (Epoxy-B, Epoxy-C, and Epoxy-E) and three did not (Epoxy-A, Epoxy-D, and Epoxy-F).

Appendix A contains tables showing the voltages measured across the resistor and mat-to-mat resistances measured for the various configurations and types of specimens. This appendix also contains adhesion data obtained from the epoxy-coated bars after 96 weeks of testing and the autopsy information for the individual bars. Results from the tests are discussed below.

CORROSION ACTIVITY

Black Bars (BL)

Figures 7 and 8 show the general shape of the measured macrocell voltages measured on a 6-h interval over the 96-week test period for black bars in uncracked and precracked concrete, respectively. The two curves are similar; however, corrosion initiates much more rapidly in the precracked specimens than the uncracked specimens. The periods of wetting and drying and the periods of ponding are readily recognized by the changes in the measured voltages. The bars have a higher corrosion rate during the 12-week wetting and drying periods than during the 12-week constant ponding periods, probably due to the higher oxygen availability.

From the data shown in figures 7 and 8, an average voltage was determined for each condition. Tables 6 and 7 show the average voltages measured across the resistor and the average mat-to-mat resistance measured between the two layers of reinforcing bars during the 96 weeks of testing for the black and epoxy-coated reinforcing bars.

Black bars were tested in three configurations: straight uncracked, straight precracked, and bent uncracked. Average macrocell voltages were 3525, 4053 and 2141 µV, respectively. The overall average voltage for all the black bar conditions during the 96-week period for the precracked specimens was 15 percent greater than that of the uncracked specimens. As soon as the salt solution was placed on the precracked concrete, corrosion of the black bars was measured; however, it was almost 12 weeks before the non-cracked specimens began to show corrosion. This observation has significant importance to all reinforcing bar systems in that the use of high-quality concrete materials and other protection systems such as pozzolans will not prevent corrosion if concrete cracks are not repaired.

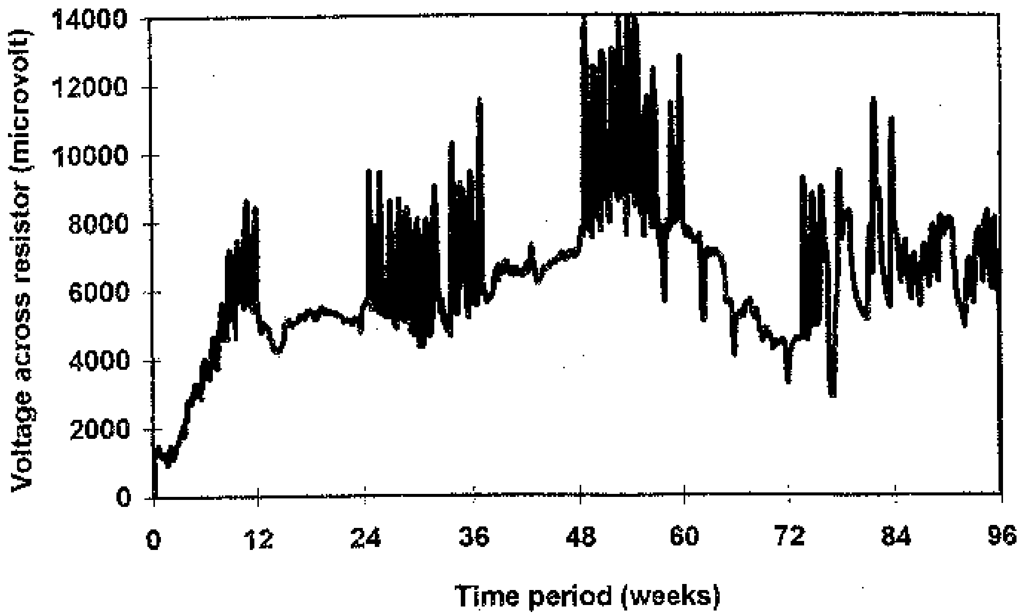

Figure 7. Measured voltage from an uncracked specimen with black bars.

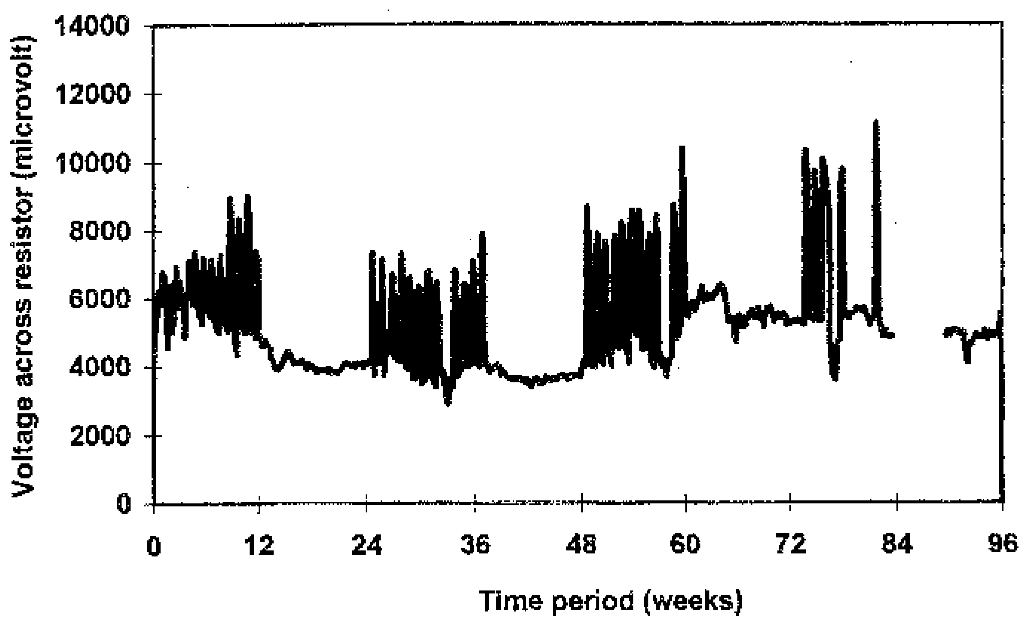

Figure 8. Measured voltage from a precracked specimen with black bars.

Table 6. Average voltage across resistor for two replicate samples — black and epoxy-coated bars, µV.

Test Condition	Black	A	B	C	D	E	F
Straight bar, black cathode, uncracked, 0.5 percent damage	3525	25	246	538	48	925	1907
Straight bar, epoxy cathode, uncracked, 0.5 percent damage		3	4	12	14	14	23
Bent bar, black cathode, uncracked, 0.5 percent damage	2142	388	308	803	302	8	1716
Straight bar, black cathode, precracked, 0.5 percent damage	4054	596	654	1037	113	1510	1883
Straight bar, black cathode, uncracked, 0.004 percent damage		3	2	43	12	125	543
Straight bar, epoxy cathode, uncracked, 0.004 percent damage		2	3	3	13	4	51
Bent bar, black cathode, uncracked, 0.004 percent damage		5	4	79	19	4	1246
Straight bar, black cathode, precracked, 0.004 percent damage		78	600	248	14	459	592

Table 7. Average mat-to-mat resistance for two replicate samples — black and epoxy-coated bars, ohms.

Test Condition	Black	A	B	C	D	E	F
Straight bar, black cathode, uncracked, 0.5 percent damage	240	3200	3400	1700	3500	1800	800
Straight bar, epoxy cathode, uncracked, 0.5 percent damage		5900	9300	7200	6900	4400	3700
Bent bar, black cathode, uncracked, 0.5 percent damage	340	1300	1900	1400	2700	3800	700
Straight bar, black cathode, precracked, 0.5 percent damage	260	1300	2900	830	1700	820	590
Straight bar, black cathode, uncracked, 0.004 percent damage		360000	540000	510000	660000	740000	90000
Straight bar, epoxy cathode, uncracked, 0.004 percent damage		490000	560000	530000	940000	260000	480000
Bent bar, black cathode, uncracked, 0.004 percent damage		14000	97000	170000	69000	170000	58000
Straight bar, black cathode, precracked, 0.004 percent damage		15000	4000	21000	100000	63000	13000

The mat-to-mat resistance measured for a specimen containing black bars in uncracked concrete is shown in figure 9. The average for the specimens containing the black bars during the 96 weeks of testing specimens was 280 ohm.

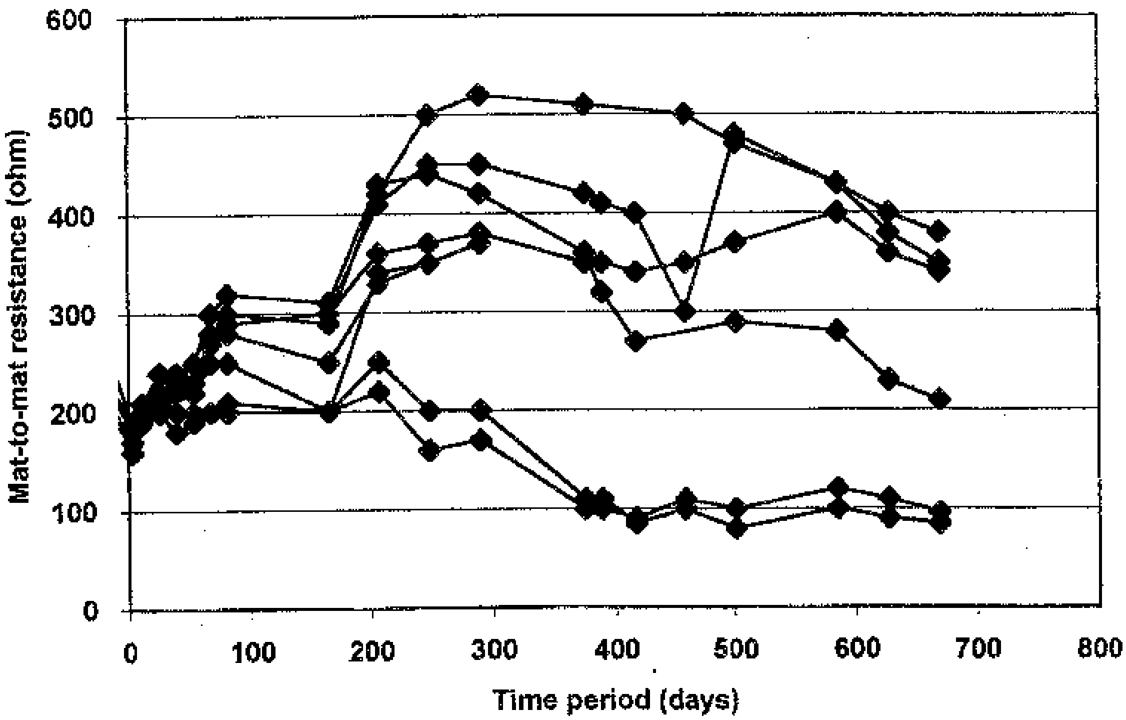

Figure 9. Measured mat-to-mat resistance for uncracked specimens with black bars.

After 96 weeks of testing, all 12 specimens exhibited cracking of their top surfaces and all top anodic bars exhibited severe corrosion. Only two of the bottom-mat bars exhibited corrosion. On several bars, green rust was identified, as shown in figure 10. A sample of this corrosion product was rapidly analyzed using x-ray diffraction techniques and identified as the iron-hydroxide-chloride "Green-rust-I." This green color disappeared within approximately 30 minutes, leaving a residual typical red oxide.

Figure 11 shows the relationship between the measured half-cell potential for the black bars and the macrocell currents in uncracked concrete determined at the same time. In general, values more positive than -200 mV indicate no corrosion, while values more negative than approximately -250 mV indicate corrosion activity.

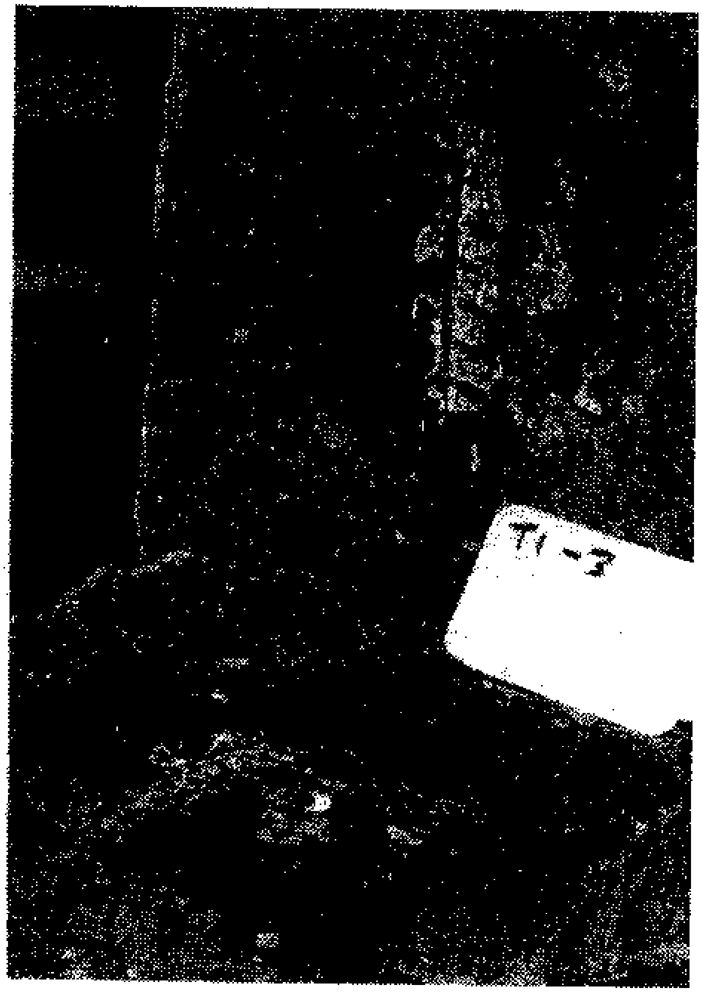

Figure 10. Green colored iron-hydroxide-chloride rust deposits on black bars.

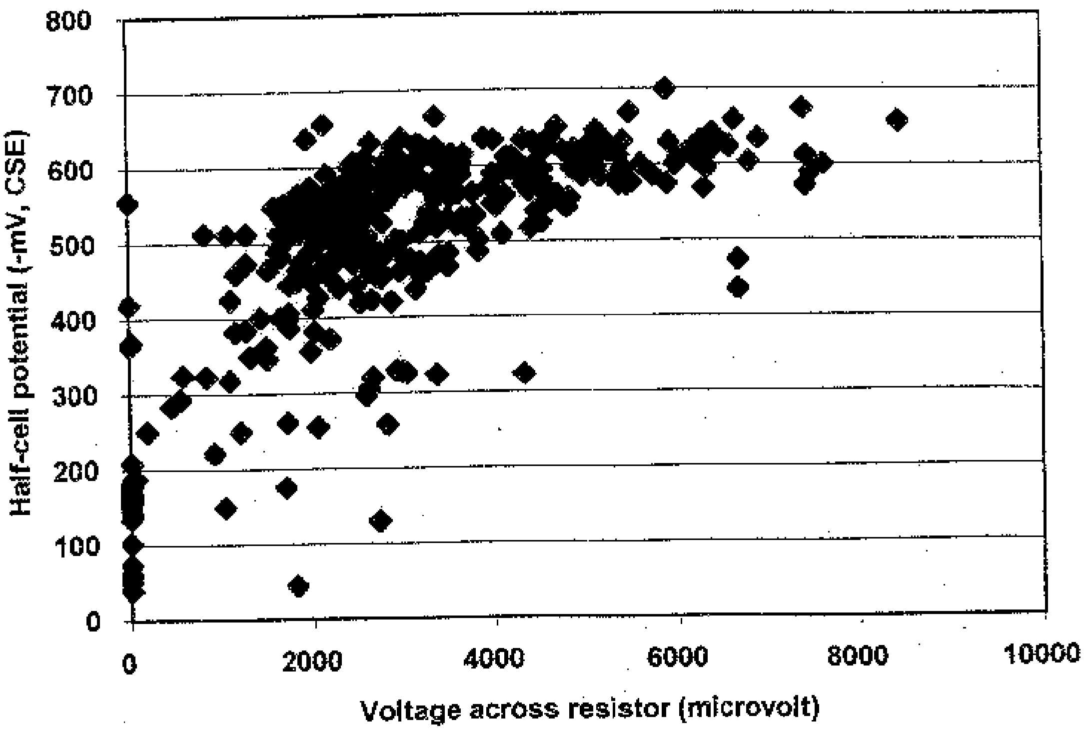

Figure 11. Measured voltage across resistor and half-cell potentials for all specimens with black bars.

Epoxy-Coated Bars (Epoxies A, B, C, D, E and F)

The six different types of epoxy-coated bars (Epoxy-A to Epoxy-F) were tested in eight different configurations. Data for these bars are shown in tables 6 and 7, while table 8 shows the range of the macrocell-corrosion and mat-to-mat resistance of the six epoxy-coated bar types relative to the average for the three test conditions from the black bars, along with the condition of the slabs after 96 weeks of testing. The average performance of the epoxy-coated bars in each of these conditions during the 96-week period is discussed below.

Straight, black cathode, uncracked, 0.5 percent damage – The average voltages measured across the 10-ohm resistor ranged from 25 to 1907 µV. Thus, under this condition, the corrosion ranged from 1.8 to 141 times lower than the black bars. The corrosion rates of bars with Epoxy-F were substantially greater than that of the other five products, while Epoxy-A and Epoxy-D exhibited the lowest corrosion rates. Corrosion determined for replicate bars with Epoxy-B, Epoxy-C, and Epoxy-E had poor repeatability.

Average mat-to-mat resistance values for the six coatings ranged from 800 to 3500 ohm. These were approximately 3 to 14 times that of the black bars. The amount of corrosion measured correlated well with the mat-to-mat resistances. The mat-to-mat resistance values determined for Epoxy-C, Epoxy-E and Epoxy-F were significantly lower than that of Epoxy-A, Epoxy-B and Epoxy-D.

After 96 weeks of testing, the condition of the slabs and bars was as follows. The concrete slabs containing bars with Epoxy-A, Epoxy-D, and Epoxy-E did not exhibit any surface distress, while one slab with Epoxy-B exhibited minor corrosion at the end of the concrete specimen. A single slab with Epoxy-C was cracked, while both slabs containing Epoxy-F were stained and cracked. These observations correlate well with the average voltage across the 10-ohm resistor.

Table 8. Epoxy-coated and black bar test results.

Bar type and test condition	Average macrocell voltages (μV)	Mat-to-mat resistance (times greater than the black bar specimens)	Slab condition after 96 weeks of testing
Average Black - straight bar, uncracked concrete - straight bar, precracked concrete - bent bar, uncracked concrete	3525 2142 4054	—	All slabs cracked
Six different epoxy-coated bar types			
Straight, black cathode, uncracked, 0.5 percent damage	25 to 1907	3 to 14	Slabs with coatings Epoxy-C and Epoxy-F cracked
Straight, epoxy cathode, uncracked, 0.5 percent damage	3 to 23	15 to 38	No cracked slabs
Bent, black cathode, uncracked, 0.5 percent damage	8 to 1716	2.1 to 11	Slabs with Epoxy-B, Epoxy-C, and Epoxy-F cracked
Straight, black cathode, precracked, 0.5 percent damage	113 to 1883	3.1 to 11	Slabs with Epoxy-C, Epoxy-E, and Epoxy-F exhibited extension of precrack
Straight, black cathode, uncracked, 0.004 percent damage	2 to 543	375 to 3083	Slabs with Epoxy-F cracked
Straight, epoxy cathode, uncracked, 0.004 percent damage	2 to 51	1083 to 3916	No cracked slabs
Bent, black cathode, uncracked, 0.004 percent damage	4 to 1246	41 to 500	Slabs with Epoxy-F cracked
Straight, black cathode, precracked, 0.004 percent damage	14 to 600	15 to 384	Rust staining for Epoxy-E and Epoxy-F

Bars with Epoxy-C, Epoxy-E, and Epoxy-F exhibited cracks in the coating, while bars with Epoxy-A, Epoxy-E, and Epoxy-F exhibited surface corrosion, ranging from minor for Epoxy-A to significant for Epoxy-F. Epoxy-B and Epoxy-C exhibited unusual white deposits on the bar surface between the coating and the bar.

Bars tested in this condition exhibited poor adhesion at the drill hole. Epoxy-A and Epoxy-D had low macrocell corrosion and excellent away-from-hole adhesion, while Epoxy-C, Epoxy-E, and Epoxy-F had high macrocell corrosion and poor away-from-hole adhesion. In general, bars with severe corrosion also had low adhesion of the coating to the bars.

Straight, epoxy cathode, uncracked, 0.5 percent damage — The average voltages measured across the 10-ohm resistor ranged from 3 to 23 μV. Thus, under this condition, the corrosion ranged from 150 to 1175 times lower than the black bars. The corrosion rates of all bars are considered to be very low. In this condition, the bars with Epoxy-F had greater corrosion than the other products, while Epoxy-A and Epoxy-B exhibited the lowest corrosion rates.

Use of the coated cathode significantly reduced the corrosion rates of all bar types, suggesting that the corrosion mechanism of epoxy-coated bars may be inhibition of the cathodic reaction that requires electrons, oxygen, and hydroxide to be present at the cathode bar surface.

The highest mat-to-mat resistances were obtained by Epoxy-B, Epoxy-C, and Epoxy-D, while the lowest resistance was obtained by Epoxy-F. The mat-to-mat resistances of these specimens were 15 to 38 times greater than the black bars.

None of the slabs exhibited any surface distress at the end of the 96 weeks; however, most of the bars exhibited some underfilm corrosion. Epoxy-C exhibited blisters at several locations along the bar. The at-the-hole adhesion for the anode was poor in all cases except for Epoxy-D, which exhibited slightly better adhesion than the other five systems. The at-the-hole adhesion for the cathode was very mixed, ranging from excellent to poor. Epoxy-C and Epoxy-E exhibited significant variations between the adhesion of their two replicates.

The away-from-the-hole adhesion for the anode was mixed, ranging from excellent to poor, and the bendable Epoxy-A, Epoxy-B, and Epoxy-C exhibited poor replication. The away-from-the-hole adhesion for the cathode was excellent in all cases.

Bent, black cathode, uncracked, 0.5 percent damage — The average voltages measured across the 10-ohm resistor ranged from 8 to 1716 μV. Thus, under this condition, the corrosion ranged from 1.2 to 257 times lower than the bent black bars. The corrosion rates of bars with Epoxy-F were substantially greater than that of the other products, while Epoxy-E exhibited the lowest corrosion rate. The corrosion rate of all bars was considerably greater than that of Epoxy-E.

The bent bars with Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-D exhibited greater macrocell corrosion than their companion straight bars. This increase in corrosion currents for Epoxy-A, Epoxy-B, and Epoxy-C may be explained by cracking and stresses in the coating caused by the bending, while increases in currents for Epoxy-D may be explained by manufacturing problems with the bent bars. It is highly unusual that the bent bars with Epoxy-E exhibit such dramatic differences between the bent and straight bars, suggesting significant manufacturing differences between the two bar types. Epoxy-F exhibits extremely high corrosion currents.

The highest mat-to-mat resistances were obtained by Epoxy-E, while the lowest resistance was obtained by Epoxy-F. Values obtained were 2.1 to 11 times that of the bent black bar slabs. For all systems, apart from Epoxy-E, the mat-to-mat resistance of the bars significantly decreased when the coatings were tested in the bent condition. The data suggest that the Epoxy-E bent bars were significantly different from the Epoxy-E straight bars.

Slabs containing bars with Epoxy-B, Epoxy-C, Epoxy-D, and Epoxy-E exhibited some concrete surface cracking when tested in this condition, while one slab with Epoxy-D exhibited some concrete surface staining. Corrosion of bars with Epoxy-E would be described as minor. Epoxy-C and Epoxy-F exhibited cracking in the coatings, while Epoxy-B exhibited some blistering. In only one case was corrosion observed on a bottom-mat bar.

All at-the-hole adhesion values are considered to be poor, while away-from-hole adhesion for Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-D are considered to be poor. Away-from-hole adhesion of coating F is considered to be excellent.

Based upon previous results from screening tests[16,17], it was expected that the adhesion of Epoxy-A, Epoxy-B, and Epoxy-C would decrease when bent. Epoxy-A exhibited excellent away-from-hole adhesion when tested straight, but poor adhesion when tested in the bent condition. It was unexpected that Epoxy-D exhibited a similar property, as this nonbendable coating had been applied to prebent bars. It was also unexpected that Epoxy-E and Epoxy-F exhibited improvements in away-from-hole adhesion when tested in the bent condition. The data suggest that the nonbendable epoxy coatings are susceptible to manufacturing differences and that extra care may be required when coating products of different shapes, since all three nonbendable Epoxy-D, Epoxy-E, and Epoxy-F had significant variability in adhesion performance.

Straight, black cathode, precracked, 0.5 percent damage – The average voltages measured across the 10-ohm resistors ranged from 113 to 1883 μV. Thus, under this condition, the corrosion ranged from 2.1 to 36 times lower than the straight black bars in precracked slabs. The corrosion rates of bars with Epoxy-F were substantially greater than that of the other products, while Epoxy-A and Epoxy-D exhibited the lowest corrosion rates.

The highest mat-to-mat resistances were obtained by Epoxy-A, Epoxy-B, and Epoxy-D, while the lowest resistance was obtained by Epoxy-F. These resistance values were approximately 3.1 to 11.1 times that of the straight black bars in precracked concrete.

Slabs containing Epoxy-A, Epoxy-B, and Epoxy-D did not exhibit any concrete surface distress, while slabs containing Epoxy-C, Epoxy-E, and Epoxy-F exhibited some extension of the initial precrack. In many cases, significant corrosion was observed on the bar surfaces during the autopsies. Bars with Epoxy-A, Epoxy-B, Epoxy-D, and Epoxy-E exhibited blisters, while Epoxy-C and Epoxy-F exhibited cracks in the coatings.

In general, bars tested in this condition exhibited poor adhesion at the drill hole. In general, the adhesion measured away from the drill hole correlated well with the macrocell corrosion. Epoxy-A and Epoxy-D had low macrocell corrosion and excellent adhesion, while Epoxy-C and Epoxy-F had high macrocell corrosion and poor adhesion.

Straight, black cathode, uncracked, 0.004 percent damage – The average voltages measured across the 10-ohm resistors ranged from 2 to 543 μV. Thus, under this condition, the corrosion ranged from 6.5 to 1762 times lower than the straight black bars in uncracked concrete. The corrosion rates of bars with Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-D are very low, while the corrosion rates of Epoxy-E and Epoxy-F were substantially greater; however, they were still significantly lower than that of the black bars.

Decreasing the coating damage percentage to 0.004 percent significantly reduced the corrosion rate in all cases, suggesting that for reduced corrosion rates, it would be important to reduce damage to the coated reinforcing bar.

Resistance values were 375 to 3083 times greater than that of the straight black bar specimens in uncracked concrete. The highest mat-to-mat resistances were obtained by Epoxy-B, Epoxy-C, and Epoxy-D, while the lowest resistance was obtained by Epoxy-F. These values are significantly greater than that measured for the bars with the 0.5 percent damage formed using two 6-mm (¼-in) drill holes, suggesting that mat-to-mat resistances are greatly affected by the amount of exposed metal surface.

All slabs, except those containing bars with Epoxy-F, had no concrete surface corrosion or cracking after the 96 weeks of testing. In addition, bars with Epoxy-A, Epoxy-B, and Epoxy-D had no surface corrosion on the bars, while coating Epoxy-C exhibited some cracking of the coating, coating Epoxy-E exhibited minor rust staining, and coating Epoxy-F exhibited significant corrosion staining of the bars. Corrosion of the cathode was not observed in any slabs.

The at-hole adhesion for the various coatings ranged from excellent for Epoxy-A, Epoxy-B, and Epoxy-D to mixed for Epoxy-C, Epoxy-E, and Epoxy-F. This suggests that manufacturing or other differences are playing a role in the adhesion performance of Epoxy-C, Epoxy-E, and Epoxy-F.

Straight, epoxy cathode, uncracked, 0.004 percent damage – The average voltages measured across the 10-ohm resistor ranged from 2 to 51 μV. Thus, under this condition, the corrosion ranged from 69 to 1762 times lower than the straight black bars. The corrosion rates of bars with Epoxy-F were substantially greater than that of the other products; however, all coatings exhibited very low corrosion rates.

Resistance values were approximately 1083 to 3916 times greater than that of the straight black bars in uncracked concrete. The highest mat-to-mat resistances were obtained by Epoxy-A, Epoxy-B, and Epoxy-D, while the lowest resistance was obtained by Epoxy-E.

In all cases under this condition, the concrete slabs did not exhibit any distress, nor did the anodic or cathodic bars exhibit surface distress. In all cases, except for one bar with Epoxy-E, the at-hole adhesion for the bars was excellent.

Bent, black cathode, uncracked, 0.004 percent damage – The average voltages measured across the 10-ohm resistors ranged from 4 to 1246 μV. Thus, under this condition, the corrosion ranged from 2.8 to 881 times lower than the black bars. The corrosion rates of bars with Epoxy-F are substantially greater than that of the other products, while Epoxy-A, Epoxy-B, and Epoxy-E exhibited the lowest corrosion rates. One bar with Epoxy-F exhibited significantly greater corrosion than the other, indicating variability in this product.

For Epoxy-A, Epoxy-B, and Epoxy-D, the macrocell corrosion results for the straight and bent bars are similar. The macrocell corrosion rates for the bent bars with Epoxy-C and Epoxy-F are significantly greater than that of the straight bars, while the average for the straight bars with Epoxy-E are significantly greater than that of the bent bars.

The mat-to-mat resistance for bars with Epoxy-A are substantially lower than that of the other products, probably a result of holidays formed during bending. The highest mat-to-mat resistances were obtained by Epoxy-B, Epoxy-C and Epoxy-E. The values are 41 to 500 times that of the bent black bar specimens.

Except for a single slab with Epoxy-F, none of the slabs exhibited corrosion staining or cracking. Underfilm corrosion was observed for Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-F, while no corrosion was observed for Epoxy-D and Epoxy-E. None of the cathodic bars exhibited corrosion.

Epoxy-A, Epoxy-B, and Epoxy-C exhibited poor at- and away-from-hole adhesion ratings. Epoxy-D exhibited excellent at-hole adhesion and good away-from-hole adhesion; while Epoxy-E and Epoxy-F exhibited variable coating adhesion.

Straight, black cathode, precracked, 0.004 percent damage – The average voltages measured across the 10-ohm resistors ranged from 14 to 600 μV. Thus, under this condition, the corrosion ranged from 6.7 to 289 times lower than the straight black bars in precracked concrete. The corrosion rates of bars with Epoxy-F are substantially greater than that of the other five products, while Epoxy-A and Epoxy-D exhibited the lowest corrosion rates.

The highest mat-to-mat resistances were obtained by Epoxy-A, Epoxy-B, and Epoxy-D, while the lowest resistance was obtained by Epoxy-F. Resistance values were variable for all coating systems. These resistance values were approximately 15 to 384 times that of the straight black bars in precracked concrete.

At the end of 96 weeks of testing, only bars with Epoxy-E and Epoxy-F exhibited any surface corrosion. Bars in slabs containing Epoxy-A, Epoxy-B, and Epoxy-E exhibited blisters, while Epoxy-C and Epoxy-F exhibited cracks in the coating. Epoxy-D was free from blisters and corrosion. Only one bottom-mat bar exhibited any corrosion. In general, bars tested in this condition exhibited poor adhesion at the drill hole, and the adhesion measured away from the drill hole correlated well with the macrocell corrosion. Epoxy-A and Epoxy-D had low macrocell corrosion and excellent adhesion, while Epoxy-C and Epoxy-F had high macrocell corrosion and poor adhesion.

Relationship between coating resistance and corrosion current – Figure 12 shows the relationship between the mat-to-mat resistance determined for the epoxy-coated bars and the voltages measured across the resistor. In general, low corrosion rates are obtained for samples where the mat-to-mat resistance exceeds 10,000 ohm. This resistance value is approximately 25 times greater than that measured for the black bar specimens. As the mat-to-mat resistance falls, there is a roughly linear relationship between lower mat-to-mat resistances and higher corrosion rates. It may be concluded from these data that better corrosion protection will be provided by those coating systems that have high electrical resistivities and/or that the corrosion rates are strongly dependent on the amount of damage in the coating.

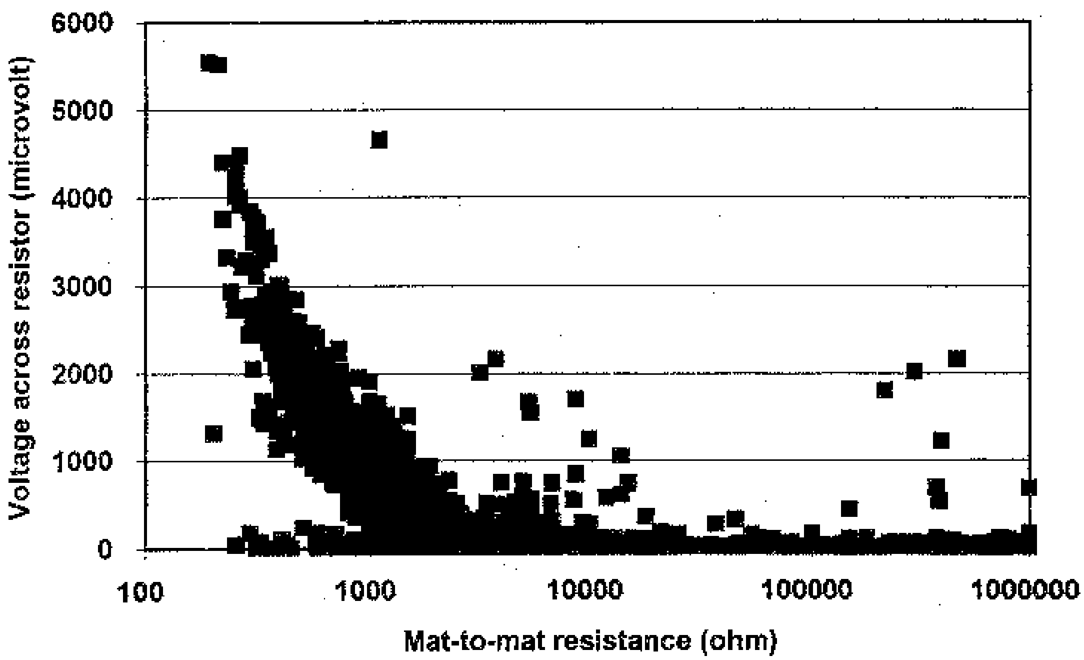

Figure 12. Relationship between mat-to-mat resistance and voltage measured across resistor for epoxy-coated bars.

Comparison of in-concrete and accelerated adhesion testing of epoxy-coated bars – During the first 2½ yr of the project, considerable work was conducted investigating the adhesion of the coatings using solution immersion tests and cathodic debonding tests. This work is reported in detail in references 13 and 14. The aim of the tests was to enable selection of products with a wide range of adhesion properties for the in-concrete tests.

Adhesion testing results from the screening tests reported in reference 14 are summarized in table 9 along with the coating identification code used in the prescreening tests. This table shows the percentage of excellent to good adhesion ratings obtained from the various products. It should be noted that the reference 14 report does not contain screening data for Epoxy-F.

Table 9. Adhesion results from Phase II screening tests, percentage of bars with excellent adhesion, 1 and 2 ratings.

Epoxy	A	B	C	D	E
Bar identification in reference 17	B31	B33	B35	N6	N3
Solution immersion tests, p. 43, reference 17					
Overall	13	38	19	77	79
At hole	0	13	8	58	67
Away from hole	25	63	29	96	92
Cathodic debonding tests, p. 73, reference 17					
Overall	20	40	40	60	98
At hole	0	10	30	36	95
Away from hole	40	70	50	95	100
Solution immersion and cathodic debonding tests, p. 98, reference 17					
Straight	44	69	78	75	100
Bent	4	17	4	71	83

From the solution immersion tests and the cathodic debonding tests, it was found that the percentage of bars with excellent to good adhesion for Epoxy-A was lower than that of all other bars. In comparison, the percentage of bars with excellent to good adhesion for Epoxy-E was greater than that of all other bars, except for one instance when it was ranked just below that of Epoxy-D. Thus, based upon the solution immersion and cathodic debonding tests, it may be expected that Epoxy-A would have poorer performance in concrete than Epoxy-E.

Results from the in-concrete tests are shown in table 6. For the eight test conditions, the corrosion of bars with Epoxy-E was greater than that of Epoxy-A in six out of eight cases. The performance of Epoxy-E was only better than that of Epoxy-A when bent bars with either 0.004 or 0.5 percent damage were tested. However, it should be noted that Epoxy-A developed a significant number of holidays during bending.

Based upon this review, it appears that the solution immersion and cathodic debonding tests for adhesion are poor predictors of long-term performance of the coated bars in concrete. It should be noted that the use of cathodic debonding tests is still recommended for determining consistency of coating application during manufacture of the coated reinforcing bars; however, it is difficult to support use of either cathodic debonding tests or solution immersion adhesion tests for coating selection in specification documents.

Galvanized Bars (GL)

The galvanized bars were tested in five configurations. The average voltage and mat-to-mat resistance measured across the 10-ohm resistor are shown in table 10.

The lowest corrosion rates were obtained when the galvanized bars were used in both mats and there was no initial crack in the concrete. The average corrosion obtained in this configuration was 38 times lower than that of the black bars. When the bars were tested in precracked concrete, the corrosion rates of slabs with a black cathode significantly increased by 41 percent. While galvanized bars are commonly bent, these data show that the corrosion increased almost a factor of 1.8 when bent bars were tested with a black cathode. These data suggest that bending of galvanized bars after coating may reduce their performance in corrosive environments, and that the coating should be done after fabrication.

Table 10. Galvanized bar test results.

Configuration	Average voltage across resistor (μV)	Average mat-to-mat resistance (ohm)	Slab condition after 96 weeks
Straight, black cathode, uncracked	2079	413	Slabs cracked
Straight, galvanized cathode, uncracked	85	522	Slabs cracked
Straight, black cathode, precracked	2941	318	Slabs cracked
Straight, galvanized cathode, precracked	287	410	Minor cracking in slabs
Bent, black cathode, uncracked	3733	325	Slabs cracked

In uncracked concrete, the corrosion rate increased 24 times when a black bar cathode was used, compared to when a galvanized cathode was used. Therefore, combining a black cathode with the galvanized anode increased the corrosion rates significantly. Thus, when using galvanized bars, care should be taken to eliminate electrical contact between the galvanized steel and other metals. Mat-to-mat resistance values obtained for the galvanized bars were similar to that obtained for the black bars.

At the end of 96 weeks, almost all slab specimens exhibited cracks running parallel with the bars. Green and white corrosion products were observed along the length of the bars and red rust was observed at a drill hole on one of the bars. The straight, black cathode, precracked slabs had significant rust stains on the top of the bar. Bars from these specimens exhibited significant section loss along the bar and black corrosion products. The straight, galvanized cathode, uncracked slabs exhibited minor cracks at the ends of the slabs. Red and black corrosion products were observed along these bars. Red rust was observed at the hole in the bars. The precracked specimen with straight bars and a galvanized cathode had minor or no additional cracking in the slabs; however, the bars exhibited red and black corrosion at one end of the bar. The slabs containing the bent galvanized bars and the black cathode exhibited significant cracking. Black and green corrosion products were generally observed over the top surfaces of these bars.

Zinc Alloy-Clad Bars (SM)

The zinc alloy-clad bars (SM) were tested in five configurations. The average voltage and mat-to-mat resistance measured across the 10-ohm resistor are shown in table 11.

The lowest corrosion rates were obtained when the zinc alloy-clad bars were used in both mats and there was no initial crack in the concrete. The average corrosion obtained in this configuration was 5.5 times lower than the black bars. When the bars were tested in precracked concrete, the corrosion rates increased by two times. This product also exhibited a significant increase in corrosion when the bars were bent. Combining a black cathode with the zinc alloy-clad bars did not increase the corrosion rate as significantly as the combining of a black cathode with galvanized bars. Mat-to-mat resistance values were similar to that obtained for the black bars.

At the end of 96 weeks, most of the slabs containing the zinc alloy-clad bars exhibited cracks. The only systems that did not exhibit surface cracking were one of the two slabs containing straight bars and a black cathode in uncracked concrete, one of the uncracked slabs with the zinc alloy-clad cathode and two of the uncracked slabs containing bent bars. In general, the bars exhibited black corrosion products over all bar surfaces.

Table 11. Zinc alloy-clad bar test results.

	Average voltage across resistor (μV)	Average mat-to-mat resistance (ohm)	Slab condition after 96 weeks
Straight, black cathode, uncracked	1267	385	One slab cracked
Straight, zinc alloy-clad cathode, uncracked	588	381	One slab with minor cracking
Straight, black cathode, precracked	2730	325	Slabs cracked
Straight, zinc alloy-clad cathode, precracked	1208	526	Slabs cracked
Bent black cathode, uncracked	2342	345	Minor cracking in slab

Copper-Clad Bars (CU)

The copper-clad bars (CU) were tested in four configurations. These particular copper-clad bars were unable to be bent without cracking the copper coating. The average voltage and mat-to-mat resistance measured across the 10-ohm resistor are shown in table 12.

The lowest corrosion rates were obtained when the copper-clad bars were used in the top mat only and there was no crack in the concrete; however, under all conditions, the corrosion rates were significantly lower than that measured for the black bars. The corrosion rates ranged from 23 to 92 times lower than that of the black bars. Minor corrosion currents were measured during the first 20 weeks of testing, suggesting that the bars passivate over time in the concrete environment. Mat-to-mat resistance values were similar to that obtained for the black bars.

Table 12. Copper-clad bar test results.

Configuration	Average voltage across resistor (μV)	Average mat-to-mat resistance (ohm)	Slab condition after 96 weeks
Straight, black cathode, uncracked	37	584	No cracked slabs
Straight, copper-clad cathode, uncracked	79	466	No cracked slabs
Straight, black cathode, precracked	142	491	No cracked slabs
Straight, copper-clad cathode, precracked	111	353	No cracked slabs

After 96 weeks of testing, no cracking or staining was observed on the top surface of the concrete specimens and the bars were generally clean. As discussed elsewhere, the retardation of cement paste surrounding the reinforcing bars has been observed in previous studies[5]. The retardation only extends a small distance into the concrete and testing of the bond strengths of manufactured copper-clad reinforcing bars should be considered. None of the black bottom-mat bars exhibited corrosion.

Type 304 Stainless Steel Bars (304)

The Type 304 stainless steel bars were tested in five configurations. The average voltage and mat-to-mat resistance measured across the 10-ohm resistor are shown in table 13.

Table 13. Type 304 stainless steel bar test results.

Configuration	Average voltage across resistor (μV)	Average mat-to-mat resistance (ohm)	Slab condition after 96 weeks
Straight, black cathode, uncracked	5	602	No cracked slabs
Straight, Type 304 cathode, uncracked	3	474	No cracked slabs
Straight, black cathode, precracked	113	566	Minor staining on concrete surface
Straight, Type 304 cathode, precracked	2	459	No cracked slabs
Bent, black cathode, uncracked	267	552	No cracked slabs

The lowest corrosion rates were obtained when the Type 304 stainless steel bars were used in both mats. This configuration of bars was not influenced by the presence of the crack; both conditions have about 1500 times lower corrosion than the black bar specimens. Of the 10 bars that were coupled with the black bar cathodes, 5 bars exhibited moderate to high corrosion currents. Mat-to-mat resistance values were about twice that obtained for the black bars.

Figure 13 shows the relationship between the voltage measured across the 10-ohm resistor and the half-cell potential for the Type 304 and Type 316 reinforcing bars. These data are similar to that obtained for the black bar specimens. Half-cell values more positive than -200 mV tend to be associated with low corrosion currents.

It was concluded that the Type 304 stainless steel was susceptible to chloride-induced corrosion when it was tested with a black bar cathode; whereas when it was tested with a stainless steel cathode, it was not susceptible to any significant chloride-induced corrosion, even when in precracked concrete slabs.

During visual inspection of the slabs, most of the Type 304 bars did not exhibit any corrosion; however, two of the bars that had black cathodes and were in a precracked location had red rust corrosion. None of the bars with the stainless steel cathodes exhibited any corrosion staining. Of the four bent bars with black cathodes that were inspected at 96 weeks, two had significant corrosion, while two others were clean.

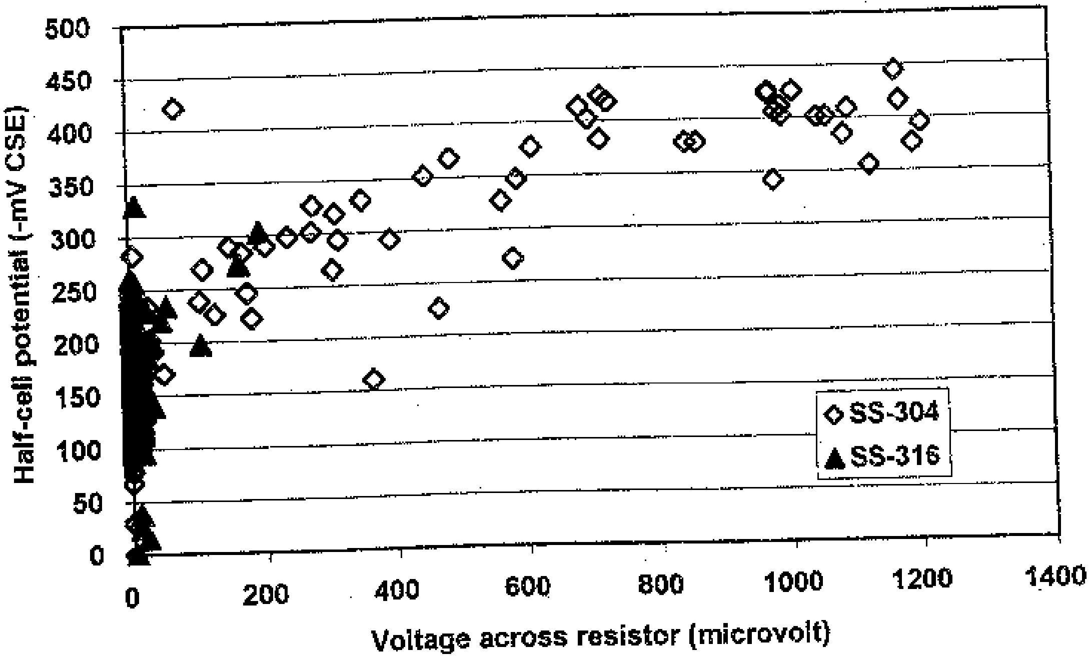

Figure 13. Relationship between half-cell potential and voltage measured across resistor for stainless steel bars.

Results obtained for the Type 304 stainless steels indicate that corrosion may occur if the bars are in a severe environment with a black cathode.

During the past 5 yrs, concern has been raised from civil engineers regarding the possibility of stress-corrosion cracking of stainless steel reinforcement. Stress-corrosion cracking typically occurs under conditions of high stress and low pH. We believe that stress-corrosion cracking is unlikely to occur in reinforcing due to the low stresses present and high pH of the concrete.

Type 316 Stainless Steel Bars (316)

The Type 316 stainless steel bars were tested in five configurations. The average voltage and mat-to-mat resistance measured across the 10-ohm resistor are shown in table 14. On average, the mat-to-mat resistance of the concrete specimens increased during the test period and values for the various configurations were similar. The extremely low macrocell corrosion voltages did not vary.

Low corrosion rates were obtained for all specimens containing the Type 316 stainless steel bars. The performance of the bars was not influenced by the presence of the crack or the use of a black cathode, with all conditions having about 800 times lower corrosion than the black bar specimens.

During visual inspection of the slabs, only one of the bars exhibited any corrosion and in that instance the corrosion was regarded as minor. Results obtained for the Type 316 stainless steels indicate that these bars may be more suitable for in-concrete use than the Type 304 reinforcing bars and that these bars are less susceptible to galvanic effects if used in conjunction with black bars.

Table 14. Type 316 stainless steel bar test results.

Configuration	Average voltage across resistor over 96 weeks (μV)	Average mat-to-mat resistance (ohm)	Slab condition after 96 weeks
Straight, black cathode, uncracked	5	476	No cracked slabs
Straight, Type 316 cathode, uncracked	5	422	No cracked slabs
Bent, black cathode, uncracked	9	389	No cracked slabs
Straight, black cathode, precracked	5	429	No cracked slabs
Straight, Type 316 cathode, precracked	5	409	No cracked slabs

Time Period Before Significant Corrosion

As discussed earlier in this report, it may be shown that sustained macrocell voltages less than 10 μV are unlikely to cause significant damage to concrete structures in a 100-year period. For this reason, the time for voltage across the 10-ohm resistor to first exceeded 10 μV was considered significant. Note that the first reading was taken 11 d after initiation of ponding. The times for the voltage to exceed 10 μV for the companion specimens for each test condition are shown in tables 15 and 16 for the epoxy-coated and metallic-clad bars, respectively.

The time period for the black bars in uncracked concrete to show voltages greater than 10 μV was generally about 11 to 25 d after initiation of the chloride ponding, with 2 of the 12 specimens taking from 53 to 165 d. The six epoxy-coated bars with the 0.5 percent damage sites exhibited similar times; however, when the epoxy-coated bars were also used as the bottom-mat cathode, the times were generally increased.

When the epoxy-coated bars were used in both top and bottom mats with the 0.004 percent coating damage in uncracked concrete, the time for the voltage to exceed 10 μV was significantly extended to average values of 508, 165, 130, 53, 214, and 74 d for Epoxy-A, Epoxy-B, Epoxy-C, Epoxy-D, Epoxy-E, and Epoxy-F, respectively.

The galvanized, zinc alloy-clad and copper-clad bars had time periods of 11 to 39 d, regardless of the test condition. These times were essentially the same as the black bar specimens.

When Type 304 stainless was used with a black bottom-mat cathode, the time period for the voltage to exceed 10 μV was also 11 to 25 d; however, when Type 304 was used in both top and bottom mats, the time was significantly increased to 207 and >672 d, averaging at least 420 d. As previously noted, these Type 304 specimens had very low corrosion currents after corrosion initiation.

Table 15. Time for voltage across resistor to exceed 10 μV for black and epoxy-coated bar specimens, d.

Test condition	Black	A	B	C	D	E	F
Straight bar, black cathode, uncracked, 0.5 percent damage	165 25 11 11	67 207	37 207	39 67	53 53	11 53	25 25
Straight bar, epoxy cathode, uncracked, 0.5 percent damage		81 67	165 67	53 25	53 33	11 11	25 25
Bent bar, black cathode, uncracked, 0.5 percent damage	11 25 53 11	67 53	25 53	11 53	11 53	53 235	25 25
Straight bar, black cathode, precracked, 0.5 percent damage	11 11 11 11	11 11 25 25	11 11	11 11	53 53	11 11	25 25
Straight bar, black cathode, uncracked, 0.004 percent damage		389 333	207 207	207 53	123 53	11 11	39 39
Straight bar, epoxy cathode, uncracked, 0.004 percent damage		627 389	165 165	207 53	53 53	207 221	81 67
Bent bar, black cathode, uncracked, 0.004 percent damage		11 333	53 53	53 53	53 25	333 >672	39 25
Straight bar, black cathode, precracked, 0.004 percent damage		11 11 67 25	11 11	53 11	25 53	11 11	25 25

When Type 316 was used with either a black or Type 316 bar cathode, the time periods ranged from 193 to 672 d and averaged about 450 d for these 12 specimens. None of these 12 specimens developed any significant corrosion-induced currents when either a black or Type 316 stainless cathode was used.

All specimens with the 12 bar types indicated some degree of corrosion activity, ranging from 2 to 4054 μV, equivalent to uniform corrosion current densities ranging from 0.016 to 32 mA/m^2 (0.015 to 30 mA/ft^2).

Table 16. Time for voltage across resistor to exceed 10 μV for black and metallic-clad or solid metallic bar specimens, d.

Test condition	Black	Galvanized	Zinc alloy-clad	Copper-clad	Type 304	Type 316
Straight bar, black cathode, uncracked, 0.5 percent damage	165 25 11 11	11 11	11 25	11 11	25 25 25	207 193
Straight bar, same-metal cathode, uncracked, 0.5 percent damage		11 11	25 39	11 11	375 207	>672 333
Straight bar, black cathode, precracked, 0.5 percent damage	11 11 11 11	25 11	25 25	11 11	25 25 25	207 193
Straight bar, same-metal cathode, precracked, 0.5 percent damage		11 11	25 25	11 11	417 >672	>672 >672
Bent bar, black cathode, uncracked, 0.5 percent damage	11 25 53 11	11 11 11 11	11 11 11 11	11 11 11 11	11 11 11 11	>672 473 473 >672

DISCUSSION OF CHLORIDE THRESHOLDS FOR BLACK, EPOXY-COATED AND STAINLESS STEEL BARS

Chloride Threshold for Black Bars

It is commonly assumed that the threshold for corrosion of black reinforcing bars is 0.2 percent chloride ion by weight of cement. For this concrete with 370 kg/m^3 (623 lb/yd^3) of cement and a unit weight of 2315 kg/m^3 (144.5 lb/ft^3), this is equivalent to a chloride content of 0.74 kg/m^3 (1.25 lb/yd^3) chloride or 0.032 percent chloride ion by weight of concrete. As shown later in this report, the chloride at the 25-mm (1-in) depth was greater than 0.032 percent by weight of concrete after 6 weeks of ponding at the level of the reinforcing bars. From the measured initiation of corrosion current in the uncracked concrete specimens containing the black bars, it appears that corrosion occurred in about 3 weeks of initial ponding.

After 48 weeks of testing, the chloride content at the 25.4-mm (1-in) depth level was approximately 0.5 percent chloride ion by weight of concrete, which is approximately 15 times the corrosion threshold, or approximately 11.6 kg/m^3 (19.5 lb/yd^3). After 96 weeks of testing, the chloride at the 25.4-mm (1-in) depth level was approximately 0.8 percent chloride ion by weight of concrete, which is approximately 25 times the corrosion threshold, or approximately 17.8 kg/m^3 (30.1 lb/yd^3). At the 70-mm (2.75-in) depth level commonly used for the clear cover design for bridge decks in the United States, the 96-week chloride was 0.34 percent by weight of concrete, which is approximately 11 times the corrosion threshold or approximately 7.8 kg/m^3 (13.3 lb/yd^3).

Chloride Threshold for Epoxy-Coated Bars

The macrocell data and the half-cell potential values for the epoxy-coated bars were reviewed to determine if the chloride threshold of damaged epoxy-coated bars was the same as that of the black bars. Half-cell potentials obtained for the damaged epoxy-coated bars were similar to that determined for the black bars. Based upon this review, it was determined that the chloride threshold for damaged epoxy-coated bars is similar to that of black bars. Furthermore, it appears that the epoxy coating is acting as a rate-limiting process in reducing the corrosion rates.

Chloride Threshold for Stainless Steel Bars

Previous studies by the authors on Type 304 stainless bars have determined that the chloride threshold to initiate corrosion was greater than 5.5 kg/m^3 (9.3 lb/yd^3), a value 7 to 10 times greater than necessary to initiate corrosion on black bars[4].

The Type 304 and Type 316 stainless steel bars tested in this current study were able to tolerate significant chloride levels prior to initiation of corrosion, particularly when both the top and bottom mats were stainless. For Type 304 bars in both mats, the chloride level to initiate corrosion ranged from 0.32 to >0.77 percent chloride ion by weight of concrete and averaged about 0.50 percent by weight of concrete. These threshold values are equivalent to about 7 to 18 kg/m^3 (12 to 30 lb/yd^3), and have an average value of 11 kg/m^3 (19 lb/yd^3). This average value is 15 times the chloride threshold for corrosion of black steel. When Type 304 stainless was electrically connected to a black bottom mat, the estimated chloride content to initiate corrosion averaged about 0.05 percent by weight of concrete, about twice the level for black bar initiation.

For the Type 316 bars, when both mats were Type 316, the chloride level to initiate corrosion ranged from about 12 to 20 kg/m^3 (20 to 33 lb/yd^3) and averaged about 0.80 percent by weight of concrete, which is equivalent to 18 kg/m^3 (31 lb/yd^3). This value is 24 times the chloride threshold for corrosion of black bar. When a black bar cathode was used with the Type 316 bars, the chloride threshold averaged about 0.5 percent by weight of concrete, which is about 15 times the chloride level to initiate corrosion of black bars.

It appears that both Types 304 and 316 have reduced chloride thresholds where black bar cathodes are electrically connected to the stainless; however, when both mats are stainless, the average chloride thresholds are very high, even in precracked concrete ranging from 0.50 to 0.80 percent by weight of concrete.

DISCUSSION OF MACROCELL TEST RESULTS AND THE OBSERVED BAR CONDITION AFTER 96 WEEKS

Previous corrosion studies with epoxy-coated bar specimens using black bar and epoxy-coated bar cathodes found that voltage reductions of 90 to 97 percent after 1-yr test periods did not provide long-term durability after about 10 yrs of outdoor storage[26]. These previous observations suggest that a voltage reduction of about 99.8 percent or 500 times less corrosion activity is necessary to provide 75 to 100 yrs of corrosion damage-free service life in harsh chloride environments.

This present research measured average corrosion current densities of the black bar control specimens of over 32 mA/m^2 (2.9 mA/ft^2) during the 96-week test period. This current would be classified as high[32-33], with damage anticipated in short periods. All 12 black bar specimens with three different test conditions were severely cracked and the bars were significantly corroded after 96 weeks. This research also found that companion Type 316 and 304 stainless steel bars under the same test conditions had average corrosion current densities of only 0.05 mA/m^2 (0.005 mA/ft^2). This 0.05-mA/m^2 (0.005-mA/ft^2) value is significantly less than the 0.9- to 1.9-mA/m^2 (0.08- to 0.18-mA/ft^2) passive range suggested by Rodriguez[32] and less than the 1.8-mA/m^2 (0.17-mA/ft^2) passive value suggested by Broomfield[33]. These stainless steel current densities averaged about 650 times less than the black bar control specimens.

A previous FHWA report from this 5-yr study suggested that a corrosion rate of 0.00025 to 0.0003 mm/yr (0.000010 to 0.000013 in/yr) was necessary to allow a 75- to 100-yr crack-free design life[4]. Similar calculations based on these 96-week in-concrete tests resulted on-average in corrosion rates of 0.036 mm/yr (0.0014 in/yr) for the black bar control specimen, a value 100 times higher than that necessary to have a crack-free 75-yr design life. Similar calculations from this 96-week test using the Type 304 and Type 316 stainless steel bars resulted in corrosion rates of 0.000051 mm/yr (0.000002 in/yr) in uncracked and precracked concrete slabs when the cathode was also stainless steel. This metallic loss rate with Type 304 and Type 316 stainless is six times lower than the 0.00030-mm/yr (0.000013-in/yr) loss rate necessary to allow a 75- to 100-yr crack-free design life.

Table 17 shows test conditions that exhibited corrosion rates 500, 100 and 10 times less than the black bar control specimens. This is equivalent to macrocell voltage reductions of 99.8, 99.0 and 90.0 percent, respectively. Results are discussed below.

Table 17. Test conditions with 99.8, 99.0 and 90.0 percent reduction in macrocell corrosion when compared to black bar specimens.

	Black bar cathode						Corrosion-resistant bar cathode		
	Straight bars				Bent bars		Straight bars		
	Uncracked concrete		Precracked concrete		Uncracked concrete		Uncracked concrete		Precracked concrete
Bar type	0.50%	0.004%	0.50%	0.004%	0.50%	0.004%	0.50%	0.004%	0.50%
Epoxy-A	✓	✓✓	●	○	●	✓	✓✓	✓✓	
Epoxy-B	○	✓✓	●	●	○	✓	✓	✓✓	
Epoxy-C	●	○	●	○	●	○	✓	✓✓	
Epoxy-D	○	✓	○	✓	○	✓	✓	✓	
Epoxy-E	●	○	●	●	✓	✓	✓	✓	
Epoxy-F	●	●	●	●	●	●	✓	○	
Galvanized	●		●		●		○		○
Zinc-alloy Clad	●		●		●		●		●
Copper-Clad	○		○				○		○
Type 304	✓✓		○		○		✓✓		✓✓
Type 316	✓✓		✓✓		✓		✓✓		✓✓

✓✓ = 99.8 percent less than control
✓ = between 99.8 and 99.0 percent less than control
○ = between 99.0 and 90.0 percent less than control
● = lower than 90.0 percent less than control
Note: Average black bar average voltage across resistor during the 96-week test period from the three black bar test conditions was 3240 μV.

MEASURED CORROSION ACTIVITY

99.8 Percent Reduction of Corrosion Activity

Only 13 of the 72 test combinations indicated by ✓✓ in table 17 had a macrocell voltage that was at least 500 times less than that of the black bar control specimens. Of these, seven were with

Type 304 or Type 316 stainless steel, and six were with the three bendable coatings Epoxy-A, Epoxy-B, and Epoxy-C.

The best performance of the six epoxy-coated bar types was with the three bendable coatings Epoxy-A, Epoxy-B, and Epoxy-C on straight bars in uncracked concrete, when the coating damage was 0.004 percent of the surface area. Epoxy-A was the only epoxy-coated bars to achieved this level of corrosion reduction when the damage was 0.5 percent and tested with an epoxy-coated cathode. Epoxy-D, Epoxy-E, and Epoxy-F did not achieved 99.8 percent reduction in macrocell corrosion with any of their eight test conditions. In addition, the galvanized, zinc alloy- and copper-clad bars also did not achieve this 99.8 percent reduction with any of their five test conditions. The excellent performance of the six coated-bar combinations meeting the 99.8 percent corrosion-induced voltage reduction was also confirmed by the EIS and PR testing discussed later in this report. The six combinations meeting the 99.8 percent reduction criteria also had the highest impedance and PR values in each configuration, except that Epoxy-D had higher values than Epoxy-A, Epoxy-B, and Epoxy-C.

None of the 11 corrosion-resistant bars achieved this reduction in corrosion with bent bars in uncracked concrete with a black cathode, with either the 0.5 or 0.004 percent surface damage; however, the Type 316 bars achieved this 99.8 percent reduction in all other test conditions.

99.0 Percent Reduction of Corrosion Activity

Twenty-nine of the 72 test conditions indicated by ✓ or ✓✓ in table 17 were able to have at least 100 times less corrosion-inducted voltage or 99.0 percent reduction in corrosion when compared to the black bar controls. Of these, 8 were Type 304 or Type 316 stainless and 21 were epoxy-coated bars, predominantly with Epoxy-A, Epoxy-B, Epoxy-D, and Epoxy-E. At this level of corrosion activity, the best performance was with Type 316 stainless with all five test conditions achieving this level of corrosion reduction.

Twenty-one of the 48 combinations with epoxy-coated bars produced this 99.0 percent reduction in corrosion activity. Of these 21 combinations, 13 were with the 0.004 percent coating damage. Essentially, none of the six epoxy coatings showed this level of reduction in corrosion when a black bar cathode was used with 0.50 percent coating damage. In addition, essentially none of the precracked slabs with a black cathode with either 0.5 or 0.004 percent coating damage achieved this reduction.

Epoxy-C and Epoxy-F achieved this level of corrosion reduction in fewer cases than Epoxy-A, Epoxy-B, Epoxy-D, and Epoxy-E. Epoxy-A and Epoxy-D achieved the best performance within the 6 epoxies, with 5 of their 8 test conditions having at least 100 times less corrosion than the control specimens. However, both Epoxy-A and Epoxy-D had poorer performance in precracked concrete and when tested in a bent condition, with 0.50 percent coating damage.

The performance of the bars meeting the 99 percent reduction was also confirmed by the PR and EIS testing. The bars meeting the 99 percent reduction generally had higher impedance, and lower PR values than the other bars in these conditions, as discussed later in this report.

The galvanized, zinc alloy- and copper-clad bars did not achieve the 99.0 percent reduction in corrosion activity under any test condition.

90.0 Percent Reduction of Corrosion Activity

Forty-eight of the 72 test conditions indicated by O, ✓ or ✓✓ in table 17 were able to achieve at least 10 times less corrosion-induced voltage or 90.0 percent reduction when compared to the black bars. All of the Type 304 and Type 316 stainless, copper-clad, and Epoxy-D bars achieved this reduction level for all of their test conditions. The galvanized bar was only able to achieve this level when a galvanized bottom-mat cathode was used. The zinc alloy-clad bars did not achieve this level under any test condition.

For the epoxy-coated bars, Epoxy-D achieved this reduction level for all eight test conditions, Epoxy-A and Epoxy-B achieved this level for six test conditions, and Epoxy-C and Epoxy-E achieved this level for five test conditions. Epoxy-F only achieved this reduction under two conditions. The data again illustrate that the performance of epoxy-coated bars is poorer when bars are in precracked concrete and when subjected to high levels of coating damage. The data also show that when an epoxy-coated bar cathode was used, all specimens achieved the 90 percent reduction level with both coating damage percentages.

Although the EIS and PR data generally support the relative performance of the coated-bar conditions with a 90 percent reduction in corrosion currents, there are more inconsistently performing pairs of specimens at the lower impedance and PR values associated with this level of performance.

Neither the galvanized or zinc alloy-clad bars achieved this 90 percent reduction when a black bar cathode was used; however, the galvanized bars achieved the reduction when tested with a galvanized bottom mat in either uncracked or precracked concrete.

COMPARISON OF AUTOPSY RESULTS AND MACROCELL VOLTAGE

Table 18 indicates the condition of the concrete slabs and bars at the end of the 96 weeks of testing. This table indicated those test conditions where the bars were free of corrosion and those test conditions where corrosion of the bars produced new cracks in the initially uncracked concrete slabs or developed crack extension in the precracked slabs. Of the 72 test conditions, 24 test conditions exhibited noncorroded bars and uncracked concrete, 26 exhibited corroded bars and uncracked concrete, and 22 conditions exhibited corroded bars and cracked concrete.

Table 19 combines information from tables 17 and 18, showing those bars in various test conditions that exhibited various corrosion-reduction rates.

These data indicate that none of the 29 test conditions with greater than 99.0 percent voltage reduction cracked and only 3 of the 48 conditions with greater than 90 percent voltage reduction cracked. Two of the three test conditions with 90.0 percent voltage reduction that exhibited cracking were galvanized bars with galvanized cathodes in uncracked and precracked concrete slabs. The other 45 test conditions that achieved the 90.0 percent voltage reduction did not crack. In contrast, of the 24 test conditions that attained less than 90 percent voltage reduction, 19 had cracked at the end of the test period. This data indicates that the macrocell voltage is a reasonable indicator of the condition of the specimens at the end of the test period and it also indicates that the macrocell voltage may be used to rank the long-term performance of the various bar systems.

Table 18. Condition of slabs and bars after 96 weeks of testing.

	Black bar cathode						Same bar cathode		
	Straight bars				Bent bars		Straight bars		
	Uncracked concrete		Precracked concrete		Uncracked concrete		Uncracked concrete		Precracked concrete
Bar type	0.50%	0.004%	0.50%	0.004%	0.50%	0.004%	0.50%	0.004%	0.50%
Epoxy-A	+	□	□	+	+	+	+	□	
Epoxy-B	+	□	+	+	■	+	+	□	
Epoxy-C	■	+	■	+	■	+	+	□	
Epoxy-D	+	□	+	□	+	+	□	□	
Epoxy-E	+	+	■	■	+	□	+	□	
Epoxy-F	■	■	■	■	■	■	+	□	
Galvanized	■		■		■		■		■
Zinc alloy-Clad	■		■		■		■		■
Copper-Clad	□		□				□		□
Type 304	□		+		+		□		□
Type 316	□		□		+		□		□

□ = uncracked, no corrosion on bar
\+ = uncracked, corrosion on bar
■ = cracked, corrosion on bar

Table 19. Number of test conditions with various corrosion rates and respective conditions of bars and slabs.

		99.8 percent less than control	between 99.8 and 99.0 percent less than control	between 99.0 and 90.0 percent less than control	lower than 90.0 percent less than control
		✓✓	✓	○	●
uncracked, no corrosion on bar	□	12	6	5	1
uncracked, corrosion on bar	+	1	10	11	4
cracked, corrosion on bar	■	0	0	3	19

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

The use of EIS testing techniques was adopted to aid in understanding the performance of the different coating systems under test. The low-frequency impedance values were found to be somewhat useful in characterizing the performance of the different systems. The techniques were particularly useful in characterizing changes in the exposed underlying bar area due to bending or other damage causes. The effectiveness of the test technique was lessened as the damaged areas of the bars increased, as relatively small areas of exposed steel can dominate the test results, overshadowing the effect of the coating itself. Results are discussed in detail in Appendix B. The primary conclusions that can be drawn from the EIS testing are as follows:

- An increase from 0.004 to 0.5 percent damage greatly reduces the measured impedance of the coatings and reduces the observed differences between different coatings.
- Bent bars had lower impedance values than straight bars for all but Epoxy-E. The bent bars had lower initial impedances than the straight bars, and also had larger drops in impedance during the testing.
- The presence of a crack over the reinforcing bar had a variable affect on the initial impedance of the bars, but bars in precracked concrete generally exhibited a greater loss in impedance during the testing, except for Epoxy-F at the 0.004 percent damage level and Epoxy-E and Epoxy-F at the 0.5 percent damage level.
- When the bars were coupled with a coated cathode, there was generally a smaller drop in impedance during the testing, indicating that less damage was taking place during the 96 weeks. This was true for all coatings except Epoxy-A and Epoxy-B with 0.004 percent damage, and Epoxy-E with 0.5 percent damage.
- At the 0.004 percent damage level, the low-frequency impedance values measured at 96 weeks reflected the bar condition during the autopsy. Impedance values greater than approximately $10^{5.0}$ indicated that the bars were undamaged, although some bars with 0.004 percent damage were undamaged with impedance values as low as $10^{4.0}$.
- The low-frequency impedance values at 96 weeks were not effective predictors of the bar conditions for bars with 0.5 percent damage, due to the overpowering effect of the damaged area on the measurements.

POLARIZATION RESISTANCE

PR testing techniques were used to show the relative corrosion rates of the different coating systems under test and were found to be useful in characterizing the performance of the different systems. The techniques were particularly useful in characterizing the during- and after-test condition of the test bars. The technique was not effective in identifying bars that exhibited good performance prior to exposure. As in the EIS testing, the effectiveness of the test technique decreased as the damaged areas of the bars increased, due to the area effect dominating the test results and overshadowing the effect of the coating itself. Results are discussed in detail in Appendix B. The primary conclusions which can be drawn from the PR testing are as follows:

- Increases from 0.004 to 0.5 percent damage areas reduced the PR by three to eight orders of magnitude.

- Bent bars with bendable coatings generally had lower PR values than straight bars, while those with nonbendable coatings had higher PR values; however, all the bent bars had lower PR values than companion straight bars.

- The presence of a crack over the reinforcing bar generally decreased the PR of the bars, except when the bars had relatively low initial PR values.

- When the bars were coupled with a coated cathode, there was generally an increase or small drop in PR during the testing, indicating that less corrosion and damage was taking place. This was true for all coatings except Epoxy-A and Epoxy-C with 0.004 percent damage (that had very high PR values to start with), and Epoxy-E with 0.5 percent damage.

- The PR test is an effective nondestructive indicator of the bar condition. In general, PR values greater than approximately 10^5 showed excellent performance except in isolated instances.

COMPARISON OF EIS AND PR TESTING

The EIS and PR testing were effective indicators of the performance of the coatings at the conclusion of the testing, with the EIS testing revealing the coating integrity and the PR testing showing the amount of corrosion. Although working in different manners, both tests showed similar results.

The relationship between the results of the two test methods can be seen in figure 14, showing the final impedance determined using EIS and the final PR test results for the coated bars. The final measurements are compared because they are most representative of the coating performance, as previously discussed. Also shown are the approximate 10^5-ohm values found to generally indicate good performance in the EIS and PR testing. There is a linear relationship between the test results, with the higher PR results associated with the higher EIS results.

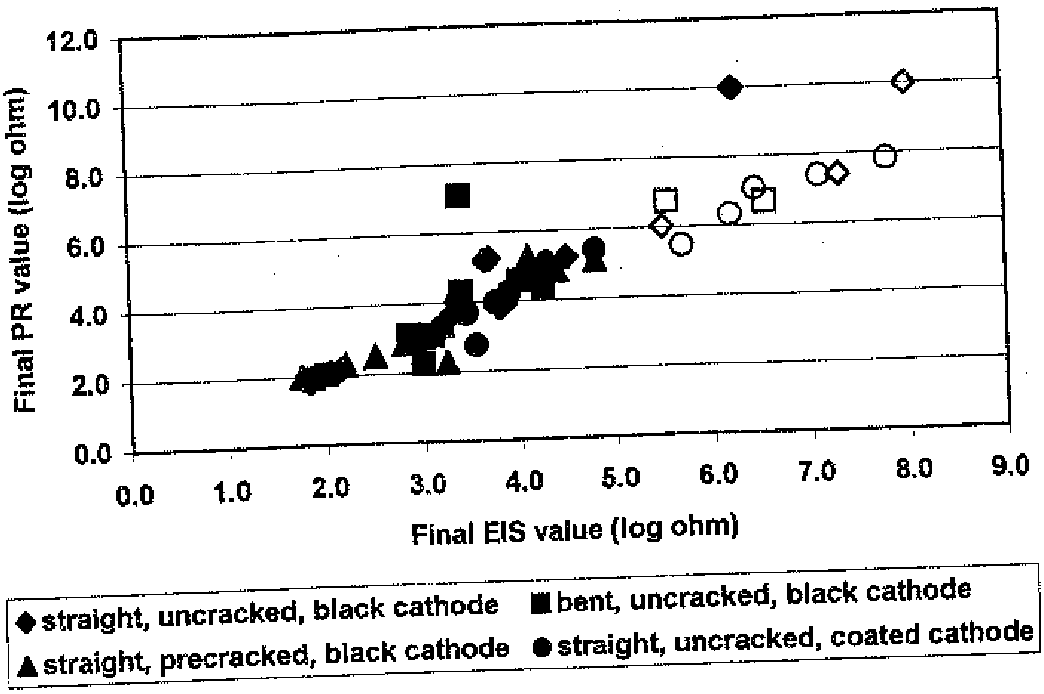

Figure 14. Relationship between PR and EIS measurements after 96 weeks of testing. Note that empty symbols indicate bars with no corrosion at the end of testing.

CHAPTER 5. CHLORIDE INGRESS, DIFFUSION AND THRESHOLDS

INTRODUCTION

Four 300- x 300- x 178-mm (12- x 12- x 7-in) unreinforced concrete slabs were used to determine the rate of chloride ingress into the uncracked slabs during the tests. These slabs were subjected to the same 12-week wetting/drying, 12-week constant ponding cycle used for the reinforced concrete specimens.

Cores were removed from three of the four slabs about every 6 weeks to enable life-prediction measurements to be made. These specimens were cut into 9.5-mm (⅜-in) slices centered on 12.7-, 31.7-, 50.8-, and 63.5-mm (½-, 1¼-, 2-, and 2½-in) depths from the ponded concrete surface. The three samples at each depth were then combined and ground for testing. The chloride contents were determined by an acid-digestion potentiometric titration procedure essentially in accordance with ASTM C 1152, *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.*[34] The test data are given in figure 15 and table 20. Also shown is the chloride at the 25-mm (1-in) level, estimated using linear interpolation using the 12.7- and 31.7-mm (½- and 1¼-in.) data.

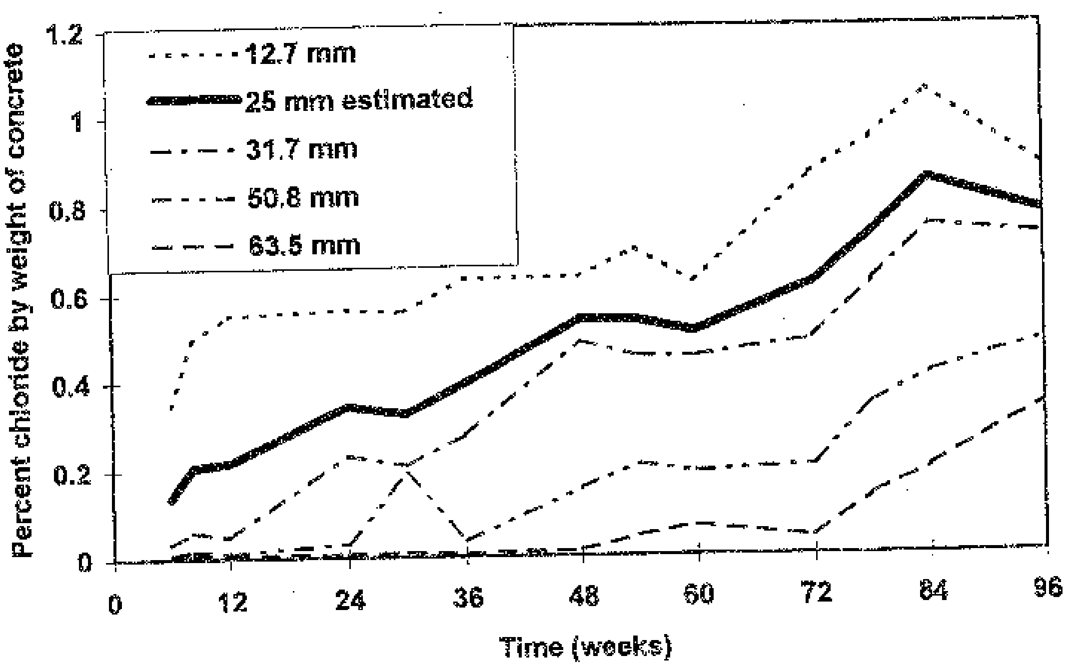

Figure 15. Measured acid-soluble chloride during 96 weeks of testing.

Table 20. Acid-soluble chloride contents (percent chloride by weight of concrete).

Test period (weeks)	7.9 to 17.5 mm (5/16 to 11/16 in)	27.0 to 36.5 mm (1 1/16 to 1 7/16 in)	46.0 to 55.6 mm (1 13/16 to 2 3/16 in)	58.7 to 68.3 mm (2 5/16 to 2 11/16 in)	Estimated chloride at 25.4 mm (1 in)
6	0.347	0.032	<0.007	<0.007	0.137
8	0.495	0.061	0.018	<0.007	0.206
12	0.551	0.048	0.011	<0.007	0.216
24	0.562	0.231	0.031	<0.007	0.341
30	0.556	0.209	0.189	0.009	0.325
36	0.628	0.274	0.035	<0.007	0.392
48	0.630	0.484	0.152	0.012	0.533
54	0.693	0.451	0.207	0.044	0.532
60	0.615	0.450	0.189	0.068	0.505
72	0.860	0.489	0.204	0.040	0.613
78	0.940	0.616	0.342	0.135	0.724
84	1.050	0.745	0.411	0.196	0.847
96	0.873	0.721	0.485	0.341	0.772

It is commonly assumed that the threshold for corrosion of black reinforcing bars is 0.2 percent chloride ion by weight of cement. For this concrete with 370 kg/m^3 (623 lb/yd^3) of cement and a unit weight of 2315 kg/m^3 (144.5 lb/ft^3), this is equivalent to a chloride content of 0.74 kg/m^3 (1.25 lb/yd^3) chloride or 0.032 percent chloride ion by weight of concrete. As shown in table 20, the chloride at the 25-mm (1-in) depth was greater than 0.032 percent by weight of concrete after 6 weeks of ponding at the level of the reinforcing bars. From the measured initiation of corrosion current in the uncracked concrete specimens containing the black bars, it appears that corrosion occurred in about 3 weeks of initial ponding.

After 48 weeks of testing, the chloride content at the 25.4-mm (1-in) depth level was approximately 0.5 percent chloride ion by weight of concrete, which is approximately 15 times the corrosion threshold, or approximately 11.6 kg/m^3 (19.5 lb/yd^3). After 96 weeks of testing, the chloride at the 25.4-mm (1-in) depth level was approximately 0.8 percent chloride ion by weight of concrete, which is approximately 25 times the corrosion threshold, or approximately 17.8 kg/m^3 (30.1 lb/yd^3).

DIFFUSION PROPERTIES

Despite its shortcomings, it is common to model chloride ingress into concrete using Fick's law. The limitations of this technique is that Fick's Law assumes that the diffusion is constant with time and that the surface concentration of chloride ions is also constant over time. Neither of these assumed factors are present in these long-term in-concrete studies. Just as the laboratory concrete test slabs were subjected to wetting and drying periods, concrete bridge structures are also subject to wetting and drying. During the wetting periods, absorption effects may dominate the chloride ingress in the first 10 to 20 mm (0.4 to 0.8 in) of the concrete. The issue of absorbed and diffused chloride ions needs additional research, and tests for these elements require standardization. However, the authors of this report believe that the effective diffusion coefficients and surface concentrations determined from this reported data provide useful and realistic information for ranking material performance.

A least-squares curve fitting technique was used to calculate the chloride diffusion coefficients and the saltwater-exposed surface chloride concentration. This technique may be simply conducted using most spreadsheet programs, such as Excel, which includes a minimization "solver" function. All calculations were performed assuming Fick's law of diffusion[35-36] according to the following equation.

$$C(x,t,C_0,D_{eff}) = C_0\left[1 - erf\left[\frac{x}{2\sqrt{tD_{eff}}}\right]\right]$$

x = *depth*, t = *time*,
C_0 = *surface concentration*,
D_{eff} = *effective diffusion coefficient*,
erf = *error function*

The 52 measured chloride concentrations at the four tested depths in table 20 were used along with least-squares fitting techniques to determine the effective diffusion coefficient, D_{eff}, and the surface chloride concentration, C_0. Figure 16 shows the measured and predicted chloride ingress curves. The data are relatively well fitted by the diffusion curves for all time periods, except possibly the data at the 58.7- to 68.3-mm (2$\frac{5}{16}$- to 2$\frac{11}{16}$-in) level at later ages. A surface concentration of 1.047 percent by weight of concrete and a diffusion coefficient of 2.6 x 10^{-5} mm^2/s were determined.

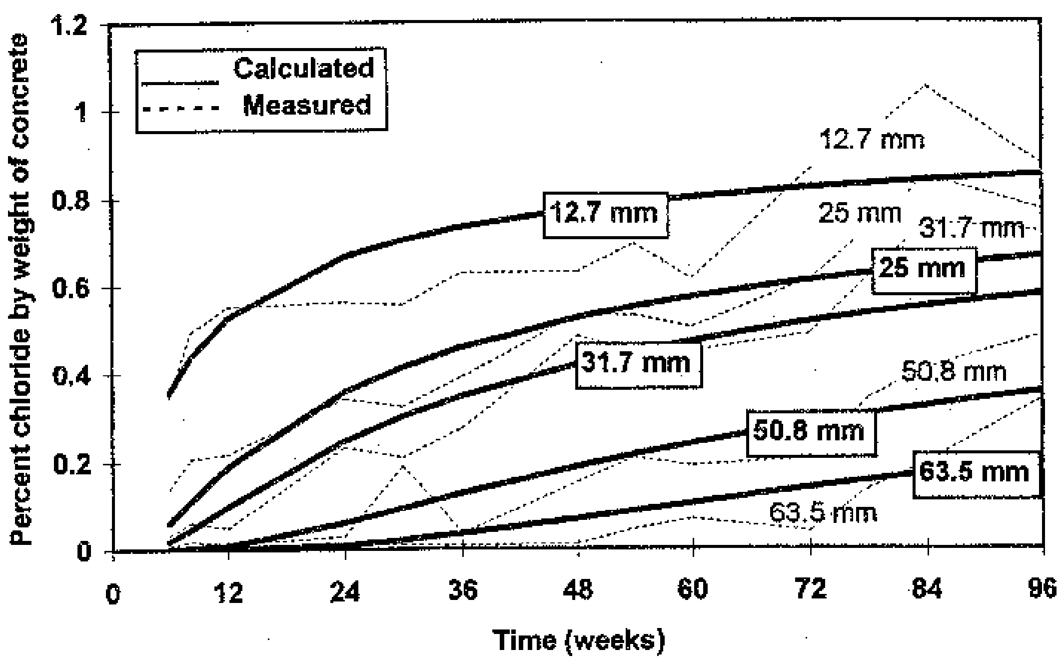

Figure 16. Chloride ingress data and predicted diffusion curves.

The data obtained for the representative AASHTO-specified 0.47 w/c ratio burlap-cured concrete subjected to the wetting and drying can be compared with data for concrete with a similar mix design that was subjected to continuous ponding. In 1993, the Precast/Prestressed Concrete Institute (PCI) funded a comprehensive 1-yr laboratory study to answer questions relating to chloride

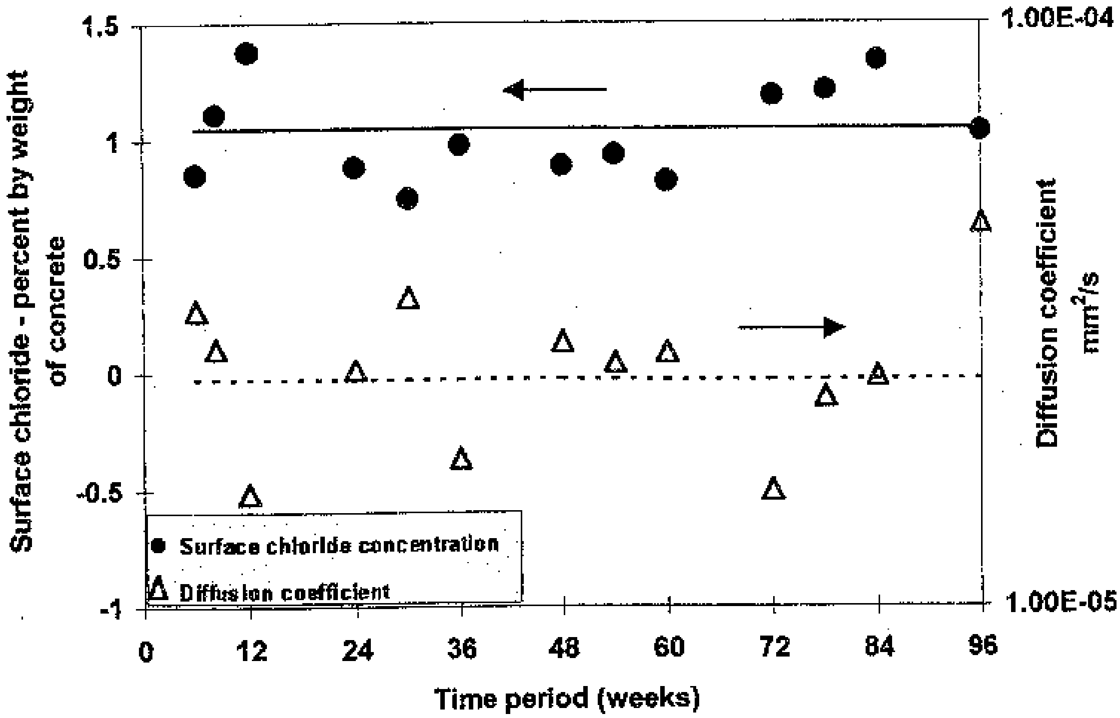

Figure 18. Surface chloride and diffusion coefficients from table 22 determined at various time periods.

CHAPTER 6. METHODS FOR ESTIMATING REPAIR PERIODS USING STATISTICAL METHODS

INTRODUCTION

Repair to concrete structures due to corrosion-induced delamination or spalling only occurs when there has been sufficient damage. This research has been directed towards the primary problem of bridge decks; thus, it is important to consider how we analyze the in-concrete corrosion test data with respect to a real bridge deck. Methodology presented here is believed to be applicable to all corrosion protection systems and this may be adapted for other protection strategies.

Values used in this chapter are based upon estimates obtained from the current field data available for structures containing epoxy-coated reinforcing bars. At the time of writing, there have been few reports of delamination of concrete from bridge decks and no repairs to decks containing epoxy-coated bars. In several reports, minor corrosion of the epoxy-coated reinforcing, not causing distress, has been observed. These have typically occurred where decks have been constructed using an epoxy-coated top mat and a black bar bottom mat or stay-in-place steel or galvanized-steel formwork. In several marine piles, corrosion of epoxy-coated reinforcing bars and delamination of concrete have been observed. For this reason, it is believed that the following discussion should be limited to the protection and estimation of repair periods for bridge decks containing top-mat coated bars and bottom-mat black bars.

Due to the relatively good performance of decks that contain two mats of epoxy-coated bars compared with those containing a top coated mat and a bottom black mat, it is difficult to determine field lives for systems that have been constructed in this manner and to use estimated design lives in calculations. For this reason, only the worst case for structures constructed with epoxy-coated bars and a black bar bottom mat will be considered.

The in-concrete studies conducted as part of this study intentionally utilized four different real-world conditions for the concrete and the coated bar damage to better understand corrosion performance and repair consequences. These conditions are:

- Uncracked concrete, 0.5 percent coating damage
- Uncracked concrete, 0.004 percent coating damage
- Cracked concrete, 0.5 percent coating damage
- Cracked concrete, 0.004 percent coating damage

In addition, the studies used specimens with black bar cathodes and coated cathodes. The studies have been conducted on a concrete slab that measures 300 x 300 mm (1 x 1 ft); significantly smaller than a real bridge deck. It is reasonable to assume that decks contain areas that are cracked and uncracked, that some locations on decks have damaged bars, and other locations on the deck have coated bars with minimal damage.

INITIATION OF CORROSION

Based upon Fick's diffusion calculations and data from laboratory studies, high-quality uncracked concretes with proper cover should not reach the corrosion initiation until, say, 40 yrs after construction. It is also known that not all the deck reaches this initiation state at the same time. Thus, use of statistical estimates for time-to-initiation of corrosion is appropriate.

Let us assume that the time to reach corrosion initiation has a mean of 40 yrs and a coefficient of variation (CV) of 25 percent (that is, a standard deviation of 10 yrs) and that the time-to-initiation is normally distributed. This distribution accounts for variances in salt accumulation across an uncracked deck and variability in micro-environments. From this mean and standard deviation, one can calculate that after approximately 26 yrs, 10 percent of an uncracked deck has reached corrosion initiation. The normally distributed probability distribution for the time to reach the chloride initiation is shown in figure 19.

However, not all of a concrete deck is uncracked. It has been assumed that 5 percent of the deck is influenced by the presence of cracks, and that the time-to-initiation for bare and damaged epoxy-coated bars in a cracked section of a deck is 5 yrs. The CV is also considered to be 25 percent, resulting in a standard deviation of 1.25 yrs. Using this information and the information for the uncracked deck, one can construct a cumulative probability distribution for initiation of corrosion (shown in figure 20). From this graph, we can tell that it takes approximately 25 yrs to reach corrosion initiation on 10 percent of the deck and approximately 30 yrs to reach corrosion initiation on 20 percent of the deck.

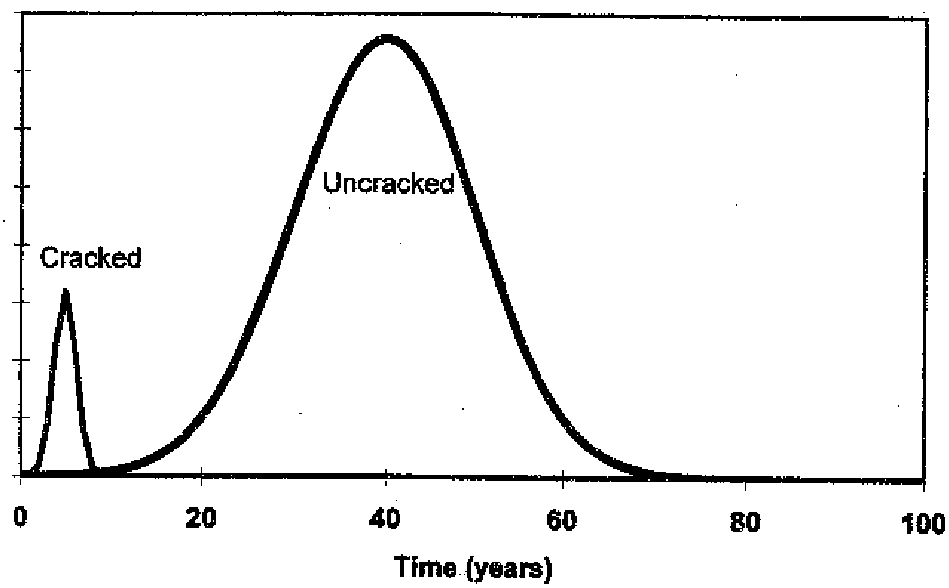

Figure 19. Probability distribution for initiation of corrosion of black bars in cracked and uncracked concrete deck.

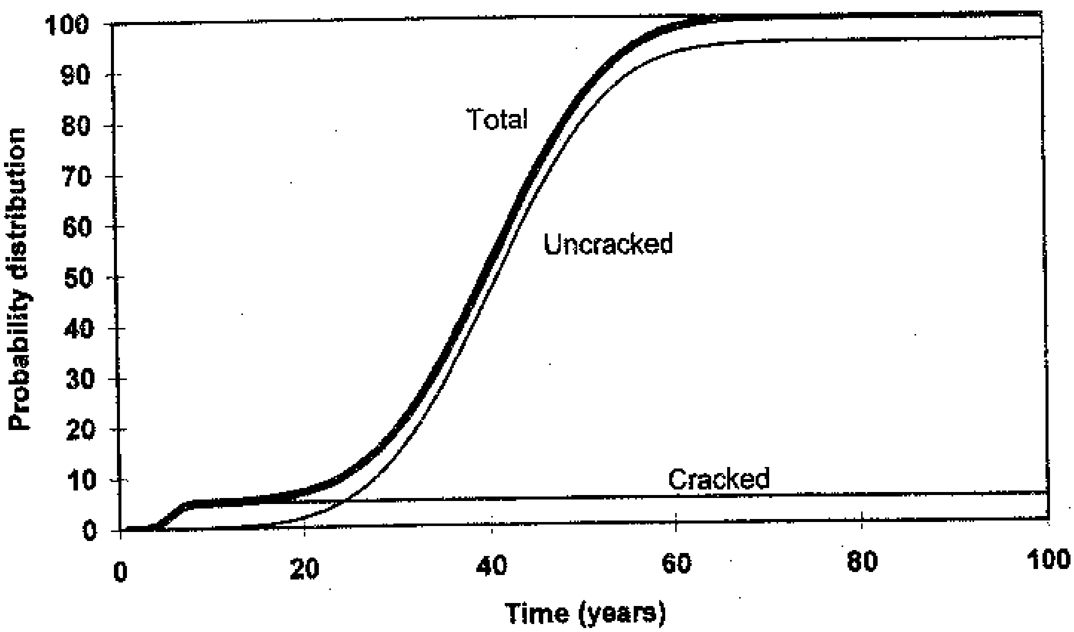

Figure 20. Cumulative distribution for initiation of corrosion in cracked and uncracked concrete deck.

TIME-TO-DELAMINATION

Once corrosion has initiated, it takes a certain period of time before delaminations occur. It has been assumed that the time-from-initiation to delamination for both cracked and uncracked decks is normally distributed. For this example, the time-from-initiation to delamination has a mean of 5 yrs and a CV of 25 percent (that is, a standard deviation of 1.25 yrs).

Using the statistical estimates for the time-to-initiation and the time-from-initiation to delamination, one can calculate the overall time-to-delamination. The mean time-to-delamination for the uncracked decks will be the sum of the mean time-to-initiation (40 yrs) and time-from-initiation to delamination (5 yrs), or 45 yrs. The time-to-delamination will have a standard deviation equal to the square root of the sum of standard deviations for the time-to-initiation and the time-from-initiation to delamination; or $\sqrt{(10^2 + 1.25^2)} = 10.77$ yrs. Similarly, for a cracked deck, the mean time to delamination will be the sum of the mean time-to-initiation (5 yrs) and time-from-initiation to delamination (5 yrs), or 10 yrs, and the standard deviation will be $\sqrt{(1.25^2 + 1.25^2)} = 1.77$ yrs. Figure 21 shows the cumulative probability distribution for time-to-delamination for a deck with 5 percent cracked areas and 95 percent uncracked areas. Using this figure, 10 percent of the deck will be delaminated after approximately 30 yrs and 20 percent after 35 yrs. The bridge use and other serviceability factors will affect when repairs are actually undertaken.

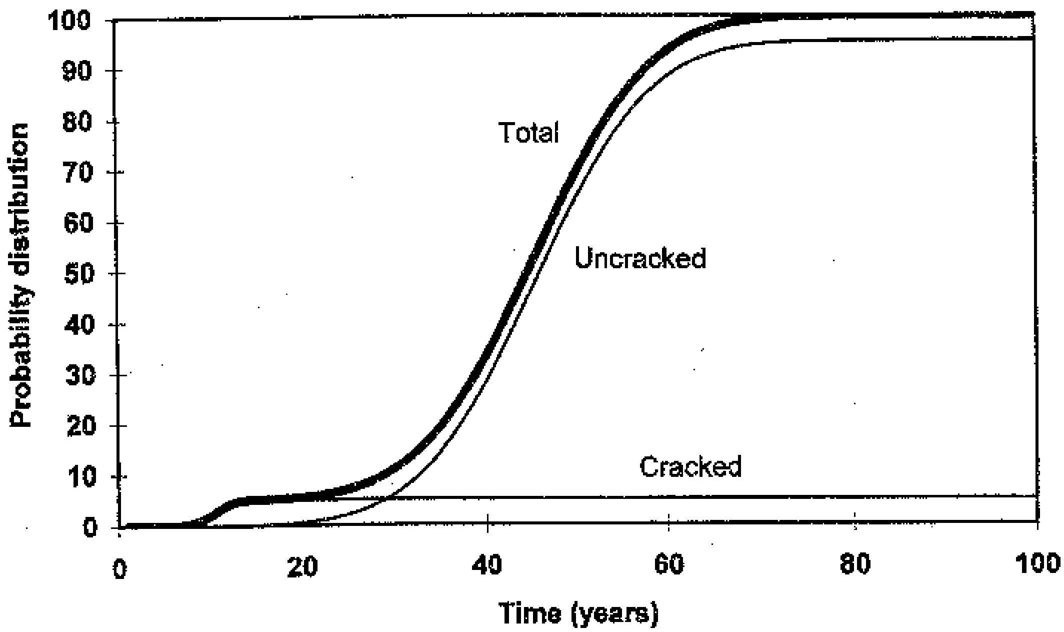

Figure 21. Cumulative distribution for delamination of deck with black bars.

When one considers decks with epoxy-coated bars, one has to estimate the quantity of deck under the various conditions of cracked and noncracked concrete, with minor and significant coating damage. As in the above discussion, it was assumed that the deck has 95 percent uncracked areas and 5 percent cracked areas. It was further assumed that 85 percent of the deck had locations with minor damage to the coated bars and that 15 percent of the decks had significant damage to the coated bars.

Thus, the following conservative percentages were assumed:

• Uncracked concrete, minor coating damage	80.75 percent of total deck area
• Uncracked concrete, significant coating damage	14.25 percent of total deck area
• Cracked concrete, minor coating damage	4.25 percent of total deck area
• Cracked concrete, significant coating damage	0.75 percent of total deck area

It was earlier assumed that the time from corrosion initiation to delamination for black bars was 5 yrs in both cracked and uncracked locations. Again, using a conservative assumption that the time from corrosion initiation to delamination for epoxy-coated bars with significant damage sites is 10 yrs with a CV of 25 percent (that is, SD = 2.5 yrs) and that the time from corrosion initiation to delamination for epoxy-coated bars with minor damage sites is 25 yrs with a CV of 25 percent (that is, SD = 6.25 yrs), the time to delamination was determined as follows:

- Uncracked concrete, minor coating damage:
  - mean = 40 + 25 = 65 yrs
  - $SD = \sqrt{(10^2 + 6.25^2)} = 11.79$ yrs

- Uncracked concrete, significant coating damage:
  mean = 40 + 10 = 50 yrs
  SD = $\sqrt{(10^2 + 2.5^2)}$ = 10.31 yrs

- Cracked concrete, minor coating damage:
  mean = 5 + 25 = 30 yrs
  SD = $\sqrt{(1.25^2 + 6.25^2)}$ = 6.37 yrs

- Cracked concrete, significant coating damage:
  mean = 5 + 10 = 15 yrs
  SD = $\sqrt{(1.25^2 + 2.5^2)}$ = 2.80 yrs

Using these data, one can plot the probability distribution cumulative delamination occurring to the structure as shown in figures 22 and 23. Data shown in figures 21 and 23 are combined in figure 24.

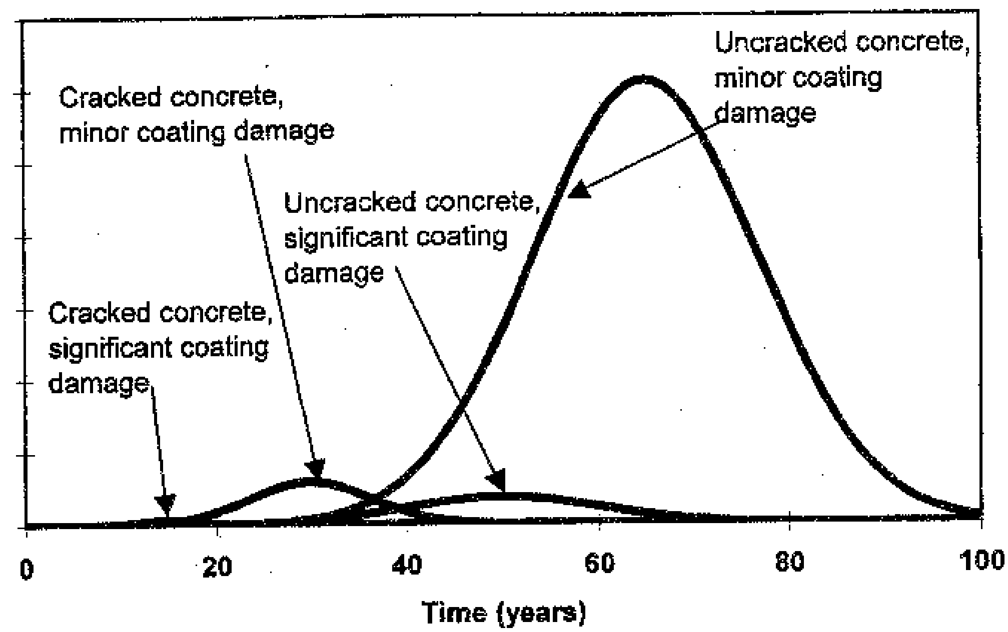

Figure 22. Probability distribution for delamination of deck with epoxy-coated bar in cracked and uncracked concrete.

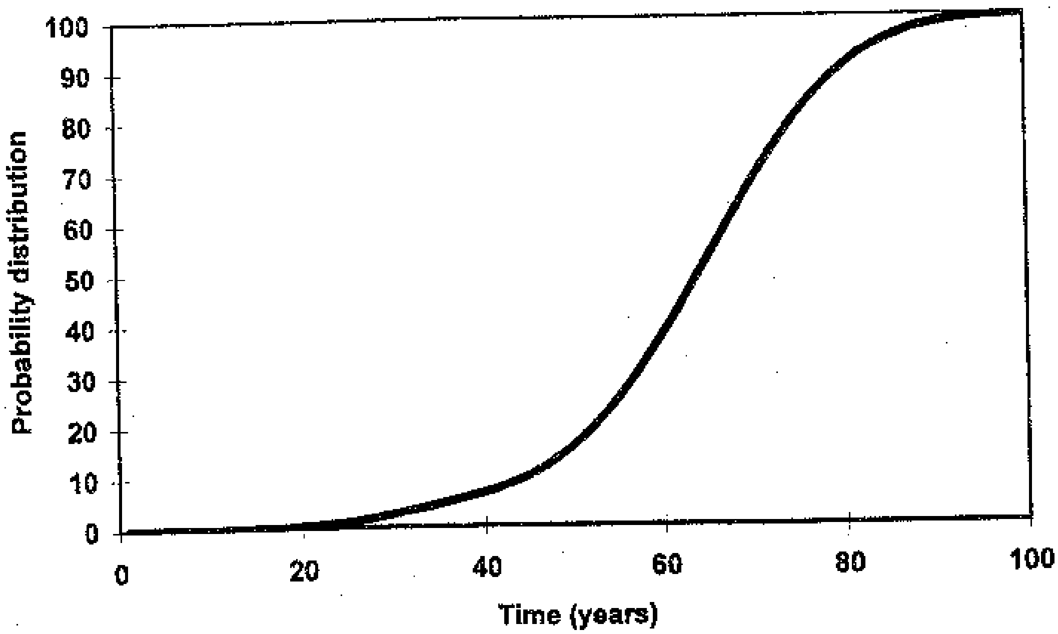

Figure 23. Cumulative distribution for delamination of deck with epoxy-coated bars in cracked and uncracked concrete with minor and significant coating damage.

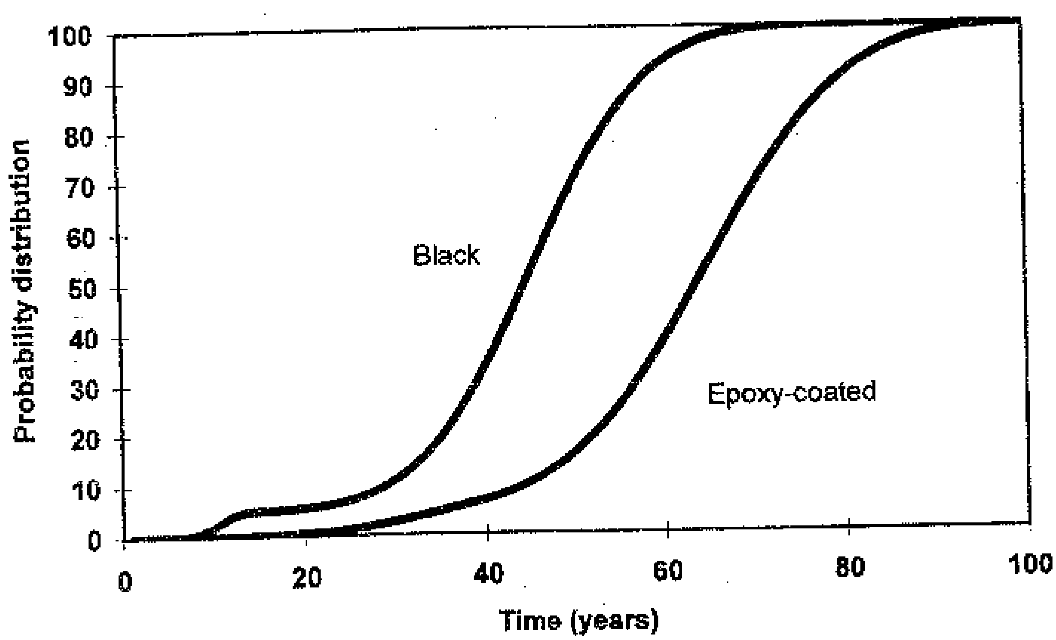

Figure 24. Cumulative distribution for delamination of concrete decks containing black and epoxy-coated bars.

From figure 24, it is possible to estimate the time period before 1, 2.5, 5, 10, 20, and 30 percent of the structure has delaminated. Table 23 shows the estimated time for various amounts of delamination to occur based on the reasonable assumptions used in this discussion.

Table 23. Estimated time-to-repair.

Amount of delamination, %	Black bars, yrs	Top-mat epoxy-coated bars, yrs
1	8	20
2.5	9	27
5	14	33
10	28	42
20	35	49
30	38	54

Thus, for a structure with high vehicle frequency, such as a freeway or interstate highway bridge, allowing only 2.5 percent delamination, the difference in performance prior to repair may be substantially different (that is, 9 versus 27 yrs); whereas, if the vehicle frequency is low, such as a rural bridge, allowing 20 percent delamination, then the difference between the black and epoxy-coated bars is less (that is, 35 versus 49 yrs). Thus, from this example, it is clear that the selection of the protection system will be governed by the performance requirements of the structure.

It is now possible to consider what would happen if large defects in the epoxy-coated bars were eliminated through strict quality control measures or cracks in bridge decks containing either epoxy-coated or black bars were eliminated or repaired, as shown in table 24.

Table 24. Estimated time-to-repair using different construction strategies.

Amount of delamination, %	Black bars, yrs		Top-mat epoxy-coated bars, bottom mat black, yrs			
	No repair of cracks in concrete	Repair of cracks in concrete	No repair of cracks and poor quality control for epoxy-coated bars	Repairing cracks in concrete	Repairing holes in epoxy through on-site quality control	Repairing cracks in concrete and repairing holes in epoxy
1	8	21	20	32	24	37
2.5	9	25	27	37	29	42
5	14	28	33	41	36	45
10	28	32	42	46	46	50
20	35	36	49	50	53	55
30	38	39	54	56	57	58

For a critical structure with a delamination limit of 2.5 percent, the best protection strategy would be to choose epoxy-coated bars, minimize the damage to the coated bars, and then repair all cracks. Using this strategy, one may expect 42 yrs prior to initial repair for a structure using a top mat of epoxy-coated bars and bottom mat of black bars. If one repairs cracks in decks containing black bars, then repairs to the corrosion-inducted delaminations would be required after 25 yrs. If one had poor quality control on a structure where large damage sites in the epoxy-coated bars occurred, and cracks in the concrete were not repaired, one may only expect 27 yrs prior to repair, compared to 25 yrs for a structure with repaired cracks and black bars. By using the same quality control procedures as made for the black bar deck through the repair of cracks, you could improve the deck's life to 37 yrs.

For a non-critical structure with a delamination limit of 20 percent, the best protection strategy would again be to chose epoxy-coated bars, minimize the damage and then repair any cracks in the concrete. Using this strategy, one may expect 55 yrs prior to initial repair. If one prevented cracks in decks containing black bars, then repairs would be required after only 36 yrs. If one allowed large damage sites in the epoxy-coated bars and did nothing to repair cracks in the concrete, one may expect 49 yrs prior to repair. Even better performance is expected if one used two layers of epoxy-coated bars.

The time-to-repair is the most critical decision-making step in selecting corrosion protection strategies. Thus, although the research data indicate that epoxy-coated bars in cracked locations with a black bar cathode and large coating damage percentage may not dramatically reduce the corrosion rates, this analysis has shown that use of epoxy-coated bars under this worst-case scenario will still significantly increase the time before repair.

CHAPTER 7. SUMMARY AND DISCUSSION

This report discusses results obtained from in-concrete tests conducted on 12 different types of reinforcing bars. The 12 bar types selected for the in-concrete tests were:

- ASTM A 615 black reinforcing bar (BL)
- Epoxy-coated bars coated with 3M Scotchkote 213 (Epoxy-A)
- Two bendable epoxy-coated bar types (Epoxy-B, Epoxy-C)
- Two nonbendable epoxy-coated bar types (Epoxy-D, Epoxy-E)
- One post-baked nonbendable epoxy-coated bar type (Epoxy-F)
- ASTM A 767 galvanized bars (GL)
- Zinc alloy-clad bars (SM)
- ASTM A 955 Type 304 and Type 316 solid stainless steel bars (304, 316)
- Copper-clad bar (CU)

Of the six epoxies selected, three utilized steel pretreatments prior to coating (Epoxy-B, Epoxy-C, and Epoxy-E), and three did not (Epoxy-A, Epoxy-D, and Epoxy-F). The tests are described in chapter 2. Most of the test conditions used a straight black bar bottom mat; however, in other test conditions, the same corrosion-resistant bars were used in both the top and bottom mats.

Various measurements were made to enable the corrosion rates of the reinforcing bars to be determined. These included macrocell currents, linear polarization and ac impedance. All of these measurements provide a value that relates to the corrosion rate occurring at the instant of measurement. Results of the testing are summarized below.

Black Bars (BL)

Black bars were tested in three configurations: straight uncracked, straight precracked, and bent uncracked. Average macrocell voltages were 3525, 4053 and 2141 μV, respectively. The overall average voltage for all the black bar conditions during the 96-week period for the precracked specimens was 15 percent greater than that of the uncracked specimens. As soon as the salt solution was placed on the precracked concrete, corrosion of the black bars was measured; however, it was almost 12 weeks before the uncracked specimens began to show corrosion. After 96 weeks of testing, all 12 specimens exhibited cracking of their top surfaces and all top anodic black bars exhibited severe corrosion. On several bars, green rust was identified, and was determined to be an iron-hydroxide-chloride "Green-rust-I."

Epoxy-Coated Bars (Epoxies A, B, C, D, E and F)

The six different types of epoxy-coated bars (Epoxy-A to Epoxy-F) were tested in eight different configurations described below:

- Straight, black cathode, uncracked, 0.5 percent damage
- Straight, epoxy cathode, uncracked, 0.5 percent damage
- Bent, black cathode, uncracked, 0.5 percent damage
- Straight, black cathode, precracked, 0.5 percent damage
- Straight, black cathode, uncracked, 0.004 percent damage
- Straight, epoxy cathode, uncracked, 0.004 percent damage
- Bent, black cathode, uncracked, 0.004 percent damage
- Straight, black cathode, precracked, 0.004 percent damage

The best performance was obtained when the bars were tested in a straight condition, with 0.004 percent damage in uncracked concrete using an epoxy-coated cathode. Under this test condition, none of the concrete slabs cracked and corrosion rates were 63 to 1620 times lower than that of the black bars. When the bars were tested in a straight condition with 0.5 percent damage in precracked concrete using a black bar cathode, many of the epoxy-coated bar slabs cracked. Under this condition, corrosion rates were only 1.7 to 28 times lower than that of the black bars.

It was found that there was a clear relationship between the mat-to-mat resistance values of the epoxy-coated bars and their corrosion performance. Better corrosion protection was provided by those coating systems that had high electrical resistivities, that is, the corrosion was strongly dependent on the amount of damage in the coating.

Comparison of in-concrete and accelerated testing of epoxy-coated bars – During the first 2½ yrs of the project, considerable work was conducted investigating the adhesion of the coatings using solution immersion tests and cathodic debonding tests, as described in this report. Based upon review of the data, it appears that the adhesion, as tested by solution immersion and cathodic debonding tests, is a poor predictor of long-term performance of the coated bars in concrete. Use of cathodic debonding tests is still recommended for determining consistency of coating application during manufacture of the coated reinforcing bars; however, it is difficult to support use of either cathodic debonding tests or solution immersion tests for coating selection in specification documents.

Galvanized Bars (GL)

The galvanized bars were tested in five configurations. The lowest corrosion rates were obtained when the galvanized bars were used in both mats in uncracked concrete. The average corrosion obtained in this configuration was 38 times less than that of the black bars. When a precracked specimen was used, the corrosion rates of slabs with a black cathode significantly increased. While galvanized bars are commonly bent, these data show that the corrosion increased when bent bars were tested with a black cathode. These data suggest that coating should be done after fabrication. At the end of 96 weeks, almost all slab specimens exhibited cracks running parallel with the bars.

Zinc Alloy-Clad Bars

The zinc alloy-clad bars were tested in five configurations. The lowest corrosion rates were obtained when the zinc alloy-clad bars were used in both mats in uncracked concrete. The average corrosion obtained in this configuration was 5.5 times less than that of the black bars. When a precracked specimen was used, the corrosion rates increased by two times. This product also exhibited a significant increase in corrosion when the bars were bent. Combining a black cathode with the zinc alloy-clad bars did not increase the corrosion rate as significantly as the combining of a black cathode with galvanized bars.

At the end of 96 weeks, most of the slabs containing the zinc alloy-clad bars exhibited cracks. The only systems that did not exhibit surface cracking was one of the two slabs containing straight bars and a black cathode in uncracked concrete, one of the uncracked slabs with the zinc alloy-clad cathode, and two of the uncracked slabs containing bent bars.

Copper-Clad Bars (CU)

The copper bars were tested in four configurations. These particular copper-clad bars were unable to be bent without cracking of the copper coating. The lowest corrosion rates were obtained when the copper-clad bars were used in both mats and there was no crack in the concrete; however, in all conditions, the corrosion rates were significantly less than that for the black bars. The corrosion rates ranged from 23 to 92 times lower than that of the black bars. Minor corrosion currents were measured during the first 20 weeks of testing, suggesting that the bars passivate over time in the concrete environment. After 96 weeks of testing, no cracking or staining was observed on the top surface of the concrete specimens and the bars were generally clean; however, retardation of cement paste surrounding the copper-clad bars was observed.

Type 304 Stainless Steel Bars (304)

The Type 304 stainless steel bars were tested in five configurations. The lowest corrosion rates were obtained when the Type 304 stainless steel bars were used in both mats. This configuration of bars was not influenced by the presence of the crack; both conditions had about 1500 times less corrosion than the black bar specimens. Of the 10 bars that were coupled with the black bar cathodes, 5 bars exhibited moderate to high corrosion currents. It was concluded that the Type 304 stainless steel was susceptible to chloride-induced corrosion when it was tested with a black bar cathode, whereas when it was tested with a stainless steel cathode, it was not susceptible to any significant chloride-induced corrosion, even when in precracked concrete slabs.

During visual inspection of the slabs, most of the Type 304 bars did not exhibit any corrosion; however, two of the bars that had black cathodes and were in a precracked location had moderate red rust corrosion. None of the bars with the stainless steel cathodes exhibited any corrosion staining. Of the four bent bars with black cathodes that were inspected at 96 weeks, two had significant corrosion, while two others were clean.

Type 316 Stainless Steel Bars (316)

The Type 316 stainless steel bars were tested in five configurations. Low corrosion rates were obtained for all specimens containing the Type 316 stainless steel bars. The performance of the bars was not influenced by the presence of the crack, with all conditions having about 800 times less corrosion than the black bar specimens. During visual inspection of the slabs, only one of the bars exhibited any corrosion and in that instance the corrosion was regarded as minor. Results obtained for the Type 316 stainless steels indicate that these bars may be more suitable for in-concrete use than the Type 304 reinforcing bars and that these bars are less susceptible to galvanic effects if used in conjunction with black bars.

RANKING OF BAR SYSTEMS

This report documents findings of corrosion based upon a very accelerated and aggressive test. Concrete with a relatively high diffusion rate was utilized and saltwater ponding was conducted using a solution with a very high chloride concentration. During the 2-yr test period, almost all of the specimens for a particular test condition exhibited corrosion rates that were relatively uniform over time. We did not observe corrosion currents that rapidly increased, which would have indicated catastrophic and rapid failure. For this reason, we believe that the macrocell current data obtained over the 96 weeks of evaluation is sufficient for ranking product performance.

As the metallic-clad and solid metallic bars were only evaluated with 0.5 percent damage, it is necessary to rank the performance of the epoxy-coated bars based upon data obtained from those with 0.5 percent damage only. Data from tables 6, 10, 11, 12, 13 and 14 were utilized to construct the rankings shown in table 25. Due to the poor performance of Epoxy-F in almost all tests, the values for all epoxy-coated bars, except Epoxy-F (not currently used for reinforcing bars), were averaged to determine the average macrocell value for the epoxy-coated bars. It should be noted that the rankings would improve if repairs were made to damage in the coated bars in the field and care was taken in placement of the concrete to avoid additional coating damage.

Table 25. Ranking of protection systems with 0.5 percent coating damage.

Average macrocell voltage, μV	Straight bars, uncracked concrete	Bent bars, uncracked concrete	Straight bars, precracked concrete
	Top mat/bottom mat	Top mat/bottom mat	Top mat/bottom mat
2			304 SS/304 SS
3	304 SS/304 SS		
5	304 SS/black 316 SS/316 SS 316 SS/316 SS		316 SS/316 SS 316 SS/black
8		316 SS/black	
9	epoxy/epoxy*		
37	copper/black		
79	copper/copper		
85	galvanized/galvanized		
111			copper/copper
113		304 SS/black	
142			copper/black
267			304 SS/black
287			galvanized/galvanized
356	epoxy/black*		
361		epoxy/black*	
588	zinc alloy/zinc alloy		
782			epoxy/black*
1208			zinc alloy/zinc alloy
1267	zinc alloy/black		
2079	galvanized/black		
2142		black/black	
2342			zinc alloy/black
2730		zinc alloy/black	
2941		galvanized/black	
3525	black/black		
3733			galvanized/black
4054			black/black

* Results obtained for Epoxy-A, Epoxy-B, Epoxy-C, Epoxy-D and Epoxy-E were averaged to determine values.

The Type 316 bars were consistently in the top portion of the table, indicating excellent performance in the test program. The Type 304 bars had excellent corrosion performance when evaluated straight in uncracked concrete; however, when these bars were bent and used with a black bar cathode, moderate corrosion was observed. For this reason, we do not recommend use of Type 304 reinforcing bars, particularly when used with black cathodic bars.

For the straight epoxy-coated bars tested in uncracked concrete with an epoxy-coated bottom mat, the macrocell currents obtained for these bars were almost as low as that obtained for the stainless steel bars; however, when a black cathode was present, the corrosion rates significantly increased. Additional work is being conducted by the authors for other agencies on bent epoxy-coated bars in uncracked concrete with an epoxy-coated cathode and straight epoxy-coated bars in precracked concrete with an epoxy-coated cathode. Data reviewed to date from this test program indicates that the performance of the epoxy-coated bars will be significantly improved compared to those that utilize the black bar cathode.

The copper-clad bars performed relatively well when tested with either a copper or a black cathode; whereas the zinc alloy-clad and the galvanized bars had significantly different performance when evaluated with a black or a similar metal cathode. When tested in uncracked concrete, the performance of the galvanized bars with a galvanized cathode was relatively good; however, in precracked concrete, the performance of the bars dropped considerably. The performance of the galvanized bars when coupled with a black cathode was little better than the black bar specimens. The zinc alloy-clad bars performed better than the black bars in almost all cases; however, improvements observed in corrosion protection are not viewed as sufficient to warrant their use in concrete.

In almost all cases, the corrosion-resistant bars had lower corrosion rates than those of the black bars.

EVALUATION METHODS

The four reports written under this research program present a large database of material performance. For this reason, it is appropriate to comment on suitable testing techniques for evaluation of reinforcing bars. Some simple mechanical tests have been found to eliminate many reinforcing bar types from further consideration; for example, the bending test. Several products have failed either by crushing, cracking, cold flow or brittle fracture. This simple test should be conducted prior to accelerated corrosion testing.

The adhesion as tested by cathodic debonding and solution immersion tests described in references 16 and 17 was found to be inadequate for selection of the best-performing organic coatings for use in concrete. These tests did, however, eliminate certain products from further consideration. These included products that exhibited degradation in an alkaline environment and blistering. The cathodic debonding and solution immersion tests are considered to be useful for quality control purposes and for determining if poorly prepared and cleaned steel surfaces were coated.

The solid metallic and metallic-clad bar screening tests described in reference 4 utilized wetting and drying procedures in pH-7 and pH-13 solutions. These more rapid tests were found to be reasonable indicators of in-concrete performance.

The test program relied heavily on the accelerated in-concrete testing that was conducted on uncracked and precracked slabs. It was found in every instance that the macrocell currents were sufficient indicators of the condition of the reinforcing bars at the end of the 96 weeks of testing. Results were confirmed through electrical impedance spectroscopy and linear polarization; however, it is believed that interpretation of data from these two other techniques is very time-consuming and impractical for future large-scale test programs. Mat-to-mat resistance measurements between the top and bottom mats of steel were made using a Neilson soil resistance meter. For the coated bars, these resistance results provided an insight into reasons for good and poor coating performance. We believe that techniques used for the 96 weeks of in-concrete testing are suitable for evaluation of the corrosion resistance of other reinforcing bars. Although this method is similar to ASTM G 109, we believe that simple modifications should be made to the ASTM G 109 test to improve it. Results obtained from 96 weeks of testing in the future may be compared with the database of information provided within this final report.

CHAPTER 8. CONCLUSIONS

This report outlines findings of 5 yrs of research into corrosion-resistant reinforcing bars. The aim of the research was to evaluate products that are "significantly more corrosion-resistant than the fusion-bonded, epoxy-coated reinforcement that has been used in the United States since 1975." It was also required that the "corrosion-free design life shall be 75 to 100 yrs for the proposed study when exposed to adverse environments."

From the research, it was found that low corrosion rates could result in development of cracks in concrete due to corrosion. A corrosion rate of 0.00025 to 0.0003 mm/yr (0.000010 in/yr to 0.000013 in/yr) was necessary to allow a 75- to 100-yr crack-free design life[4]. The current 96-week in-concrete tests resulted, on average, in corrosion rates of 0.036 mm/yr (0.0014 in/yr) for the black bar control specimen, a value 100 times higher than that necessary to have a crack-free 75-yr design life. Similar calculations from this 96-week test using the Type 304 and Type 316 stainless steel bars resulted in corrosion rates of 0.000051 mm/yr (0.000002 in/yr) in uncracked and precracked concrete slabs when the cathode was also stainless steel. This metallic loss rate with Type 304 and Type 316 stainless is six times lower than the 0.0003-mm/yr (0.000013-in/yr) loss rate necessary to allow a 75- to 100-yr crack-free design life.

It is concluded that Type 316 stainless-steel reinforcing bars should be considered at the design stage as a potential method for obtaining a 75- to 100-yr design life. These bars had corrosion rates averaging 800 times lower than that of the black bars, even when tested in precracked concrete. It is believed by the researchers that present costs associated with the bars limit their current widespread use in concrete structures. However, for structures where repair to corrosion-induced damage is difficult, the additional costs associated with the stainless steel bars may be justified and life-cycle cost studies over a 75- to 100-yr period should be made. Potential use includes marine substructures, tunnels, and bridges that carry significant traffic where closure for repair would be problematic.

The research supports continued use of epoxy-coated reinforcing bars as a corrosion-protection system, as in all cases, the corrosion rates of the epoxy-coated bars were less than that observed for the black bars. However, when epoxy-coated bars are to be used, it is appropriate to:

- Use epoxy-coated reinforcing for both top and bottom mats of slabs, or all of the reinforcing in each element
- Minimize damage to the reinforcing bars during shipment and placement
- Repair coating damage on-site
- Repair cracks in the concrete

Additionally, it was found for the epoxy-coated bars that:

- Use of the coated cathode significantly reduced the corrosion rates of all bar types, suggesting that the corrosion mechanism of epoxy-coated bars may be inhibition of the cathodic reaction that requires electrons, oxygen, and hydroxide to be present at the cathode bar surface.
- Few of the concrete specimens containing two layers of epoxy-coated bars cracked.
- Low corrosion rates were obtained for specimens containing epoxy-coated bars with high mat-to-mat resistance measurements.
- Solution immersion and cathodic debonding tests for adhesion are poor predictors of long-term performance of the coated bars in concrete.
- Bars that used pretreatments did not perform significantly better than those without pretreatments.

It is difficult to support use of either cathodic debonding tests or solution immersion tests for coating selection in specification documents.

The research also found that the lowest corrosion rates for galvanized bars were obtained when these were used in both mats when no pre-existing cracks were present in the concrete. When a crack was introduced, the corrosion rates of slabs containing galvanized bars with a black cathode significantly increased. The corrosion rate of galvanized bars increased almost two times when tested bent with a black cathode, suggesting that bending of galvanized bars after coating may reduce their performance in corrosive environments, and that the coating should be done after fabrication. If galvanized bars are to be used, care should be taken to eliminate electrical contact between the galvanized steel and other metals.

Low corrosion rates were obtained for copper-clad bars, supporting results from previous research. However, as with prior research, retardation of cement paste surrounding the copper-clad reinforcing bars was observed.

Low corrosion rates for Type 304 stainless steel bars were obtained when they were used in both mats. The Type 304 stainless steel bars were found to be susceptible to moderate chloride-induced corrosion when they were tested with a black bar cathode; whereas when it was tested with a stainless steel cathode, it was not susceptible to any significant chloride-induced corrosion, even when in precracked concrete slabs.

The measured macrocell voltage was a reasonable indicator of the condition of the specimens at the end of the test period. It is believed that the macrocell voltage may be used to rank the long-term performance of the various bar systems. Results obtained from the more complex polarization resistance and electrochemical impedance spectroscopy tests generally reflected the data obtained from measurements of the macrocell currents and mat-to-mat resistances.

FUTURE PRODUCT DEVELOPMENTS

During the 5-yr research period, many different products have been reviewed by the researchers. At this time, it is appropriate to consider developments that may occur in the next 10 yrs.

Improvements are continually being made in the area of coating technologies. These improvements are being made through the development of products for the automobile industry and the chemical industry. Some of these developments include:

- Increased use of surface pretreatments prior to coating
- Increased use of more abrasion- and impact-resistant coatings
- Use of thicker coatings that rely on surface roughness to provide bond to the concrete
- Epoxy coatings that contain corrosion-inhibiting compounds
- Increased use of multiple-coat techniques

It is believed that over the next 10 yrs, there will be an increased use of bars that have been clad with various metallic coatings. Techniques such as plasma spray technology for applying one metal onto another are becoming increasingly used in the manufacture of products for other industries and these techniques could be used for the cladding of reinforcing bars. Optimizing steel chemistry to provide corrosion resistance through the addition of metals or modifying the steel crystal structure have been studied by some researchers; however, these changes have not, as yet, had significant interest from the steel manufacturers.

It is our belief that the use of stainless steel reinforcing bars will increase in the future. The use of Type 316 and duplex stainless steels for reinforcing bars is being considered by some transportation agencies in the United States and Canada. Due to the relatively high cost of solid stainless steel reinforcing bars, a significant amount of research is being conducted into methods for manufacture of stainless steel-clad reinforcing, which may provide an alternative to epoxy-coated bars in high-quality concretes. Further corrosion research of these clad products will be required.

Table 26. Voltage and resistance of black bar (BL) specimens.

Configuration	Straight uncracked	Straight precracked	Bent uncracked
Average voltage across resistor for each replicate (μV)	2349 1813 4959 4978	4784 5824 3036 2572	2258 1613 2157 2538
Average	3525	4053	2141
Average mat-to-mat resistance for each replicate (ohm)	291 348 166 166	229 207 317 300	349 455 280 276
Average	243	263	340

Table 27. Autopsy observations of black bar (BL) specimens.

Tent	Bar	Anode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
1	3	Black	N	N	Crack over bar and corrosion formed at ends of bar	Green rust over bar, severe corrosion along length	Clean
1	4	Black	N	N	Cracks over bar and corrosion at ends of bar	Severe corrosion along bar	Clean
1	5	Black	N	N	Severe cracks over bar and stained concrete surface	Severe corrosion over bar. Green and black rust observed.	Minor corrosion on one bar from bars end
1	6	Black	N	N	Severe cracks over bar, stained concrete surface	Severe corrosion leading to delamination, significant loss of section	Green rust observed on bottom bars
1	9	Black	N	Y	Severe cracking and staining of concrete	Severe corrosion of top bar	Clean
1	10	Black	N	Y	Significant corrosion and staining. Cracking of top concrete surface	Severe corrosion of top bar	Clean
1	13	Black	N	Y	Staining above the bar and minor cracking of the concrete	Significant section loss due to corrosion	Clean
1	14	Black	N	Y	Initial crack extended by corrosion	Green rust observed on top bar	Clean
3	6	Black	Y	N	Cracked and stained surface	Significant loss of bar section on top of bar	Clean
3	5	Black	Y	N	Cracked and stained surface	Significant loss of bar section on top of bar	Clean
3	2	Black	Y	N	Cracked and stained surface	Significant loss of bar section on top of bar	Clean
3	1	Black	Y	N	Cracked and stained surface	Significant loss of bar section on top of bar	Clean

Table 28. Voltage and resistance for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (μV)	36 14	439 54	837 238	44 53	1225 624	1761 2054
Average	25	246	538	48	925	1907
Average mat-to-mat resistance for two replicates (ohm)	3233 3245	1778 4939	1146 2195	3362 3667	1162 2405	841 733
Average	3239	3359	1671	3514	1783	787

Table 29. Average adhesion rating for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

Straight bar, black cathode, uncracked, 0.5 percent damage	Average adhesion					
	A	B	C	D	E	F
At hole	5 5	5 5	5 5	5 5	5 5	5 5
Away from hole	1 1	4 2	5 5	1 1	1 1	5 5

Table 30. Autopsy results for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	5	A	Clean	Coating debonds readily away from hole.	Clean
2	7	A	Clean	Minor stain at one location of coating. Coating readily debonds from bar.	Clean
4	5	B	Corrosion at end of concrete block.	Unusual white product at bar.	Clean
4	7	B	Clean	Clean	Clean
4	14	C	Crack in center of block caused by corrosion.	Poor bond, cracks in coating, white deposit on bar.	Clean
4	16	C	Clean	Severe cracking in coating. Strange white deposit on bar away from holes.	Clean
6	22	D	Clean	Clean. Coating debonds approximately 25 mm (1 in).	Clean
6	24	D	Clean	Poor bond at hole. Coating debonds about 25 mm (1 in). Minor corrosion at hole.	Clean
10	14	E	Clean	Significant corrosion at bar center. Coating debonds readily.	Clean
10	20	E	Clean	Coating cracked and green rust under coating. (Coating readily debonds approximately 25 mm (1 in) from hole.)	Clean
7	15	F	Cracking and staining of concrete surface.	Cracks in coating. Minor rust stains on bar.	Corrosion over approximately 75 mm (3 in) of a single black bar.
7	19	F	Cracking and staining of concrete surface.	Significant red and black corrosion products present on bar. Cracks in coating. Coating readily debonds.	Clean

Table 31. Voltage and resistance for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with an epoxy-coated cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (μV)	3 3	3 5	4 19	14 14	10 17	23 23
Average	3	4	12	14	14	23
Average mat-to-mat resistance of two replicates (ohm)	6323 5559	10123 8386	7923 6572	7076 6752	4605 4258	3567 3796
Average	5941	9255	7247	6914	4431	3682

Table 32. Average adhesion rating for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with an epoxy-coated cathode.

Straight bar, epoxy cathode, uncracked, 0.5 percent damage	**Average adhesion**					
	A	B	C	D	E	F
At-hole anode	5 5	5 5	5 5	3 4	5 5	5 5
Away-from-hole anode	2 5	1 5	1 5	1 1	1 1	5 3
At-hole cathode	1 2	2 2	1 5	1 1	2 4	4 5
Away-from-hole cathode	1 1	1 1	1 1	2 1	1 1	1 1

Table 33. Autopsy results for straight, epoxy-coated bars with 0.5 percent damage in uncracked concrete with an epoxy-coated cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	14	A	Clean	Some moderate underfilm corrosion. Oxide approximately 19 mm (¾ in) in diameter around hole. Minor volume change under coating.	Clean
2	16	A	Clean	Coating readily debonds from bar. No cracking in coating.	Clean
4	18	B	Clean	Underfilm corrosion approximately 25 mm (1 in) from hole.	Clean
4	20	B	Clean	Underfilm corrosion.	Clean
5	18	C	Clean	Blisters at one hole location and underfilm corrosion.	Clean
5	24	C	Clean	Some blisters on bar near one end.	Clean
6	1	D	Clean	Clean	Clean
6	3	D	Clean	Clean. Coating debonds approximately 12-mm (½-in).	Clean
11	20	E	Clean	Clean. Coating debonds approximately 10 mm (0.40 in).	Clean
11	22	E	Clean	Rebar corroded approximately 2 mm (0.08 in) around bar.	Clean
12	12	F	Clean	Minor corrosion on bottom of bar. No rust under coating.	Clean
12	15	F	Clean	Minor red rust stains along bar. Bottom of bar coating exhibits excellent adhesion.	Clean

Table 34. Voltage and resistance for bent epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (μV)	214 561	96 519	1139 466	25 578	4 12	852 2580
Average	388	308	803	302	8	1716
Average mat-to-mat resistance for two replicates (ohm)	1441 1258	2190 1695	1356 1430	3333 2143	3600 4010	947 463
Average	1349	1943	1393	2738	3805	705

Table 35. Average adhesion rating for bent epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

Bent bar, black cathode, uncracked, 0.5 percent damage	Average adhesion					
	A	B	C	D	E	F
At hole	5 5	5 5	5 5	5 3	3 2	5 5
Away from hole	5 5	5 5	5 5	5 3	2 5	1 1

Table 36. Autopsy results for bent epoxy-coated bars with 0.5 percent damage in uncracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	22	A	Clean	Significant underfilm corrosion.	Clean
3	18	A	Clean	Significant underfilm corrosion. Coating readily debonds.	Clean
5	5	B	Clean	Coating blistered at several locations.	Clean
5	7	B	Small crack along top of slab.	Corrosion staining on bar and underfilm corrosion.	Corrosion on one bar, approximately 1900 mm^2 (3 in^2)
5	11	C	Crack in center of slab.	Minor corrosion on bend and the presence of green-colored oxide. Cracking of the coating visible.	Clean
5	14	C	Clean	Severe corrosion staining. Cracks in coating and white deposits on bar.	Clean
6	16	D	Clean	Clean	Clean
6	9	D	Corrosion stain from single location.	No corrosion from 6-mm (¼-in) drill holes. Significant staining of concrete. Significant debonding.	Clean
11	4	E	Clean	Minor corrosion near one drill hole.	Clean
11	8	E	Clean	Coating debonds at center of bend.	Clean
12	17	F	Clean	Corrosion on top and bottom of bar. Minor cracks in coating near holes. Coating readily debonds near hole.	Clean
12	21	F	Cracks in concrete and staining of surface.	Significant corrosion on bottom of bar. Coating cracked at holes.	Clean

Table 37. Voltage and resistance for straight, epoxy-coated bars with 0.5 percent damage in precracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two or four replicates (µV)	692 532 272 889	243 1065	1106 968	180 46	1772 1247	2153 1682
Average	596	654	1037	113	1510	1918
Average mat-to-mat resistance for two or four replicates (ohm)	913 1150 2045 1057	5387 921	797 816	1715 *	706 885	491 580
Average	1281	2918	831	1715	822	591

*Data contained errors preventing meaningful value from being determined.

Table 38. Average adhesion rating for straight, epoxy-coated bars with 0.5 percent damage in precracked concrete with a black cathode.

Straight bar, black cathode, precracked, 0.5 percent damage	**Average adhesion**					
	A	B	C	D	E	F
At hole	5 5 5 5	5 5	5 5	5 5	5 5	5 5
Away from hole	5 5 5 5	5 5	5 5	1 1	2 1	5 5

Table 39. Autopsy results for straight, epoxy-coated bars with 0.5 percent damage in precracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
16	20	A	Clean	Clean	Clean
16	22	A	Clean	Clean	Clean
9	16	A	Clean	Blisters near drill hole in bar.	Clean
9	22	A	Clean	Minor blisters near bar ends. Black and red rust on bar.	Clean
16	10	B	Clean	Black rust near center of bar and blisters on the bottom of the bar	Clean
16	16	B	Clean	Corrosion along bar length	Clean
16	3	C	Minor corrosion at end of slab.	Coating cracked at hole and along ribs. Red and black stains on bar	Clean
16	5	C	Clean, possible crack extension.	Cracks in coating and significant rust on bar surface	Clean
7	1	D	Clean	Blister near bar end. Significant debonding around hole. Approximately 25 mm (1 in) debonded	Clean
7	8	D	Clean	Minor corrosion on bottom of bar. Blister at end and corrosion at hole. Debonds approximately 12 mm (½ in)	Clean
11	11	E	Red rust in crack, crack extended.	Red rust at center of bar.	Minor corrosion at one end of a bar.
11	9	E	Clean	Black corrosion around bar. Minor blisters in coating [approximately 25 mm (1 in) debonds].	Moderate corrosion on single bar approximately 100 x 6 mm (4 x ¼ in).
12	2	F	Red rust at precrack and crack extension.	Corrosion occurring in crack. Minor cracking radiating from holes in bar. Red and black rust on bar surface.	Clean
12	4	F	Red rust at crack.	Coating cracks. Black rust staining along bar.	Clean

Table 40. Voltage and resistance for straight, epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (µV)	2 4	2 2	2 85	11 13	191 60	7 1078
Average	3	2	43	12	125	543
Average mat-to-mat resistance for two replicates (ohms)	322900 400514	540909 545455	962857 59805	672381 645757	13757 133800	178500 2374
Average	361707	543182	511331	659069	73779	90437

Table 41. Average adhesion for straight, epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

Straight bar, black cathode, uncracked, 0.004 percent damage	**Average adhesion**					
	A	**B**	**C**	**D**	**E**	**F**
At hole	1 1	1 1	1 5	1 1	5 4	1 5
Away from hole	1 1	1 1	1 1	1 1	5 1	1 5

Table 42. Autopsy results for straight, epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	6	A	Clean	Clean	Clean
2	8	A	Clean	Clean	Clean
4	6	B	Clean	Clean	Clean
4	8	B	Clean	Clean	Clean
4	13	C	Clean	Clean	Clean
4	15	C	Clean	Corrosion at one hole leading to cracking of the coating	Clean
6	21	D	Clean	Clean	Clean
6	23	D	Clean	Clean	Clean
10	13	E	Clean	Minor red rust stains over bar. Green corrosion products under coating.	Clean
10	19	E	Clean	Clean	Clean
7	16	F	Clean	Clean	Clean
7	20	F	Cracking and staining of concrete surface.	Significant corrosion staining on bar and cracks in coating. Black and red rust present.	Clean

Table 43. Voltage and resistance of straight epoxy-coated bars with 0.004 percent damage in uncracked concrete with an epoxy cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (μV)	2 2	2 3	3 4	13 13	4 3	99 4
Average	2	3	3	13	4	51
Mat-to-mat resistance for two replicates (ohm)	489595 487309	703810 418762	449048 607619	935000 947500	338500 180000	485000 473750
Average	488452	561286	528333	941250	259250	479375

Table 44. Average adhesion rating for straight epoxy-coated bars with 0.004 percent damage in uncracked concrete with an epoxy cathode.

Straight bar, epoxy cathode, uncracked, 0.004 percent damage	**Average adhesion**					
	A	**B**	**C**	**D**	**E**	**F**
At-hole anode	1 1	1 2	1 1	1 1	1 4	1 1
Away-from-hole anode	1 1	1 1	1 1	1 1	1 1	1 1
At-hole cathode	1 2	1 1	1 1	1 1	1 1	2 1
Away-from-hole cathode	1 1	1 1	1 1	1 1	1 1	1 1

Table 45. Autopsy results for straight epoxy-coated bars with 0.004 percent damage in uncracked concrete with an epoxy cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	13	A	Clean	Clean	Clean
2	15	A	Clean	Clean	Clean
4	17	B	Clean	Clean	Clean
4	19	B	Clean	Clean	Clean
5	17	C	Clean	Clean	Clean
5	23	C	Clean	Clean	Clean
6	2	D	Clean	Clean	Clean
6	4	D	Clean	Clean	Clean
11	19	E	Clean	Clean	Clean
11	21	E	Clean	Clean	Clean
12	11	F	Clean	Clean	Clean
12	16	F	Clean	Clean	Clean

Table 46. Voltage and resistance for epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two replicates (μV)	7 4	4 4	60 97	27 11	1 6	9 2431
Average	5	4	79	19	4	1220
Average mat-to-mat resistance for two replicates (ohms)	5682 21441	148810 46695	245350 98552	60450 77450	193500 140700	113104 2431
Average	13561	97752	171951	68950	167100	57768

Table 47. Average adhesion for bent epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

Bent bar, black cathode, uncracked, 0.004 percent damage	**Average adhesion**					
	A	**B**	**C**	**D**	**E**	**F**
At hole	5 5	5 5	5 5	1 1	2 2	2 5
Away from hole	5 5	5 5	5 5	1 2	4 3	1 5

Table 48. Autopsy results for bent epoxy-coated bars with 0.004 percent damage in uncracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
2	21	A	Clean	Minor underfilm corrosion.	Clean
3	17	A	Clean	Coating debonds readily on bend. Minor underfilm corrosion.	Clean
5	6	B	Clean	Clean	Clean
5	8	B	Clean	Underfilm corrosion.	Clean
5	12	C	Clean	Minor corrosion around bend and coating cracked.	Clean
5	13	C	Clean	Corrosion on bar surface and cracks in coating.	Clean
6	10	D	Clean	Clean	Clean
6	15	D	Clean	Clean	Clean
11	3	E	Clean	Clean	Clean
11	7	E	Clean	Clean	Clean
12	18	F	Clean	Clean	Clean
12	22	F	Cracks in concrete and staining.	Significant corrosion along bends. Cracks in coating and coating readily debonds.	Clean

Table 49. Voltage and resistance for straight epoxy-coated bars with 0.004 percent damage in precracked concrete with a black cathode.

	A	B	C	D	E	F
Average voltage across resistor for two or four replicates (μV)	154 34 18 108	79 1121	303 194	8 21	854 63	1096 13
Average	78	600	248	14	459	554
Average mat-to-mat resistance for two or four replicates (ohms)	2630 41816 15430 12153	8627 942	59881 3456	301739 3096	8713 180050	1128 35948
Average	14653	4005	21406	103722	63212	12592

Table 50. Average adhesion rating for straight epoxy-coated bars with 0.004 percent damage in precracked concrete with a black cathode.

Straight bar, black cathode, precracked, 0.004 percent damage	Average adhesion					
	A	B	C	D	E	F
At hole	5 1 1 1	5 5	5 5	2 3	5 2	5 3
Away from hole	5 1 1 1	5 5	5 2	1 1	5 1	1 1

Table 51. Autopsy results for straight epoxy-coated bars with 0.004 percent damage in precracked concrete with a black cathode.

Tent	Bar	Anode	Slab condition	Top bar condition	Bottom bar condition
16	19	A	Clean	Clean, minor blisters at one location.	Clean
16	21	A	Clean	Clean, except at one end.	Clean
9	15	A	Clean	Clean	Clean
9	21	A	Clear	Corrosion at one end of bar.	Clean
16	15	B	Clean	Minor blisters on bottom of bar and corrosion.	Clean
16	9	B	Clean	Corrosion on bar and some minor blisters on bar.	Clean
16	4	C	Clean	Corrosion and cracking of the coating at the ribs. White deposits under the coating.	Clean
16	6	C	Clean	Corrosion on bottom of bar and some minor cracks in coating.	Clean
7	2	D	Clean	Clean	Clean
7	7	D	Clean	Clean	Clean
11	10	E	Red rust at crack, and precrack extended.	Minor blisters on bottom of bar. Red and black rust in center of bar.	Clean
11	12	E	Clean	Clean	Clean
12	1	F	Red rust at precrack.	Cracks in coating and red/black rust stains on bar.	Clean
12	3	F	Clean	Clean	Clean except for minor corrosion at one end of a single bar.

Table 52. Voltage and resistance for galvanized bars (GL).

Configuration	Voltage across resistor: Average during 96 weeks (μV)	Voltage across resistor: Average (μV)	Mat-to-mat resistance: Average during 96 weeks (ohm)	Mat-to-mat resistance: Average (ohm)
Straight, black cathode, uncracked	3118 1041	2079	311 516	413
Straight, galvanized cathode, uncracked	40 131	85	565 480	522
Straight, black cathode, precracked	2922 2960	2941	279 357	318
Straight, galvanized cathode, precracked	255 318	287	456 365	410
Bent, black cathode, uncracked	2559 4321 3758 4295	3733	394 295 315 297	325

Table 53. Autopsy results for galvanized bars (GL).

Tent	Bar	Cathode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
8	14	Black	N	N	Crack along length of bar.	Green corrosion along length of bar.	Clean
8	16	Black	N	N	Crack extends along length of bar.	Green and white oxides along bar. Red rust at one drill hole.	Clean
8	20	GL	N	N	Minor crack at one end of slab.	Red rust at hole and black corrosion at end of bar.	Clean
8	22	GL	N	N	Crack along bar.	Red rust in hole; no significant red rust elsewhere.	Clean
8	13	Black	N	Y	Red rust stains on top of bar. Precrack extended.	Significant loss of bar section on top of bar. Minor corrosion on bar bottom.	Minor corrosion at one end of a single bar
8	15	Black	N	Y	Precrack extended along bar.	Black corrosion on top surface of bar.	Clean
8	19	GL	N	Y	Minor crack at one end of bar.	Red and black corrosion along bar.	Clean
8	21	GL	N	Y	Clean		Clean
9	10	Black	Y	N	Minor cracks on side of slab.	Black and green corrosion uniformly over bar surface. Bottom of bar grey colored.	Clean
9	7	Black	Y	N	Cracks around bar. Red rust stains on top of slab.	Black and green corrosion uniformly over bar surface.	Minor corrosion at one end of a bar.
9	8	Black	Y	N	Cracks in concrete.	Black and green corrosion uniformly over bar surface.	Clean
9	9	Black	Y	N	Cracks around bar ends and red rust stains.	Black and green corrosion uniformly over bar surface.	Minor corrosion on a bar.

Table 54. Voltage and resistance for zinc alloy-clad bars (SM).

Configuration	Voltage across resistor		Mat-to-mat resistance	
	Average during 96 weeks (μV)	Average (μV)	Average during 96 weeks (ohm)	Average (ohm)
Straight, black cathode, uncracked	1289 1246	1267	351 419	385
Straight, zinc alloy-clad cathode, uncracked	850 326	588	372 391	381
Straight, black cathode, precracked	3246 2215	2730	284 365	325
Straight, zinc alloy-clad cathode, precracked	1446 971	1208	356 697	526
Bent, black cathode, uncracked	2408 2358 2220 2382	2342	333 327 386 334	345

Table 55. Autopsy observations for zinc alloy-clad bars (SM).

Tent	Bar	Cathode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
8	1	Black	N	N	Clean	Corrosion along top surface of bar	Clean
8	5	Black	N	N	Crack along bar.	Black corrosion along bar	Clean
8	7	SM	N	N	Clean	Corrosion over half of bar surface	Clean
8	9	SM	N	N	Minor cracking at one end of bar.	Corrosion at one end of bar and no corrosion at other end of bar	Clean
8	2	Black	N	Y	Crack extends along bar.	Black corrosion along bar	Clean
8	6	Black	N	Y	Crack extended at ends of precrack.	Black and green corrosion over most of the bar	Clean
8	10	SM	N	Y	Precrack extends in both directions.	Black and red oxide on both surfaces of bar	Clean
8	8	SM	N	Y	Crack extends along bar.	Black corrosion over length of bar	Minor corrosion on one end of a bar.
9	3	Black	Y	N	Minor cracks around bar.	Black corrosion on all bar surfaces	Minor stain at middle of one bar.
9	4	Black	Y	N	Crack near bar ends.	Black corrosion on all bar surfaces	Clean
9	5	Black	Y	N	Clean	Black corrosion over all bar surfaces	Clean
9	6	Black	Y	N	Clean	Black corrosion over all bar surfaces	Corrosion at mid-length of bar (minor).

Table 56. Voltage and resistance for copper-clad bars (CU).

Configuration	Voltage across resistor: Average during 96 weeks (µV)	Voltage across resistor: Average (µV)	Mat-to-mat resistance: Average during 96 weeks (ohm)	Mat-to-mat resistance: Average (ohm)
Straight, black cathode, uncracked	26 47	37	603 566	584
Straight, copper cathode, uncracked	106 52	79	330 602	466
Straight, black cathode, precracked	119 165	142	503 480	491
Straight, copper cathode, precracked	117 104	111	407 299	353

Table 57. Autopsy observations for copper-clad bars (CU).

Tent	Bar	Cathode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
10	2	Black	N	N	Clean	Clean	Clean
10	4	Black	N	N	Clean	Clean	Clean
10	10	CU	N	N	Clean	Clean, minor red oxide on bar.	Clean
10	12	CU	N	N	Clean	Clean, retarded concrete around bar.	Clean
10	1	Black	N	Y	Clean	Clean	Clean
10	3	Black	N	Y	Clean	Clean	Clean
10	11	CU	N	Y	Clean	Clean	Clean, oily deposit on bar, possibly form oil?
10	9	CU	N	Y	Clean	Clean, retarded concrete around bar.	Clean

Table 58. Voltage and resistance for Type 304 stainless steel bars (304).

Configuration	Voltage across resistor		Mat-to-mat resistance	
	Average during 96 weeks (μV)	Average (μV)	Average during 96 weeks (ohm)	Average (ohm)
Straight, black cathode, uncracked	5 5 5	5	637 550 619	602
Straight, 304 cathode, uncracked	2 3	3	451 497	474
Straight, black cathode, precracked	122 32 185	113	593 535 570	566
Straight, 304 cathode, precracked	2 2	2	431 486	459
Bent, black cathode, uncracked	718 4 340 5	267	532 559 500 619	552

Table 59. Autopsy observations for Type 304 stainless steel bars (304).

Tent	Bar	Cathode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
1	17	Black	N	N	Clean	Slight darkening of bar.	Clean
1	19	Black	N	N	Clean	Clean	Clean
1	21	Black	N	N	Clean	Clean	Clean
2	2	304	N	N	Clean	Clean	Clean
2	4	304	N	N	Clean	Clean	Clean
1	18	Black	N	Y	Clean	Small area of top bar with severe corrosion loss and loss of rib section.	Clean
1	20	Black	N	Y	Clean	Corrosion at two locations on bar - small pits developed.	Clean
1	22	Black	N	Y	Small stain at end of initial crack.	Corrosion at one location on the bar that is localized.	Clean
2	1	304	N	Y	Clean	Clean	Clean
2	3	304	N	Y	Clean	Clean	Clean
3	10	Black	Y	N	Clean	Significant corrosion at top of bar around the bent area. Missing lug due to corrosion.	Clean
3	13	Black	Y	N	Clean	Clean	Clean
3	14	Black	Y	N	Clean	Significant corrosion on bend near hole.	Clean
3	9	Black	Y	N	Clean	Clean	Clean

Table 60. Voltage and resistance for Type 316 stainless steel bars (316).

Configuration	Voltage across resistor		Mat-to-mat resistance	
	Average during 96 weeks (μV)	Average (μV)	Average during 96 weeks (ohm)	Average (ohm)
Straight, black cathode, uncracked	5 5	5	448 504	476
Straight, 316 cathode, uncracked	6 4	5	415 430	422
Straight, black cathode, precracked	5 6 21 4	9	415 425 368 350	389
Straight, 316 cathode, precracked	5 6	5	424 435	430
Bent, black cathode, uncracked	5 5	5	380 438	409

Table 61. Autopsy observations for Type 316 stainless steel bars (316).

Tent	Bar	Cathode	Bent, Yes or No	Precracked, Yes or No	Slab condition	Top bar condition	Bottom bar condition
17	1	Black	Y	N	Clean	Clean	Clean
17	2	Black	Y	N	Clean	Minor corrosion under bar chair. Minor metal loss.	Clean
17	7	Black	Y	N	Clean	Clean	Clean
17	8	Black	Y	N	Clean	Clean	Clean
17	9	316	N	N	Clean	Clean	Clean
17	10	316	N	Y	Clean	Clean	Clean
17	15	316	N	Y	Clean	Clean	Clean
17	16	316	N	N	Clean	Clean	Clean
17	21	Black	N	Y	Clean	Clean	Clean
17	22	Black	N	N	Clean	Clean	Clean
17	23	Black	N	Y	Clean	Clean	Clean
17	24	Black	N	N	Clean	Clean	Clean

Table 62. EIS test results for individual specimens, log ohm.

Damage area, %	Coating type	Straight, uncracked, black cathode				Bent, uncracked, black cathode				Straight, precracked, black cathode				Straight, uncracked, coated cathode			
		Initial		Final		Initial		Final		Initial		Final		Initial		Final	
0.004	A	8.5	8.6	7.3	8.7	5.5	4.8	4.4	4.1	8.4	6.2	5.1	3.7	8.5	7.5	8.8	4.1
	B	8.6	8.3	7.5	7.1	6.1	8.5	4.6	3.8	5.2	6.7	2.7	4.2	8.5	-	6.2	-
	C	8.5	7.5	8.8	3.7	8.3	8.5	3.0	3.2	7.6	7.9	2.6	3.0	7.2	8.6	6.7	7.5
	D	7.9	-	5.5	-	8.1	8.9	5.1	6.0	8.7	-	4.8	-	8.3	-	7.8	-
	E	6.7	7.3	3.7	5.3	6.6	6.4	6.6	6.5	6.5	6.9	2.7	5.5	6.8	6.7	5.6	4
	F	7.6	7.9	5.2	2.1	8.4	7.3	4.8	2.0	5.9	8.2	2.5	4.2	8.5	8.5	5.7	5.7
0.5	A	4.3	4.3	3.9	3.8	4.2	4.3	2.7	3.1	4.4	4.6	2.9	3.1	4.3	4.4	4.1	3.7
	B	4.3	4.6	3.9	2.7	4.3	4.4	3.3	2.4	6.1	4.4	3.2	2.6	4.5	4.5	3.7	3.8
	C	4.4	4.4	2.1	2.2	4.4	4.3	1.9	2.1	4.4	4.7	2.2	2.2	4.4	4.4	3.7	3.2
	D	4.7	-	3.8	-	4.5	4.5	2.6	4.2	4.6	-	3.2	-	4.7	-	4.3	-
	E	4.4	4.5	2.1	5.3	4.2	4.3	3.9	4.1	3.2	3.0	2.6	2.4	4.3	4.4	3.2	3.2
	F	4.4	4.3	2.1	2.0	4.4	4.3	2.4	3.6	4.4	4.1	2.2	4.3	4.5	4.3	4.2	2.9
- indicates results not obtained																	

Table 63. PR test results for individual specimens, log ohm.

Damage area, %	Coating Type	Straight, uncracked, black cathode				Bent, uncracked, black cathode				Straight, precracked, black cathode				Straight, uncracked, coated cathode			
		Initial		Final		Initial		Final		Initial		Final		Initial		Final	
0.004	A	5.9	6.6	7.8	10.3	6.5	6.0	4.5	4.1	7.5	8.1	3.8	5.1	5.6	6.6	5.0	7.3
	B	4.3	5.0	7.5	7.1	-	-	4.8	4.2	10.3	7.6	2.7	4.3	5.8	-	6.3	-
	C	-	-	3.6	10.3	-	-	2.9	3.1	10.3	10.0	2.6	2.9	6.8	-	7.1	7.5
	D	6.7	-	6.0	-	6.1	6.0	6.2	6.9	6.7	-	5.1	-	6.1	-	7.8	-
	E	7.4	7.3	3.8	5.5	7.3	7.4	6.7	6.6	7.1	7.7	2.6	5.5	7.3	7.5	5.7	4.1
	F	6.3	6.5	5.5	2.2	10.0	8.0	7.3	2.0	6.6	1.2	2.6	4.6	8.2	8.5	5.7	4.3
0.5	A	5.8	5.8	4.0	3.8	5.7	5.6	2.7	3.1	5.4	5.9	2.9	3.1	5.8	5.9	4.4	3.9
	B	5.9	5.8	2.6	3.9	-	-	3.3	2.4	6.8	5.7	3.1	2.6	6.2	-	3.8	4.0
	C	-	-	2.0	2.2	-	-	1.9	2.1	5.6	6.0	2.3	2.3	5.9	-	3.8	3.2
	D	6.4	-	3.8	-	6.1	6.3	2.6	4.5	6.4	-	3.3	-	6.5	-	5.0	-
	E	5.5	5.7	2.1	5.5	5.4	5.5	4.2	4.7	3.2	3.0	2.6	2.3	5.5	5.8	3.2	3.3
	F	4.6	5.5	2.1	2.0	5.9	6.0	2.4	1.8	5.6	5.4	2.2	2.2	5.9	5.8	1.0	3.0
- indicates results not obtained																	

APPENDIX B. ELECTROCHEMICAL TESTING OF BLACK AND EPOXY-COATED BARS IN CONCRETE SLABS

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Introduction

As a part of the study, electrochemical impedance spectroscopy (EIS) was used to monitor bars in concrete. EIS is often used to investigate corroding systems based on their response to an external electrical excitation. The testing is performed by applying a low-amplitude ac potential between the reinforcing bar and a counter electrode on the surface of the concrete and measuring the response of the system, as described earlier in this report. Most of the measurements were made prior to ponding and immediately before the 96-week autopsies were performed. Selected specimens were periodically measured throughout the 96 weeks of testing. Results are discussed below.

Black Bars

The 0.1-Hz impedance values for the black bar specimens measured during the 96-week period of testing are shown in figure 25, for specimens with bent and straight bars, with and without cracks. For the black bars, the values obtained for the various configurations are similar for all conditions and a final impedance of approximately 10^2 ohm at 0.1 Hz was obtained at the end of the test period. This impedance is primarily believed to be the impedance of the concrete and does not contain a significant contribution from the polarization resistance value component of the uncoated bar.

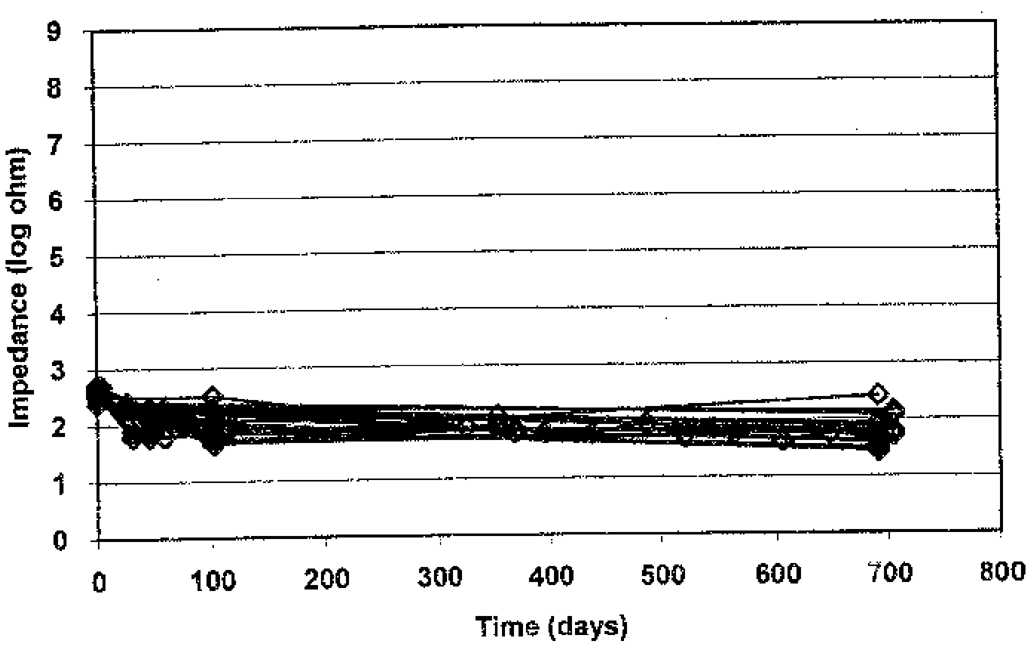

Figure 25. Impedance of black bar specimens during 96 weeks of testing.

Figure 26 shows the Bode plot for the black bar specimens determined initially and after 96 weeks. The Bode plot for the black bars is approximately a horizontal line over the frequency range from 0.1 to 100,000 Hz, indicating mainly resistive behavior. It is believed that this relates primarily to the resistance of the concrete between the bar and the measuring apparatus. The decrease in impedance from 0 to 96 weeks indicates a drop in the concrete resistivity, probably due to changes in the concrete moisture content and the addition of a large amount of conductive chloride ions from the salt solution.

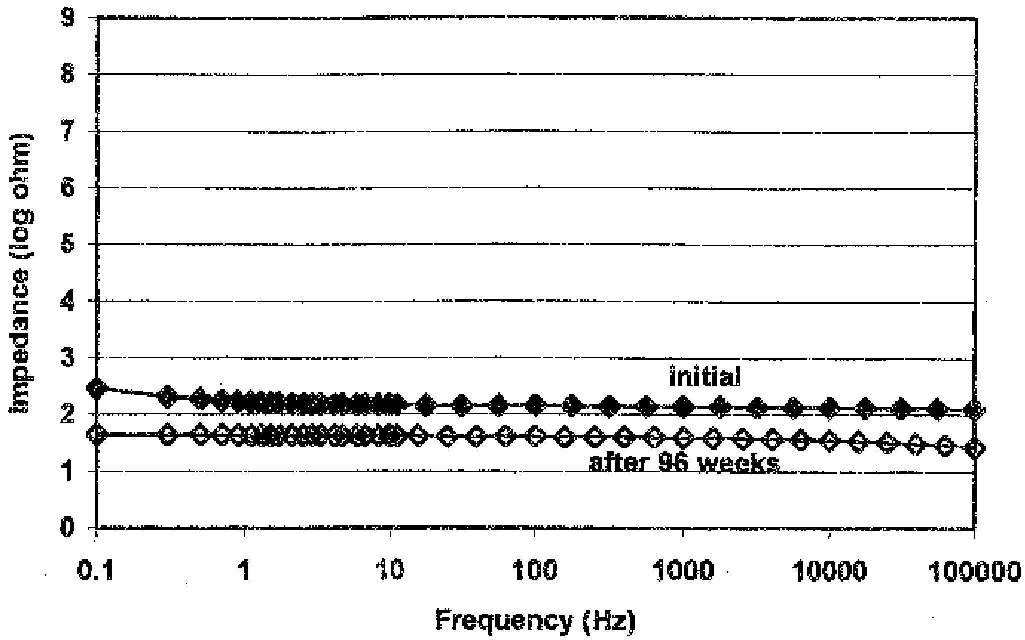

Figure 26. Bode plot for black bar specimens, initial and final measurements.

Epoxy-Coated Bars

Because of the inherent high electrical resistance of the coatings, bars in concrete tested using EIS techniques typically behave in one of three ways: capacitive, resistive, and mixed. Capacitive behavior is seen in coated bars that are free from holidays and damage. Capacitive behavior arises because of the very high impedance of the bar coatings and their insulative properties. Only intact and bonded coated bars behave in this manner. As the integrity of the coating breaks down, more "short-circuits" through the coating develop and the capacitive effect is lost. Capacitive behavior is shown by a continuous line at -45° in a Bode plot.

Resistive behavior is seen in coated bars with poor coatings and/or with significant coating damage. Because of the very high resistance of the coatings used for reinforcing, any electricity flowing from the bar to the concrete would much prefer to flow through gaps or holes in the coating where the electrical resistance is much lower. Resistive behavior is shown in a Bode impedance plot by a horizontal line.

Mixed behavior is seen with moderate coatings or slight damage. Mixed behavior occurs when neither capacitive nor resistive behavior dominates. It is shown in a Bode plot by a line with some flat and some sloping portions.

The effect of the coating on the measured impedance is most noticeable at low frequencies. For this reason, the impedance measured at a frequency of 0.1-Hz was used as a prime descriptor of the coating.

Results for each bar are shown in Appendix A and a summary of the 0.1-Hz impedance values is shown in table 64.

Table 64. Impedance values of 0.1 Hz for all coated bars, log ohm.

Damage area, %	Bar coating type	Straight, uncracked, black cathode		Bent, uncracked, black cathode		Straight, precracked, black cathode		Straight, uncracked, same cathode	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
	Black	2.5	1.8	2.3	1.9	2.6	1.8		
0.004	A	8.6	8.0	5.2	4.3	7.3	4.4	8.0	6.5
	B	8.5	7.3	7.3	4.2	6.0	3.5	8.5	6.2
	C	8.0	6.3	8.4	3.1	7.8	2.8	7.9	7.1
	D	7.9	5.5	8.5	5.6	8.7	4.8	8.3	7.8
	E	7.0	4.5	6.5	6.6	6.7	4.1	6.8	4.8
	F	7.8	3.7	7.9	3.4	7.1	3.4	8.5	5.7
	Average	7.9	5.9	7.3	4.5	7.2	3.8	8.0	6.3
0.5	A	4.3	3.9	4.3	2.9	4.5	3.0	4.4	3.9
	B	4.5	3.3	4.4	2.9	5.3	2.9	4.5	3.8
	C	4.4	2.2	4.4	2.0	4.6	2.2	4.4	3.5
	D	4.7	3.8	4.5	3.4	4.6	3.2	4.7	4.3
	E	4.5	3.7	4.3	4.0	3.1	2.5	4.4	3.2
	F	4.4	2.1	4.4	3.0	4.3	3.3	4.4	3.6
	Average	4.4	3.1	4.3	3.0	4.4	2.8	4.5	3.7

Effect of coating damage — For all coated bars, the impedance of the bars with 0.5 percent damage was significantly less than that of the bars with 0.004 percent damage. The average impedance for the black bars was $10^{2.2}$ ohm, compared with $10^{6.4}$ and $10^{3.8}$ ohm for epoxy-coated bars with 0.004 and 0.5 percent damage, respectively.

As an example of the effect of damage areas, the 0.1-Hz impedance values for Epoxy-A measured during the 96-week test period for the bent and straight uncracked concrete specimens with a black cathode are shown in figure 27. The straight bars with 0.004 percent damage area in uncracked concrete had an initial impedance of $10^{8.6}$ ohm, as compared to $10^{4.3}$ ohm for the straight bar with 0.5 percent damage area in uncracked concrete.

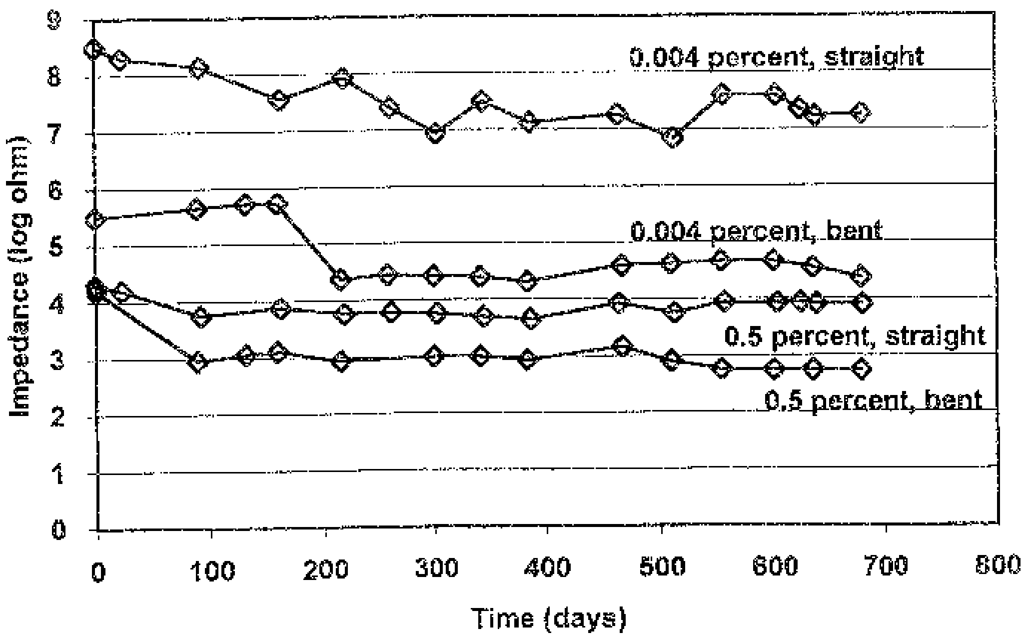

Figure 27. Impedance during 96 weeks of testing for straight and bent Epoxy-A bars, with 0.004 and 0.5 percent damage in uncracked concrete and a black cathode.

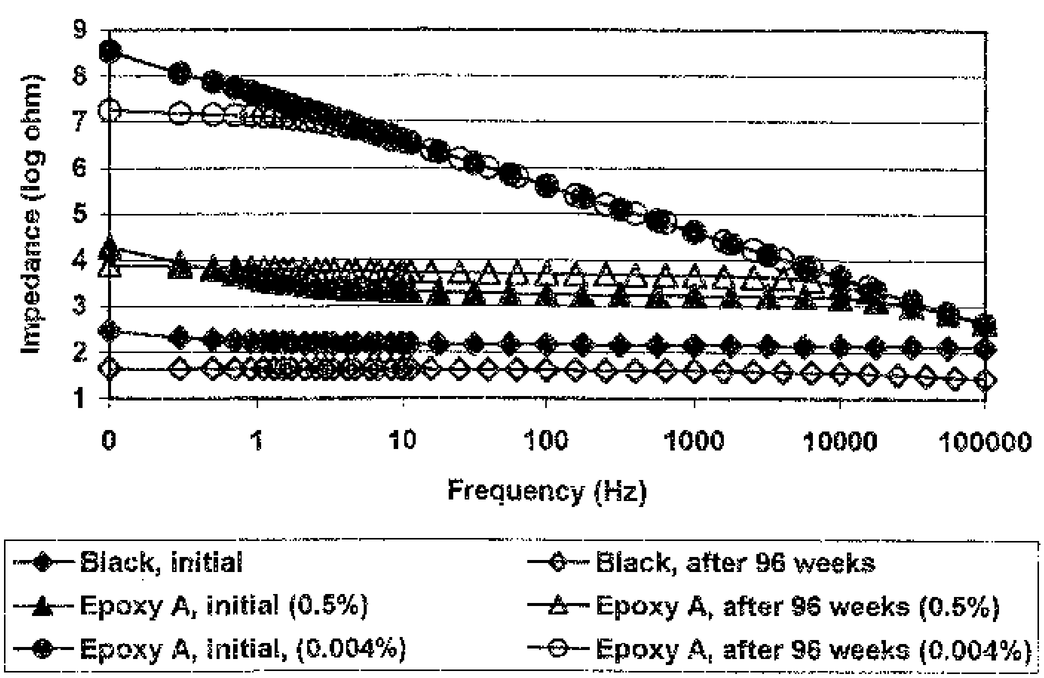

Figure 28. Bode plots for straight black bars and straight Epoxy-A bars with 0.004 and 0.5 percent damage in uncracked concrete with a black cathode.

Figure 28 shows the effect of the coating damage areas, where a significant change in the shape of the measured curves of the straight, uncracked Epoxy-A bars from mainly capacitive to mainly resistive behavior may be observed. The scans at 0 and 96 weeks for the bars with 0.004 percent damage exhibit a line at a 45° slope. This suggests mainly capacitive behavior of the coated bars. Such scans are indicative of a high-quality protective coating. In comparison, the scans at 0 and 96 weeks for the 0.5 percent damage bars are primarily horizontal, indicating a mainly resistive behavior, similar to that of the black bars. This reduction in impedance is directly related to the larger area of exposed steel. However, it is important to note that the impedance of the bars with 0.5 percent damage was still approximately two orders of magnitude greater than the black bars.

Straight, black cathode, uncracked - The initial performance of all the straight bars in uncracked concrete with a black bar cathode was generally similar, as shown in table 64. At the 0.004 percent damage level, the low-frequency impedances varied from $10^{7.0}$ to $10^{8.6}$ ohm, with Epoxy-A having the highest impedance and Epoxy-E the lowest. At the 0.5 percent damage level, the initial low-frequency impedances ranged from $10^{4.3}$ to $10^{4.7}$ ohm. This indicates that the effect of the damage area is overshadowing the resistivity of the coating type.

After 96 weeks, the low-frequency impedance values of the different coating types were significantly different, especially for the bars with 0.004 percent damage. The effect of the exposure on the Epoxy-A bars is shown in figure 27. Very little change was observed in the 0.004 percent damage Epoxy-A bars between the values initially obtained and those obtained after 96 weeks of testing. The flattening of the low-frequency portion of the curve shows the development of both capacitive and resistive behavior; however, the values are still indicative of a high-quality protective coating. The Epoxy-A bars with 0.5 percent damage were mainly unaffected during the 96 weeks of exposure, with the same approximate shape evident at the start and conclusion of testing.

An example of the performance of different coatings is shown in figures 29 and 30, which show the time history of the impedance of Epoxy-A and Epoxy-E with 0.004 and 0.5 percent damage in uncracked concrete with a black cathode. As shown in the figures, although the impedance of both coating types dropped during the testing, the Epoxy-E bars dropped significantly more. Although the initial drop in impedance may be related to the concrete and the coating absorbing water and conductive ions, which decrease their resistance, the long-term changes are most likely due to the deterioration of coating and an increase in exposed steel surface.

Bent, black cathode, uncracked - The EIS testing showed the effect of bending on the coatings to be variable. Comparison of the straight and bent bar specimens showed that some of the coatings had relatively large drops in impedance accompanying the bending, while others had very little. The effect of the bending was most pronounced on bars with 0.004 percent damage, as the relatively large size of the 0.5 percent damage overshadowed any damage caused by bending. Because the change in impedance is due mainly to the change in exposed area, a large drop in impedance is indicative of the development of cracks and exposed areas during the bending.

Based on the observed changes due to bending, Epoxy-D and Epoxy-F were largely unchanged by being tested in a bent-bar configuration, as expected for nonbendable coatings. Epoxy-E was also applied after bending, yet a small drop in impedance as compared to the straight specimens was observed. The bars with Epoxy-A and Epoxy-B showed significant drops in impedance due to bending. The bars with Epoxy-C were largely unchanged by bending.

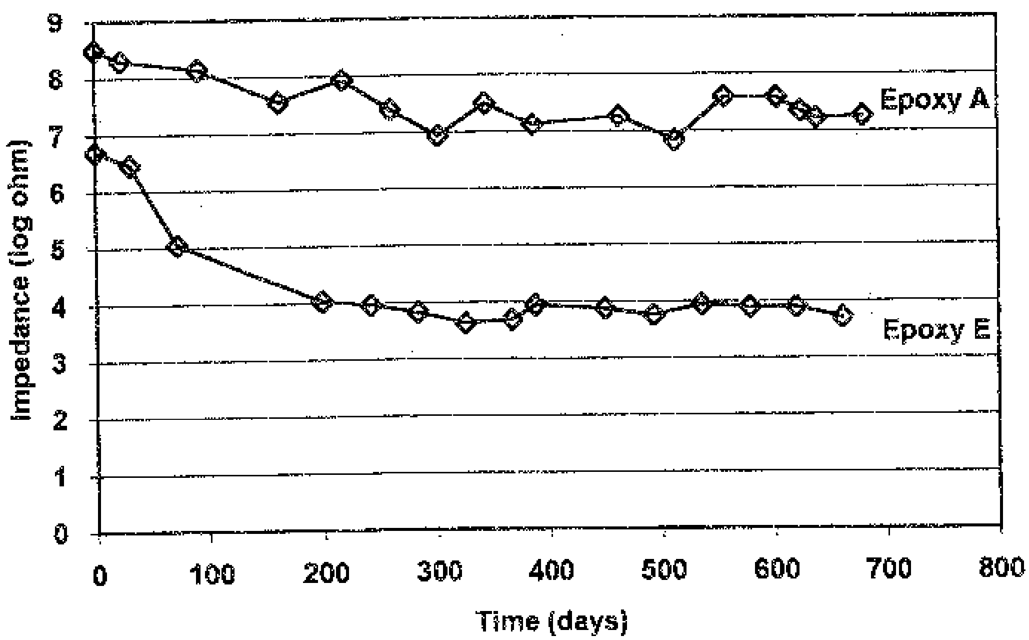

Figure 29. Impedance of epoxy-coated bars with 0.004 percent damage in uncracked concrete.

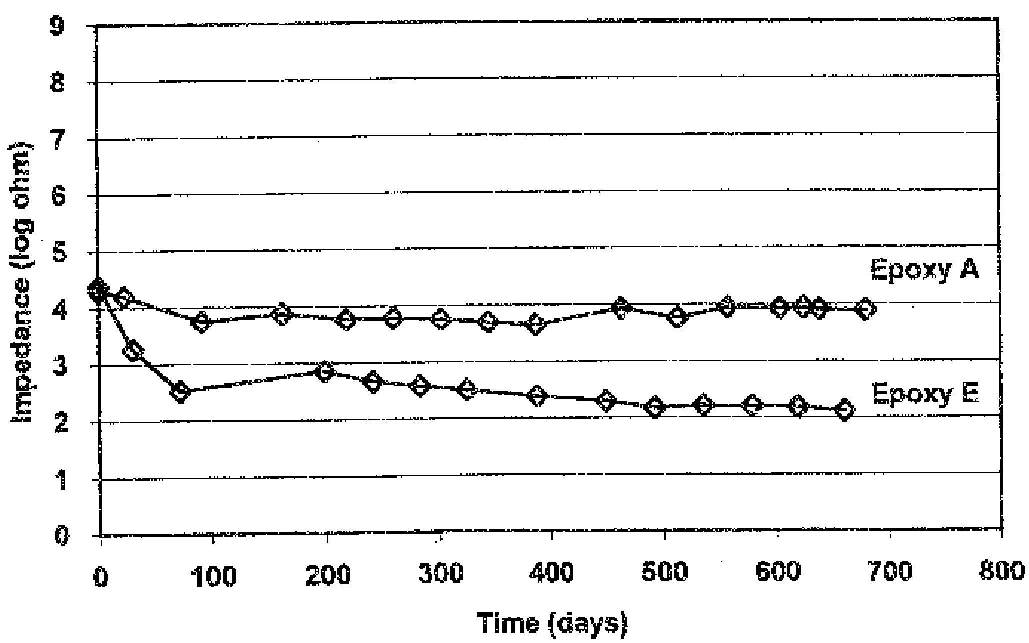

Figure 30. Impedance of epoxy-coated bars with 0.5 percent damage in uncracked concrete.

The effect of the bending on the bars with Epoxy-A is shown in figure 27. The bent bars with 0.004 percent damage area had an initial impedance of $10^{5.2}$ ohm, significantly lower than the $10^{8.6}$-ohm impedance of the companion straight bars. During bending, it was found that Epoxy-A and Epoxy-C cracked, exposing a significantly greater area of uncoated steel. After 96 weeks, the impedance of bent Epoxy-A with 0.004 percent damage was approximately $10^{4.3}$ ohm. The bent bars with 0.5 percent damage area had an initial impedance value similar to the straight bars; however, these exhibited an initial drop in impedance to 10^3 ohm soon after the testing started. It is believed that water was able to penetrate into the coating and along the bend surfaces effectively increasing the exposed steel area.

Figure 31 shows the Bode plot for the Epoxy-A bent specimens, measured initially and after 96 weeks of testing. The scans determined for the bent bars are significantly different than those determined for the straight bars, probably due to the areas exposed by cracks formed during bending. These changes are shown by a comparison between figures 28 and 31. The bars with 0.004 percent damage changed from a primarily capacitive behavior to a mixed resistive and capacitive behavior. Accompanying this change in behavior was a decrease in the 0.1-Hz impedance from $10^{8.6}$ to $10^{5.2}$ ohm. A comparison of the curves also shows that the bent 0.004 percent damage bars appear almost identical to the unbent 0.5 percent damage bars. Although less dramatic, a similar change in performance was found for the 0.5 percent damage bars, with the slight capacitive behavior lost and the 0.1-Hz impedance dropping from $10^{3.9}$ to $10^{2.9}$ ohm.

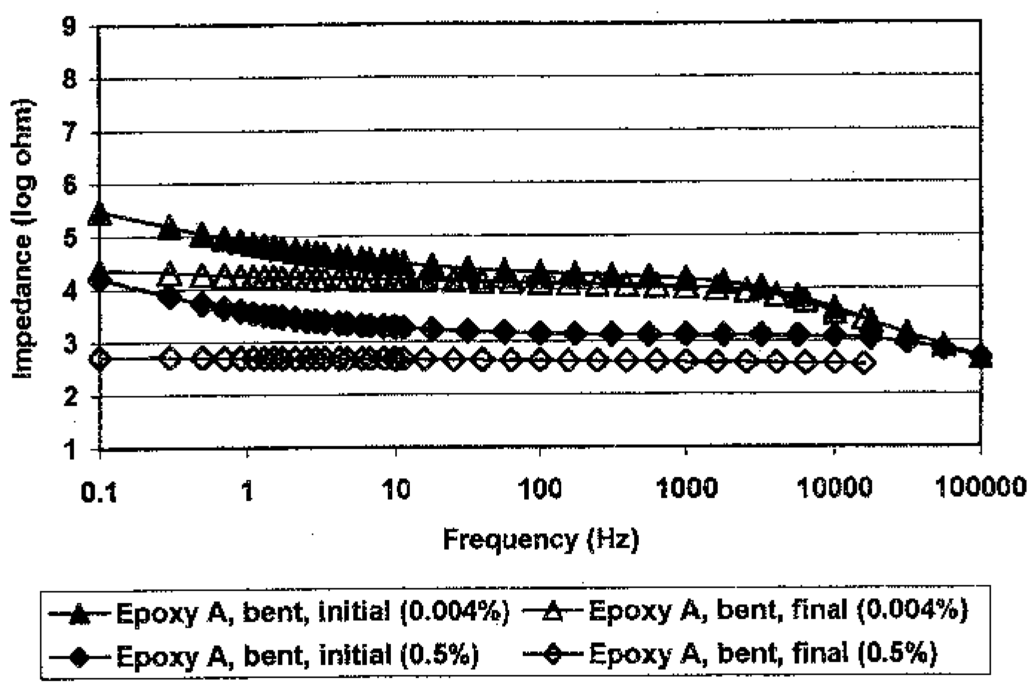

Figure 31. Bode plots for Epoxy-A bent bars with 0.004 or 0.5 percent damage in uncracked concrete.

The effect of the bending on the changes of the impedance through the testing was variable, depending on the type of coating. The changes in impedance during the testing, representing a loss in coating integrity or an increase in coating damage areas, show very different performance for the different coatings. Epoxy-B, Epoxy-C, Epoxy-D, and Epoxy-F show large drops in impedance despite their high initial impedances. Epoxy-E performed well, with no or small losses of impedance during the testing. Epoxy-A showed a modest drop in impedance at 0.004 percent damage and a somewhat higher loss of impedance at 0.5 percent damage.

Straight, black cathode, precracked — The initial and final impedance of bars in uncracked and precracked concrete is shown in table 64. As indicated by the initial EIS tests on the precracked concrete bar specimens, only the bars with Epoxy-A and Epoxy-B had a relatively large drop in initial impedance as compared to the uncracked concrete specimens, while the others had smaller changes. As before, the effect of the 0.5 percent damage area moderated the results in those specimens. The change in initial impedance (measured before any exposure to chloride) is probably due mainly to the presence of a low-impedance water path directly to the bar and the intentional damage sites, which effectively "short-circuits" the concrete resistance.

The straight bars in precracked concrete exhibited larger drops in impedance by the end of the testing than did the straight bars in uncracked concrete. These larger drops in impedance reflect the more extreme exposure conditions in the precracked concrete specimens. The effect of the crack on the changes of the impedance through the 96 weeks of testing was also variable, depending on the coating. The changes in impedance in the precracked concrete were generally larger than those for the coated bars in the uncracked concrete. All of the coatings with 0.004 percent damage show large drops in impedance by the end of the testing, with Epoxy-C, Epoxy-D, and Epoxy-F showing the largest drops. Epoxy-A, Epoxy-B, and Epoxy-E had smaller, but still large, impedance drops. At 0.5 percent damage, Epoxy-B and Epoxy-C had the largest drops, and the other coatings performed similarly.

As an example of the typical performance of the coated bars in precracked concrete, figure 32 shows the 0.1-Hz impedance for Epoxy-A during the 96-week test period for the straight uncracked and precracked concrete specimens with a black cathode. The bars in the precracked concrete exhibited significant and rapid drops in impedance during the first 50 d of testing. The bar with 0.004 percent damage initially had an impedance of $10^{6.2}$ ohm, but after only 50 d exhibited an impedance of approximately $10^{3.7}$ ohm. The bar with 0.5 percent damage initially had an impedance of $10^{4.4}$ ohm, but after only 50 d exhibited an impedance of approximately $10^{2.9}$ ohm. The precracked specimens exhibited significantly lower impedance values than respective uncracked specimens. Some of this drop in impedance may be a result of better conductivity through the crack and the presence of a relatively uninterrupted water channel from the surface of the concrete to the intentional coating holes. Some of this drop in impedance may also be caused by a reduction in coating performance due to the more direct and severe exposure to the salt solution.

Figure 33 shows the Bode plot for Epoxy-A in precracked and uncracked concrete. The initial impedance values of the bars with 0.004 percent damage in precracked and uncracked concretes are significantly different, with the 0.1-Hz impedance over two orders of magnitude lower in cracked concrete than in uncracked concrete. The bars in the precracked concrete also exhibit resistive-capacitive-resistive behavior, rather than purely capacitive behavior. Reasons for the significantly different shapes of these scans may be related to the reduced concrete impedance caused by the clear pathway to the bar, water-absorption by the coating resulting from penetration of water to the bar through the crack, or the exposure of the drill holes to the water through the crack.

The typical behavior of the 0.004 percent damage bars in precracked concrete is shown in figure 34, which shows the impedance at 0.1 Hz measured during the 96-week test period for the straight bars with Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-E bars in precracked concrete. The values and behavior for the bar systems were similar. Similarly, figure 35 shows the impedance at 0.1 Hz measured during the 96-week test period for the Epoxy-A, Epoxy-B, Epoxy-C, and Epoxy-E straight bars that were tested with 0.5 percent damage in precracked concrete. The values obtained for all bar systems are similar.

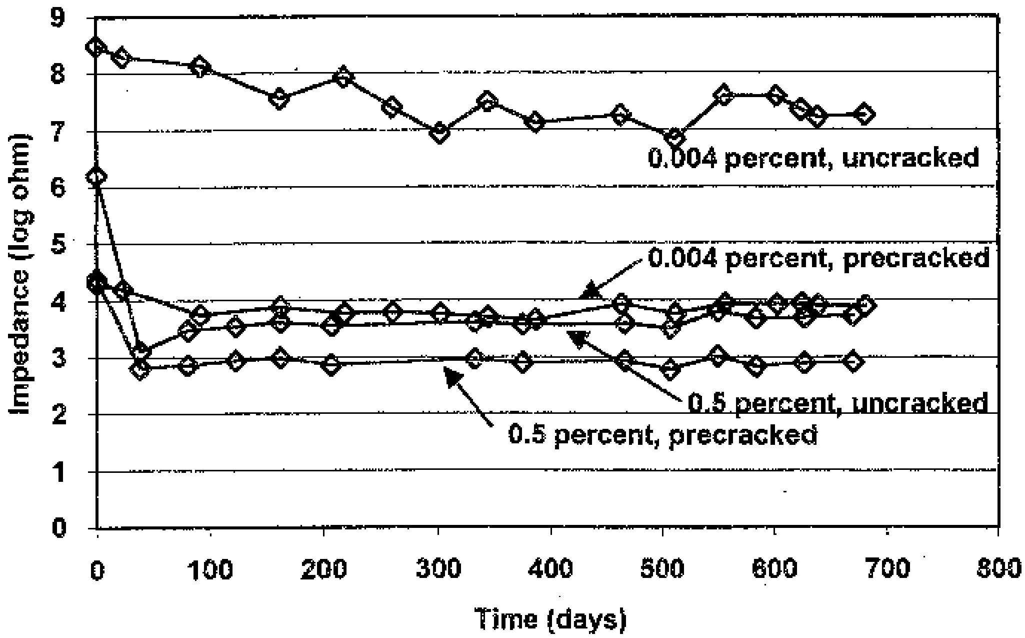

Figure 32. Impedance of Epoxy-A straight bars in uncracked and precracked concrete.

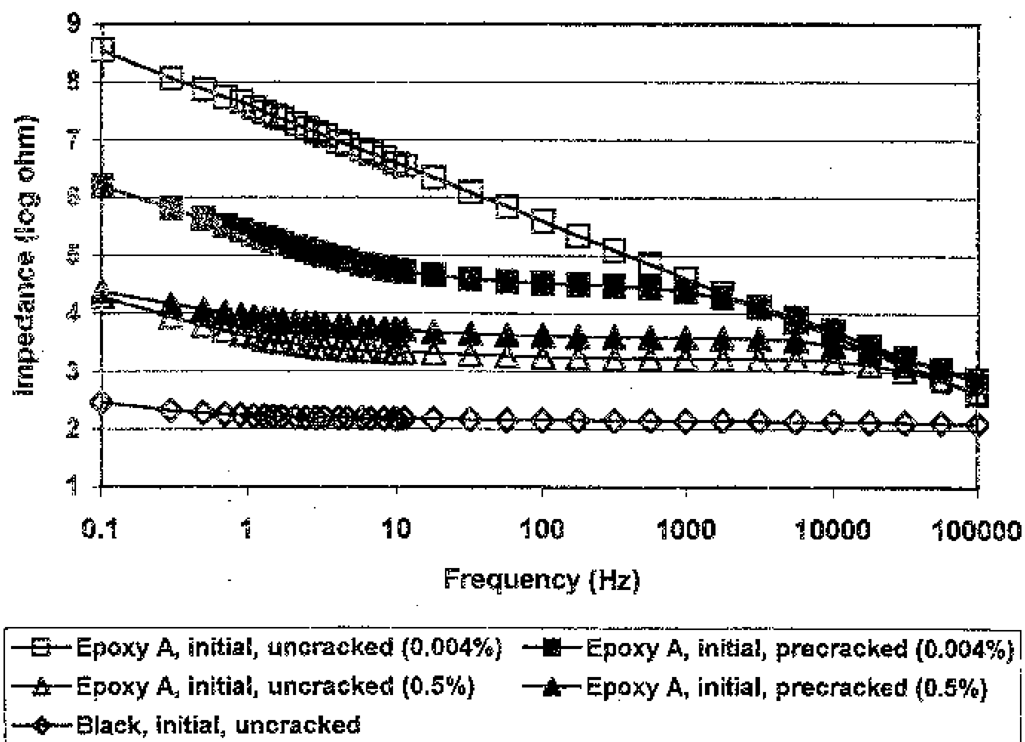

Figure 33. Bode plots of Epoxy-A straight bars in uncracked and precracked concrete.

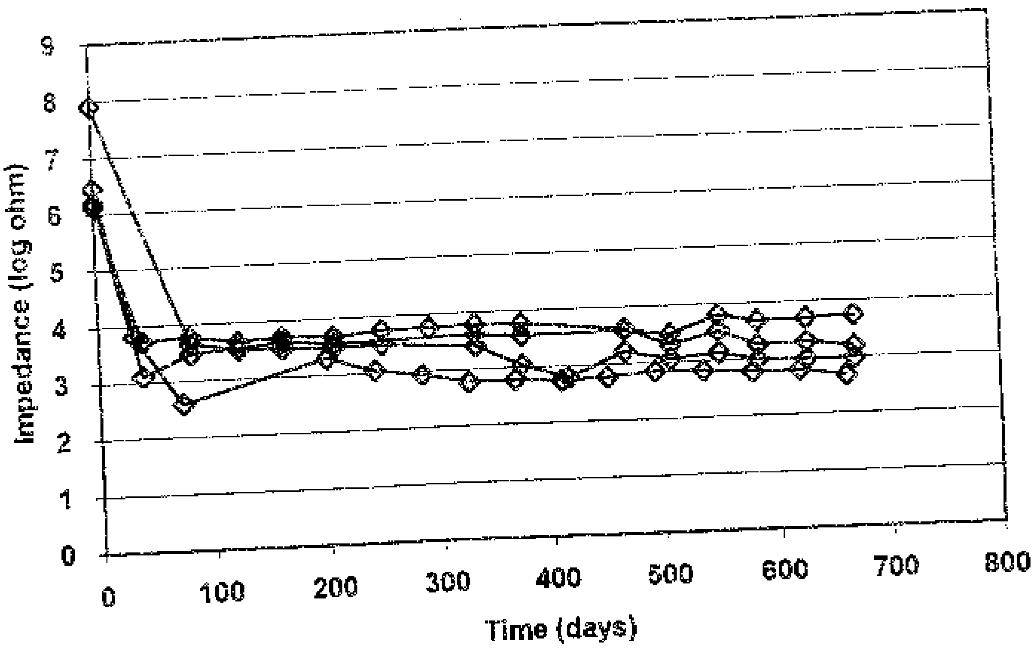

Figure 34. Impedance of straight epoxy-coated bars with 0.004 percent damage in precracked concrete (Epoxies A, B, C and E).

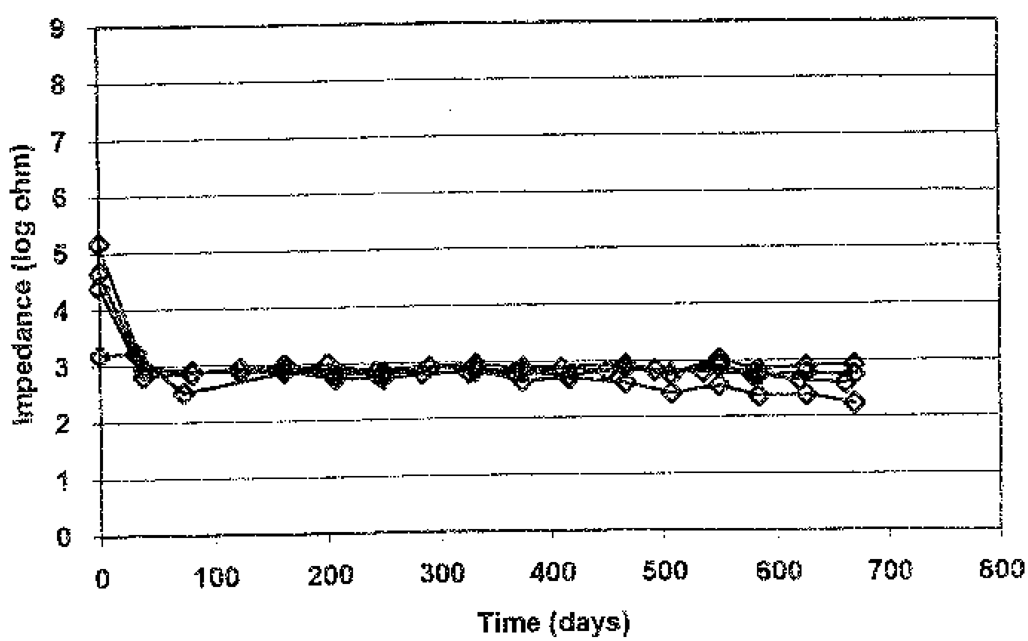

Figure 35. Impedance of straight epoxy-coated bars with 0.5 percent damage in precracked concrete (Epoxies A, B, C, and E).

Straight, epoxy cathode, uncracked - As would be expected, the EIS testing shows the effect of the same cathode type on the initial impedance to be negligible, as the anode bars measured were initially nominally identical to those paired with black cathode bars.

By the end of the testing, the straight bars paired with coated cathode bars showed smaller drops in impedance than did the straight bars paired with black bars in uncracked concrete. These smaller drops in impedance reflect the lower corrosion rates observed in this type of specimen. Despite the lower magnitude of the impedance changes, some differences in the coating performance could be seen.

The top-mat bars with Epoxy-B, Epoxy-E, and Epoxy-F showed significant drops in impedance during the testing, at the 0.004 percent damage level. The bar with Epoxy-A also had a relatively large drop in impedance during the testing. At the 0.004 percent damage level, Epoxy-C and Epoxy-D performed the best; while at the 0.5 percent damage level, Epoxy-C, Epoxy-E, and Epoxy-F had the largest impedance drops and performed the poorest.

The effect of cathode type on Epoxy-A is shown in figure 36, which shows the impedance at 0.1 Hz measured during the 96-week test period for the straight uncracked concrete specimens with black or epoxy cathodes.

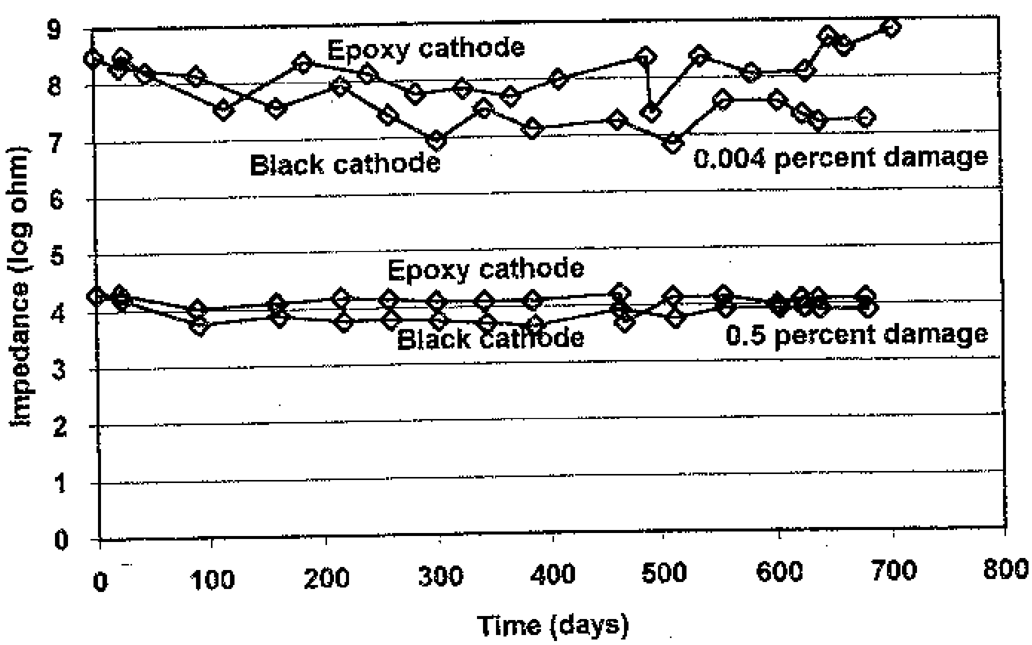

Figure 36. Impedance of Epoxy-A straight bars with either a black or epoxy-coated cathode.

Comparison of results from black and epoxy-coated bars — For all conditions tested, the impedance of the coated bars was always significantly greater than that of the black bars. On average, the final impedance of the black bars was $10^{1.8}$ ohm, compared with $10^{5.1}$ and $10^{3.2}$ ohm for epoxy-coated bars with 0.004 and 0.5 percent damage, respectively. Thus, the bars with 0.004 and 0.5 percent damage had impedance values that were 2000 ohm, or 25 times that of the black bars. Thus, it may be expected that the corrosion rates of all epoxy-coated bars would be significantly lower than that of the black bars.

Comparison to autopsy observations – To determine the usefulness of the EIS technique in characterizing corrosion of various bars, the 0.1-Hz impedance values for the bars shown in table 64 were compared to the bar observations that were made during the slab autopsies. In general, bars with concrete cracking had lower impedance than bars without corrosion. Table 65 was constructed by matching the measured impedance of each bar to its observed condition.

Table 65. Summary of final impedance values, slab and bar conditions.

Damage area, %	Observed condition	Number of occurrences	Average, log ohm	Standard deviation, log ohm	Minimum observed, log ohm	Maximum observed, log ohm
0.004	cracking of slab, corrosion on bar	4	2.33	0.33	2.0	2.7
	no cracking of slab, corrosion on bar	13	3.63	0.72	2.6	5.1
	no cracking of slab, no corrosion on bar	27	6.13	1.42	4.0	8.8
0.5	cracking of slab, corrosion on bar	10	2.52	0.79	1.9	4.3
	no cracking of slab, corrosion on bar	29	3.25	0.77	2.1	5.3
	no cracking of slab, no corrosion on bar	6	3.60	0.61	2.9	4.3

At the 0.004 percent damage level, the final impedance was an effective indicator of coating performance. The average impedance for bars with no corrosion or cracking was $10^{6.13}$ ohm, compared with the impedance for bars in cracked concrete, where the impedance was $10^{2.33}$ ohm. At the 0.5 percent damage level, where the effect of the hole area overshadowed the test results, differences were not found to be statistically significant.

POLARIZATION RESISTANCE

Introduction

As a part of the study, the bars under test were monitored using polarization resistance (PR) tests as described earlier in this report. Results obtained are discussed below.

Black Bars

The PR values measured during the 96-week period of testing for the black reinforcing bar specimens are shown in figure 37, for specimens with bent and straight bars, with and without cracks. For the black bars, the PR values obtained for the various configurations are similar for all conditions, with an average initial value of $10^{3.9}$ ohm (8000 ohm) and an average final PR of approximately $10^{1.8}$ (79 ohm). The PR of the bars quickly dropped after the initial measurements were taken and remained stable until the end of the test period.

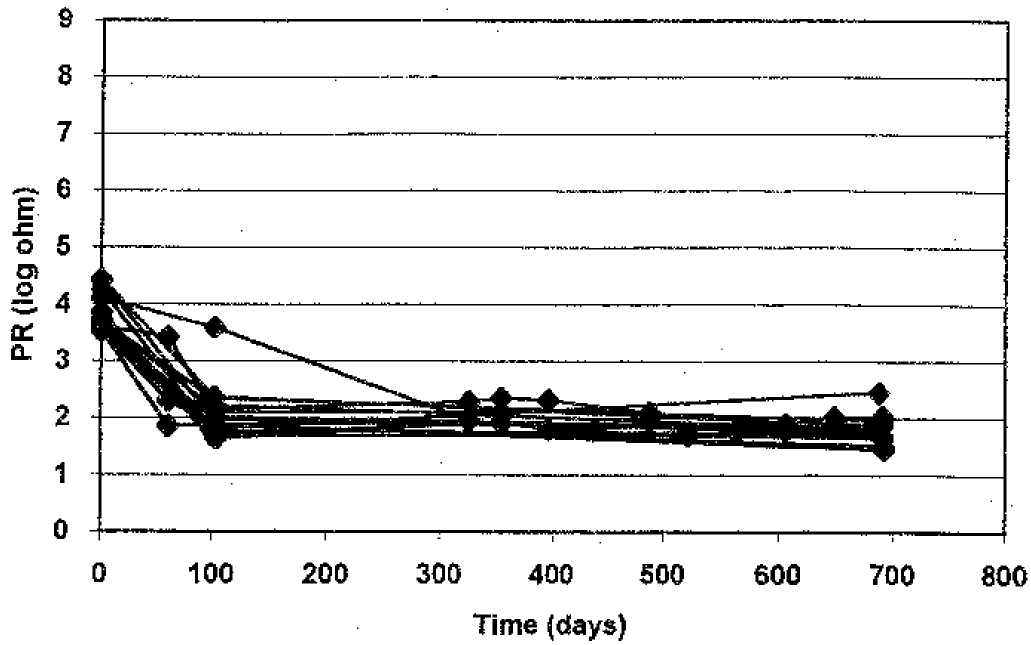

Figure 37. PR of straight and bent black bars in uncracked and precracked concrete.

Table 66 shows categories from Clear[38] along with the associated polarization resistances (calculated using the assumed polarized area of the test bars) that would correspond to the given corrosion rates. Based on these criteria, the black bars were not corroding at the start of testing. This should be expected due to the lack of chloride exposure. By the time of the next measurement, the corrosion was taking place at a much faster rate, with damage expected in 2 to 10 years. A similar table was developed by Bennett and Mitchell[39], shown in table 67.

Based on table 67, the black bars were passive at the start of testing with a PR of 8000 ohm and had a high corrosion rate at the conclusion of the testing, with a PR of 79 ohm.

Table 66. Corrosion rate interpretation guidelines (adopted from Clear).

Corrosion categories		Calculated corresponding values	
Corrosion rate, mA/m^2	Condition	Calculated PR, ohm	Log PR
<2	No corrosion expected	> 1000	> 3.00
2 to 10	Corrosion possible in 10 to 15 yrs	205 to 1000	2.31 to 3.00
10 to 100	Corrosion expected in 10 to 15 yrs	20.5 to 205	1.31 to 2.31
> 100	Corrosion expected in 2 yrs or less	< 20.5	< 1.31

Table 67. Corrosion rate interpretation guidelines (adopted from Bennett and Mitchell).

Corrosion categories		Calculated corresponding values	
Corrosion rate, mA/m^2	Condition	Calculated PR, ohm	Log PR
< 1	Passive condition	> 2050	> 3.31
1 to 5	Low to moderate corrosion	410 to 2050	2.61 to 3.31
5 to 10	Moderate to high corrosion	205 to 410	2.31 to 2.61
> 10	High corrosion	< 205	< 2.31

Epoxy-Coated Bars

The coated reinforcing bars generally had higher initial PR values than the black bars. Because the bars had not yet been exposed to the chloride solution, the differences in the initial PR values were most likely due to the different exposed areas. This is also supported by the somewhat higher initial PR values of the bars with 0.004 percent damage area, in comparison to the bars with 0.5 percent damage, as shown in table 68.

Table 68. Average PR values for all coated bars, log ohm.

Damage area, %	Bar coating type	Straight, uncracked, black cathode		Bent, uncracked, black cathode		Straight, cracked, black cathode		Straight, uncracked, same cathode	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final
	Black	4.0	1.8	4.1	1.9	3.6	2.0		
0.004	A	6.3	9.1	6.3	4.3	7.8	4.5	6.1	6.2
	B	4.7	7.3	-	4.5	9.0	3.5	5.8	6.3
	C	-	7.0	-	3.0	10.2	2.8	6.8	7.3
	D	6.7	6.0	6.1	6.6	6.7	5.1	6.1	7.8
	E	7.4	4.7	7.4	6.7	7.4	4.1	7.4	4.9
	F	6.4	3.9	9.0	4.7	3.9	3.6	8.4	5.0
0.5	A	5.8	3.9	5.7	2.9	5.7	3.0	5.9	4.2
	B	5.9	3.3	-	2.9	6.3	2.9	6.2	3.9
	C	-	2.1	-	2.0	5.8	2.3	5.9	3.5
	D	6.4	3.8	6.2	3.6	6.4	2.3	6.5	5.0
	E	5.6	3.8	5.5	4.5	3.1	2.5	5.7	3.3
	F	5.1	2.1	6.0	2.1	5.5	2.2	5.9	2.0

- Not tested

Because the PR tests indicate the corrosion state of the embedded steel, they are not as effective at categorizing the coating integrity and coating condition as the EIS tests. Thus, the usefulness of the initial PR test results is limited because all of the bars are expected to be in a passive state due to the lack of aggressive ions at the start of testing. The final PR tests are, however, much more useful as they show the effectiveness of the coatings at reducing corrosion rates and preventing the spread of corroding areas on the bar surface. For this reason, the final PR values will be relied upon more heavily than the initial values.

Effect of coating damage — Bars with 0.5 percent coating damage had lower initial PR values than those bars with 0.004 percent damage. As an example, the PR values for Epoxy-A straight bars in uncracked concrete with either a black or epoxy-coated cathode measured during the 96-week test period are shown in figure 38. Although the bars with the different damage areas had similar initial PR values, the bars with 0.004 percent damage area showed an increase in PR of 1½ to 2 orders of magnitude, while the 0.5 percent damage bars showed a 1½ to 2 order of magnitude drop in PR after 96 weeks of testing. Similar reductions were generally seen for the other coating types. The effect of initial coating damage area was also found to some degree in the bent, precracked, and same-cathode specimens.

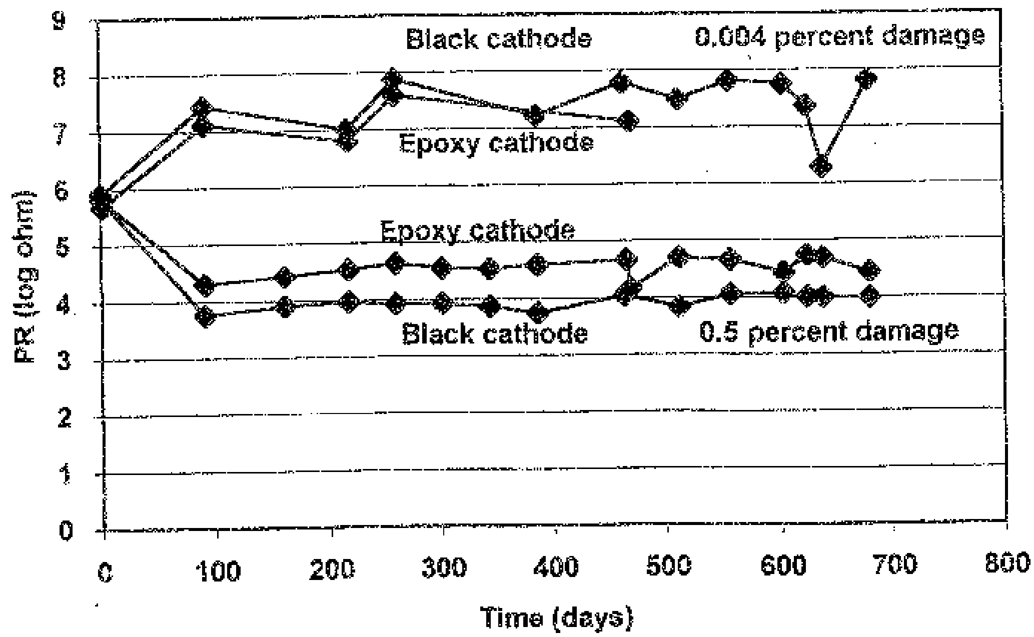

Figure 38. PR for Epoxy-A straight bars with black or epoxy-coated cathode.

Straight, black cathode, uncracked – The initial performance of all the straight bars in uncracked concrete with a black bar cathode was generally similar, although there was somewhat more data spread than in the EIS testing. At the 0.004 percent damage level, the PR values covered a spread of 2.6 orders of magnitude, with Epoxy-E having the highest PR and Epoxy-B the lowest. No bars with Epoxy-C were tested using PR before ponding started. At the 0.5 percent damage level, the initial PR values were within 1.2 orders of magnitude, with the average PR value approximately 0.5 orders of magnitude lower than that of the bars with 0.004 percent damage.

After 96 weeks, the PR values of the different coating types had changed significantly, with large changes in PR noted. The PR values for the coated bars with 0.004 percent damage changed between +2.8 to -2.6 orders of magnitude, as compared to the -2.2 order of magnitude change of the black bars. Epoxy-A bars had the largest increase, followed by Epoxy-B bars. The bars with Epoxy-D, Epoxy-F, and Epoxy-E bars all had decreases in their PR values. The Epoxy-C bars, although not initially measured, had very high PR values at the conclusion of the testing, indicating similar performance to the Epoxy-A bars.

The PR values for the bars with 0.5 percent damage were significantly lower at the end of testing than the bars with 0.004 percent damage, with the exception of the Epoxy-E bars. Also, all of the changes observed for the 0.5 percent damage bars were negative. Of the 0.5 percent damage bars, the Epoxy-E bars performed the best, followed by the Epoxy-A, Epoxy-B, Epoxy-D, and Epoxy-F bars. The PR value of the Epoxy-C bars was only slightly higher than that of the black bars at the conclusion of the testing. The worse performance of the 0.5 percent damage bars may be due in part to an area effect, but the positive changes in the 0.004 percent damage bars may indicate that very small holes in the coating are effectively self-healing with the formation of corrosion products cutting off future corrosion. Apparently, this did not take place on the bars with 0.5 percent damage.

An example of the performance of different coatings is shown in figure 39, which shows the time history of one bar with Epoxy-A, and one bar with Epoxy-E. The bars had 0.5 percent damage, were in uncracked concrete and had a black cathode. As shown in the figure, although the PR values of both coatings dropped during the testing, there were some differences between the coatings.

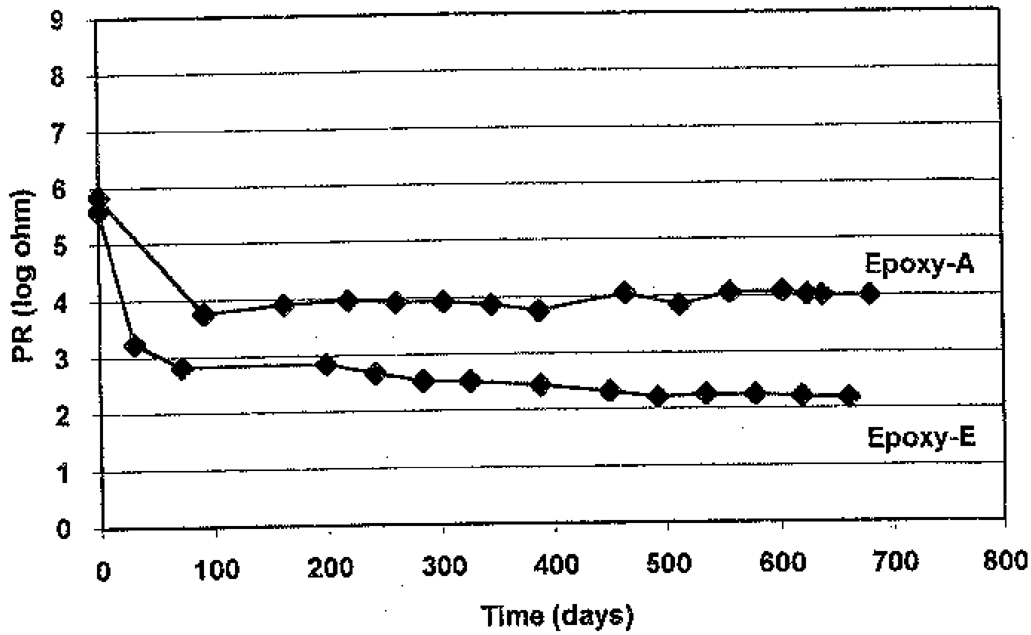

Figure 39. PR for Epoxy-A and Epoxy-E bars with 0.5 percent damage and a black cathode.

All of the specimens showed an initial drop in polarization resistance by the time the first measurement under test conditions was taken. This is due to the exposure of the bars to the chloride ponding solution and the establishment of corrosion-supporting conditions at exposed steel areas on the bar. Drops in the PR values during the testing may be related to either increases in the corrosion rate at the exposed steel areas, or to the spreading of corroding areas beyond the area of exposed steel defined by the intentional defects.

Bent, black cathode, uncracked -- The PR testing showed the effect of bending on the performance of the coatings to be variable. As indicated by the final PR tests on the bent bar specimens, some of the coatings performed well in a bent configuration, while some did not. The effect of the bending was most pronounced on the bars with 0.004 percent damage, as the relatively large size of the 0.5 percent damage area overshadowed any damage caused by bending.

Based on the observed changes due to bending, Epoxy-D and Epoxy-F exhibited improved impedance when tested in a bent-bar configuration. Epoxy-E was also applied after bending, yet a small drop in PR values for the 0.5 percent damage specimens was observed as compared to the straight specimens. The PR values for Epoxy-A, Epoxy-B, and Epoxy-C bars were significantly lower than those of the companion straight bars and the nonbendable coatings, and were only 2.5 orders of magnitude higher than the uncoated bars.

At the 0.5 percent damage level, even the nonbendable coatings had PR values that were 2.7 orders of magnitude greater than the black bars, showing the powerful effect of the larger damage areas on the overall performance of the coated bars.

The effect of bending on the changes of the PR during the 96 weeks of testing was also variable, depending on the coating. The changes in PR during the testing, representing a loss in coating integrity or an increase in coating damage areas, show very different performance for the different coatings. Epoxy-A and Epoxy-F showed large drops in PR during the testing. Based on their final PR values, Epoxy-B and Epoxy-C are expected to have performed similarly to Epoxy-A. Epoxy-E had the smallest losses of PR during the testing. Epoxy-D performed variably, with a modest increase in PR at 0.004 percent damage and an order of magnitude drop in PR of two at 0.5 percent damage.

The effect of the bending on Epoxy-A is shown in figure 40, which shows the time history of the PR values measured for the straight and bent Epoxy-A bars. All of the coated bars had similar high initial PR values. The PR value of the straight bar with 0.004 percent damage increased somewhat during testing, while the bent bar with 0.004 percent damage showed a large drop in PR after approximately 200 d, after which it remained relatively stable. The PR value of the straight bar with 0.5 percent damage dropped before the first reading was taken, after which it remained relatively constant. The PR value of the bent bar with 0.5 percent damage also dropped before the first reading was taken, and it continued to slowly drop during testing to a value significantly lower than the companion straight bar.

Straight, black cathode, precracked — The PR testing showed the presence of a crack to increase the amount of corrosion taking place on the test bars. The PR values of all of the coated bars decreased during the 96 weeks of testing, indicating that the corrosion rate was increasing or the effected area was increasing. The changes were variable, with no clear pattern differentiating between the 0.004 and 0.5 percent damage specimens. At both damage levels, Epoxy-B and Epoxy-C had large PR drops during the testing, while the performances of Epoxy-A, Epoxy-D, Epoxy-E, and Epoxy-F were variable.

Figure 41 shows the typical PR of the coated bars in precracked concrete during the 96 weeks of testing. The bars in the precracked concrete exhibited significantly lower PR values after the first 50 d of testing. The bar in uncracked concrete with 0.004 percent damage slowly climbed and remained high, but somewhat variable. In contrast, the companion bar with 0.004 percent damage in precracked concrete showed an early and severe drop in PR, remaining low and stable through the testing. At the 0.5 percent damage level, the specimen in the precracked concrete also had lower PR values throughout the testing, although the difference in performance was not as dramatic.

Based on the average final PR values, the preformed crack also decreased the overall performance by varying degrees; however, the effect was most pronounced on the 0.004 percent damage specimens with Epoxy-A, Epoxy-B, and Epoxy-C. The final PR values of the bars with 0.5 percent damage were roughly similar for all coating types.

At the 0.004 percent damage level, Epoxy-D and Epoxy-E had the highest final PR values, followed by Epoxy-A, Epoxy-F, Epoxy-B and Epoxy-C. All but Epoxy-C were more than two orders of magnitude higher than the black bars at the conclusion of the testing. Although the differences between the coating types were less noticeable at the 0.5 percent damage level, Epoxy-D performed the best, followed by Epoxy-A, Epoxy-B, Epoxy-E, Epoxy-C, and Epoxy-F.

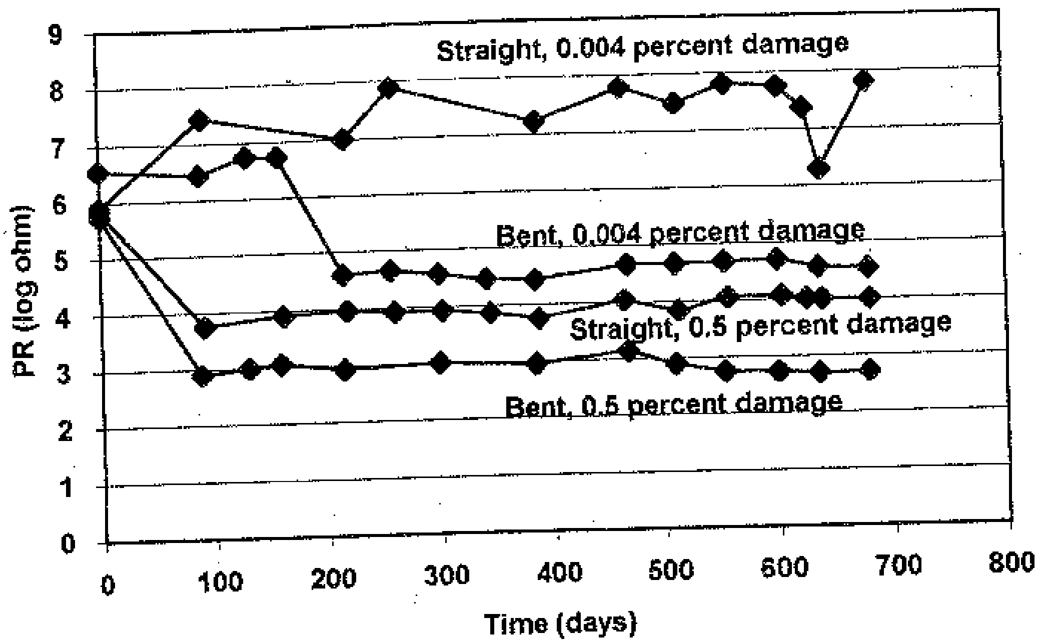

Figure 40. PR of Epoxy-A straight and bent bars, with 0.004 and 0.5 percent damage.

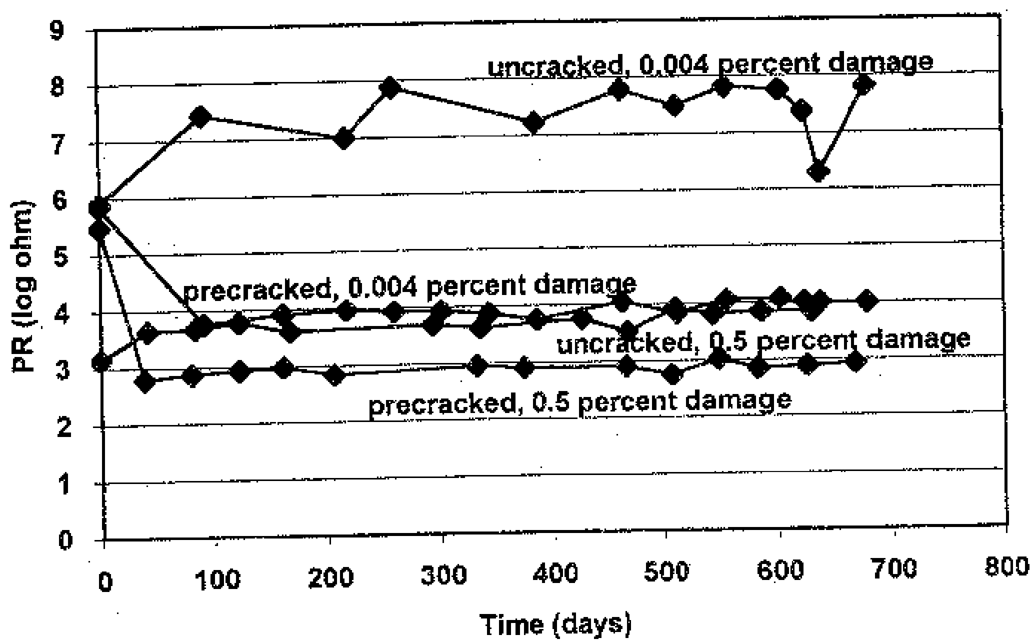

Figure 41. PR of Epoxy-A straight bars in uncracked and precracked concrete.

Straight, epoxy cathode, uncracked — As would be expected, the PR testing shows the effect of the same cathode type on the initial PR to be small, but variable, as the anode bars measured were initially nominally identical to those paired with black cathode bars. The changes in the average PR values of the bars were variable, but similar to those observed for the straight bars paired with black bar cathodes.

In general, bars with 0.004 percent damage performed better than bars with 0.5 percent damage, although this was not true for Epoxy-E and Epoxy-F. All of the bars with 0.5 percent damage showed losses in PR during the testing, but to a slightly lesser extent than the bars with black bar cathodes. As compared to the bars tested with black bar cathodes, the bars tested with coated-bar cathodes generally performed better. The measured PR values for Epoxy-A and Epoxy-C bars were the second and third highest measured, indicating very good performance.

By the end of the testing, the straight bars paired with coated cathode bars generally showed higher PR values than did the bars paired with black cathode bars, with the exception of the Epoxy-B bar with 0.004 percent damage and the Epoxy-E bar with 0.5 percent damage.

Comparison to autopsy observations — To determine the usefulness of the PR technique in characterizing the bar performance, the average final PR values for the bars were compared to the bar observations made during the slab autopsies. Table 69 shows the bar condition and relative PR values.

At the 0.004 percent damage level, the final PR was an effective indicator of coating performance during the 96 weeks of testing. Bars with no corrosion and described as "clean" had an average PR of $10^{6.5}$ ohm.

Table 69. Summary of final PR values, slab and bar conditions.

Damage area, %	Observed condition	Number of specimens	Average, log ohm	Standard deviation, log ohm	Minimum observed, log ohm	Maximum observed, log ohm
0.004	cracking of slab, corrosion on bar	4	2.4	0.31	2.07	2.69
	no cracking of slab, corrosion on bar	13	3.7	0.76	2.69	5.12
	no cracking of slab, no corrosion on bar	27	6.5	1.55	4.11	10.3
0.5	cracking of slab, corrosion on bar	10	2.2	0.20	1.83	4.47
	no cracking of slab, corrosion on bar	28	3.3	0.95	1.08	5.56
	no cracking of slab, no corrosion on bar	7	3.8	0.79	2.93	5.08

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