Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **CORROSION PERFORMANCE OF EPOXY-COATED REINFORCEMENT – SUMMARY, FINDINGS, AND GUIDELINES**		5. Report Date **July 1998** 6. Performing Organization Code
7. Author(s) Enrique Vaca-Cortés, Khaled Z. Kahhaleh, James O. Jirsa, Harovel G. Wheat, Ramón L. Carrasquillo, Reagan S. Herman, and Miguel A. Lorenzo		8. Performing Organization Report No. Research Report 1265-S
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Research Study 0-1265
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section, Construction Division P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

Research study title: "**Structural Integrity of Epoxy-Coated Bars**"

16. Abstract

The integrity and corrosion performance of epoxy-coated reinforcement in aggressive environments was investigated through a series of experimental studies, including: a) use of holiday detection for assessing damage to coating; b) hot water immersion and knife testing for assessment of coating adhesion; c) assessment of materials and procedures for repairing coating damage; d) evaluation of degree of mechanical damage caused during concrete placement when using metal head or rubber head vibrators; e) accelerated corrosion of coated bars embedded in macrocell and beam specimens placed in a corrosive environment for more than four years. The effects of coating condition and amount of damage, repaired vs. unrepaired damage, bar fabrication, and concrete cracking were studied. The findings are summarized and guidelines for quality control, design, and construction practice are included.

17. Key Words corrosion, epoxy-coated reinforcement, concrete structures, research, accelerated testing, adhesion, damage during consolidation, holiday detection, coating repair, patching materials	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 94	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Corrosion Performance of Epoxy-Coated Reinforcement – Summary, Findings, and Guidelines

by

Enrique Vaca-Cortés, Khaled Z. Kahhaleh, James O. Jirsa, Harovel G. Wheat,
Ramón L. Carrasquillo, Reagan S. Herman, and Miguel A. Lorenzo

Research Report No. 1265-S

Research Project 0-1265
STRUCTURAL INTEGRITY OF EPOXY-COATED BARS

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

July 1998

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

ACKNOWLEDGEMENTS

Research was conducted at the Phil M. Ferguson Structural Engineering Laboratory as part of the research program of the Center for Transportation Research at The University of Texas at Austin. We greatly appreciate the financial support from the Texas Department of Transportation that made this project possible. Special thanks go to Mr. Lloyd Wolf (BRG) and Mr. Robert Sarcinella (CST), project directors, for their assistance on this project. The authors would also like to express their gratitude for the assistance and cooperation of all staff of the Phil M. Ferguson Structural Engineering Laboratory.

DISCLAIMERS

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PUPOSES

James O. Jirsa, Texas P.E. #31360
Harovel G. Wheat, Texas P.E. #78364
Ramón L. Carrasquillo, Texas P.E. #63881

Research Supervisors

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The integrity and corrosion performance of epoxy-coated reinforcement in aggressive environments was investigated through a series of experimental studies. The effects of coating condition and amount of damage, repaired vs. unrepaired damage, bar fabrication, and concrete cracking were studied. It was found that regardless of coating condition, the performance of epoxy-coated bars was better than that of uncoated bars. Unlike black bars, coated bars did not exhibit deep pitting or substantial loss of cross section at crack locations. Damage to epoxy coating was the most significant factor affecting corrosion performance. Bars with coating in good condition, without any visible damage, performed best. The greater the size and frequency of damage, the more severe and extensive the amount of corrosion. The performance of bars that were fabricated or bent after coating was worse than that of coated straight bars. Mixing coated and uncoated bars in the same concrete member led to undesirable performance. Patching damaged coating reduced but did not prevent corrosion, particularly at bar ends. The most important factor in coating repair was the type and properties of the patching material. Surface preparation prior to coating had little effect. The absence of cracks in the concrete delayed, but did not prevent the onset of corrosion of coated bars. During consolidation of concrete, rubber head vibrators caused less damage to epoxy-coated reinforcement than did comparable metal heads. Hot water and adhesion tests were useful and practical for evaluating coating adhesion after production. An adhesion test procedure was developed and is recommended for quality control. A set of recommendations for proper quality control, design, and construction practice of structures with epoxy-coated reinforcement was developed.

IMPLEMENTATION

The approach for the corrosion performance evaluation of epoxy-coated reinforcement included in this report should serve as an aid to engineers involved in the specification, design, construction, inspection, and maintenance of concrete bridge and other transportation structures. Findings have been transmitted to TxDOT throughout the project to permit implementation of practices that will extend the service life of transportation structures. Guidelines for quality control, design, and construction practice of concrete structures with epoxy-coated reinforcement are included. A test procedure to evaluate the adhesive strength of the epoxy coating was developed and is recommended for quality control.

CHAPTER 1: OVERVIEW

1.1 BACKGROUND

Corrosion of reinforced concrete structures is a problem of great concern throughout the world. It causes gradual deterioration of structures and, consequently, a drastic reduction of their expected service life. In some cases, sudden collapses of concrete structures due to corrosion have been reported.[1] A great variety of concrete structures are experiencing the damaging effects of corrosion: industrial facilities, water intake facilities, storage tanks, sewage treatment plants, highway bridges, parking garages, buildings, marine structures, and others exposed to highly corrosive environments.[2,3] Corrosion attack of concrete structures takes place whenever an aggressive corrosive medium is present. The most typical source of corrosion in highway structures is provided by chlorides coming from: a) deicing chemicals applied on bridge decks, and b) marine exposure in substructure elements. The low durability of corroding concrete structures has raised great concern because of the cost associated with replacing and maintaining the existing infrastructure and the potential hazard to the public if the problem is not corrected.

A coating is a protective barrier applied to the reinforcement and is intended to protect the passive film of the steel bars from the corrosive action of chlorides and water. Coatings can be organic or inorganic. The most commonly used organic coatings are fusion-bonded epoxy coatings. The use of coatings on the bars can be very effective as a preventive measure against corrosion. Fusion-bonded epoxy coating consists of electrostatically applying finely divided epoxy powder to thoroughly cleaned and heated bars.[4] The technique is applied on new bars as a preventive measure. Application of epoxy coatings to steel reinforcement is the most popular method used today to protect embedded rebars in concrete against corrosion. However, the effectiveness of the epoxy coatings has been questioned lately and has been the center of controversy.[5] Early studies indicated that epoxy-coated reinforcement was a very promising corrosion protection material.[6,7,8] Later findings showed, however, that epoxy coating may be vulnerable to corrosion and its effectiveness came under siege.[5,9,10] Several studies showed very good performance[11,12,13,14] while other studies concluded that the protection provided by the epoxy coating was questionable.[15,16,17,18] In general, most of the observed field performance of epoxy coatings in bridge decks has been reported as satisfactory.[19]

The major problem of the epoxy coatings is that the coating can be damaged during transportation, handling, and placing of the bars at the job site, especially when bending the bars. In addition to damage, coating defects can be present in the form of small holidays and pinholes. At damaged areas and small defects, the corrosive action of chlorides can take place.[4] Nevertheless, in some cases where damage in the epoxy coating was detected, the corrosion performance of the bars was superior compared to that of the uncoated bars.[19] The corrosion mechanism has been studied by many researchers but the process is not completely understood. For the construction industry and transportation agencies, the effectiveness of coated reinforcement in extending service life must be established.

1.2 RESEARCH OBJECTIVES

1.2.1 Objectives

The main objective of this research was to investigate the performance of epoxy-coated reinforcement in corrosive environments. The purpose was to identify the conditions that affect the performance of coated bars so that proper guidelines in design, construction, and maintenance can be implemented to maximize the service life of structure.[20] The research was divided in the following tasks:

- Identify conditions conducive to corrosion of epoxy-coated bars. Implement an experimental program to evaluate performance of coated bars with different levels of coating damage, repaired or unrepaired, and subjected to different loading conditions.[20]

- Identify conditions that produce damage to epoxy coating during all stages of manufacture, transport, and construction.
- Develop quality control methods for assessing the quality and adhesion strength of the epoxy coating.
- Assess current patching materials and procedures to repair damaged epoxy coating.
- Develop guidelines and recommendations for improving performance of epoxy-coated bars.

The findings of this study should be of benefit in the selection and detailing of coated bars, and should be helpful in improving manufacturing and construction procedures critical to performance of epoxy-coated bars.

1.2.2 Research Significance

1.2.2.1 Technical Concerns

Many concerns about long-term protection of epoxy-coated bars have been expressed. Some of these concerns are as follows:

- Specifications for coated bars are inadequate.
- Corrosion propagates beneath the film after corrosion starts on exposed steel at defects and damaged spots.
- Coated bars may be susceptible to excessive defects and damage from the production stage to embedment in concrete.
- There are no specifications for adequate procedures to repair epoxy-coated bars.
- Fabrication of coated bars may introduce damage to the coating and weaken adhesion to the steel substrate, compromising corrosion behavior.
- The significance of coating adhesion and its role in the corrosion resistance of epoxy coatings is not completely understood. There is a lack of adequate test methods to reliably measure-coating adhesion.
- Coated bars may corrode at crack locations. Of particular concern is the fact that wider flexural cracks have been observed on concrete members reinforced with coated bars.
- Use of coated bars and uncoated bars in the same concrete member (bridge decks) may lead to macrocell corrosion if there is any incidental coupling between bar layers.

The above concerns were taken into account in planning the research program.

1.3 ORGANIZATION OF PROJECT

The research project was organized in five parts: 1) literature and field survey, 2) influence of coating operations, 3) influence of concreting operations, 4) durability studies in concrete, and 5) recommendations. This report describes briefly the various tasks and summarizes the main findings from the experimental studies. Test setup, variables, and findings from individual experiments are described in more detail in project Reports 1265-1,[21] 1265-2,[22] 1265-3,[23] 1265-4,[24] 1265-5,[25] and 1265-6.[26]

1.3.1 Part I: Literature and Field Survey

1.3.1.1 Literature Survey

A literature review on background information was conducted. Topics covered included background on corrosion of reinforcement in concrete, overview of epoxy coating materials and application processes, a brief review of the factors that influence performance of coated bars, a brief historical development of epoxy-coated bars, an extensive review of durability studies, and an overview of present status and future trends. References 20 and 27 include a very thorough compilation of the existing literature on epoxy-coated reinforcement. Report No. 1265-1 contains a summary of factors that may lead to damage to the epoxy coating at each stage during production, fabrication, and/or construction and addresses the related specifications that govern the quality control procedure.[21]

1.3.2 Part II: Influence of Coating Operations

1.3.2.1 Holiday Detection Study

The reliability of sponge-type, hand-held holiday detectors was assessed and factors that may influence the results were evaluated. A series of tests on 12 epoxy-coated #4 and #8 bars were performed. Bars had different damage conditions: as-received, pinholes, and hairline cracks. Test variables included degree of moisture in the sponge (wet, squeezed once, and well-squeezed), speed of operation (fast, medium, and slow), and operator (three different operators). Figure 1.1 illustrates the operation of the holiday detector. The holiday detection study is discussed in more detail in Report No. 1265-1 [21] and in Reference 20.

Figure 1.1 Operation of the holiday detector.

1.3.2.2 Coating Adhesion Study

Quality control measures industry efforts to improve quality (CRSI Certification Program), and industry standards and specifications were reviewed and discussed. The nature and factors affecting coating adhesion, mechanisms of adhesion loss, available tests to evaluate coating adhesion, and prior research on coating adhesion evaluation were analyzed. An experimental evaluation of hot water immersion and knife adhesion testing was conducted at three different stages to determine the feasibility of these tests for coating adhesion evaluation. The objective was to develop a reliable and practical adhesion test that could be performed quickly, repetitively, and economically at the coating plant and which test results could be objectively interpreted. The procedure consisted of immersing coated bar samples in hot water for a certain period followed by knife adhesion tests. In some cases, adhesion tests were performed without immersing the samples in hot water. Adhesion testing involved the application of a shearing force through the interface between coating and substrate with a sharp knife and successive prying of the disbonded coating. Pre-cuts (usually an X or V cut) through the coating were made to define the test section and eliminate the effect of cohesive forces by the surrounding coating. In the first phase of the study, hot water and adhesion tests were based on a procedure by the Ontario Ministry of Transportation. The test procedure was subsequently modified in phases 2 and 3.

ECR samples from different coating applicators, with varying bar diameters, and both straight and bent samples were tested. Other test variables included the temperature of the hot water bath, time of immersion, elapsed time between hot water immersion and adhesion test, different adhesion test operators, and different adhesion test procedures. Test results were discussed and analyzed. Different adhesion rating systems were devised and evaluated. Figures 1.2 and 1.3 show coated bar samples immersed in a hot water bath and a knife adhesion test in progress. In Report No. 1265-6,[26] the coating adhesion study is discussed in more detail and References 27 and 28 have additional information.

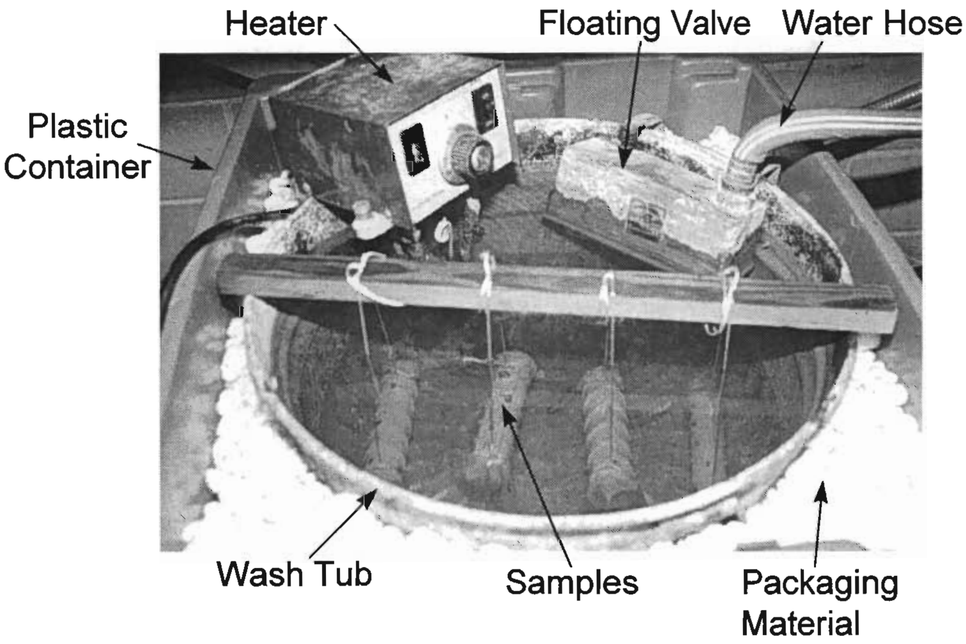


Figure 1.2 Hot water bath.

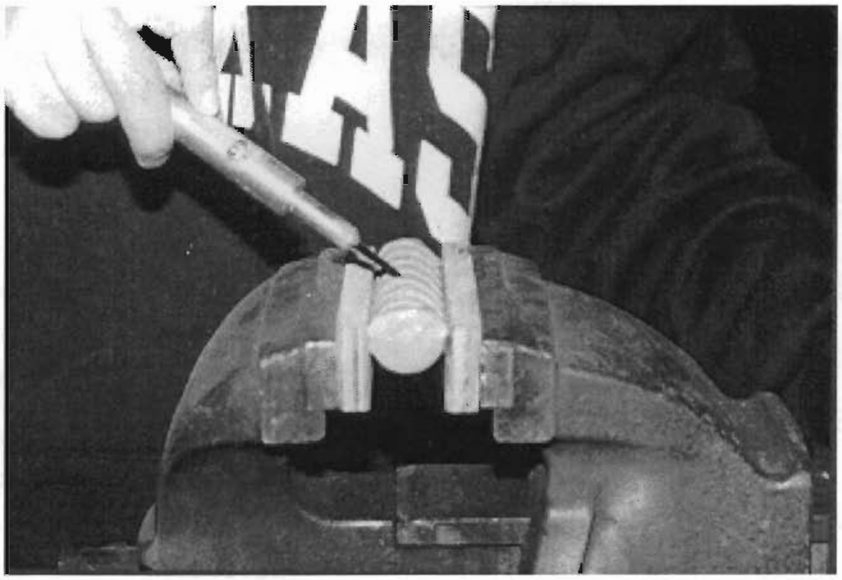


Figure 1.3 Adhesion testing of epoxy-coated bar specimen.

1.3.3 Part III: Influence of Concreting Operations

1.3.3.1 Concrete Consolidation Study

An experimental study was conducted to evaluate the degree of mechanical damage caused by concrete placement procedures. The effect of concrete consolidation on the epoxy coating using internal metal head vibrators was studied in a preliminary phase and was reported in References 20, 21, and 29. Additional tests were conducted using soft (rubber) and steel vibrator heads. In addition, the degree and quality of consolidation obtained with a rubber head vibrator as compared to a metallic head vibrator were assessed. Research Report 1265-2 describes the experimental program and findings of the second phase in greater detail.[22] Additional information can be found in Reference 30.

1.3.3.2 First Phase Study

A series of three tests were conducted. The first test specimen simulated a column base with two mats of bars. The second and third test specimens simulated partial slab sections with one top mat of bars in each specimen. All the reinforcement was epoxy-coated and was examined in advance for any existing damage. Bars in each specimen had different diameters. Concrete was placed, vibrated with a 2-in. vibrator head, removed promptly, and the bars were washed carefully. Bars were thoroughly inspected to document coating damage.

1.3.3.3 Second Phase Study

Three types of test specimens were constructed, representing a column or bridge pier, a footing, and a deck slab. All reinforcement was epoxy coated and bars in each specimen had different diameters. Two identical forms and reinforcement cages were constructed for each type of specimen: one for use with the metal head vibrator, and the other for the rubber head vibrator. After concrete was placed and vibrated, the bar cages were pulled from the forms and washed carefully. Bars were thoroughly inspected to document coating damage. Figure 1.4 illustrates the two types of vibrator heads used and Figure 1.5 shows bar column cages being washed after vibration.

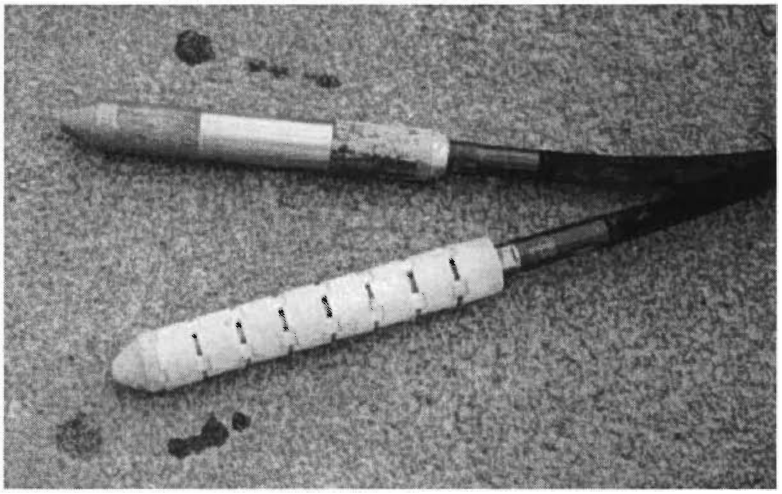


Figure 1.4 Metal (top) and rubber head vibrators.

Figure 1.5 Washing column cages after vibration.

Quality of consolidation was assessed in fresh and hardened concrete specimens. The energy imparted to fresh concrete by each type of vibrator head was measured with small, high sensitivity, high frequency accelerometers partly embedded in the concrete. Unreinforced concrete blocks were vibrated with each type of vibrator head. Frequency, horizontal and vertical acceleration were measured while the concrete was being vibrated.

A total of eight block specimens of different size and with varying amounts, of coated and uncoated reinforcement were constructed for evaluation of consolidation in hardened concrete. The degree and quality of consolidation with the rubber and metallic head vibrators was determined through both a visual examination, and measurement of density and permeable void content of extracted cores from vibrated specimens.

1.3.4 Part IV: Durability Studies

A four-part experimental program was established to study the performance of epoxy-coated bars in highly corrosive environments. Durability studies consisted of two short-term studies (immersion study and coating repair study) and two long-term studies (macrocell and beam studies). In all four studies, the selection of the exposure procedure, test parameters, and specimen characteristics was intended to produce a very aggressive environment and to accelerate corrosion of the specimens.

1.3.4.1 Immersion Study

Triplicate "U" bent bars of two different sizes (#4 and #8) were subjected to cyclic immersion in 3.5% NaCl solution for about 8 months. Damage to coating was purposely introduced at the outer radius to reach the limiting percentages of damage set for testing. The bars were grouped according to different percentages or size of damaged area (Table 1.1). For some of the groups, damaged areas were patched using a compatible two-part epoxy repair material specified by the manufacturer of the epoxy coating. Two control groups of uncoated bars were used for comparison in each series. Bar condition was examined after four, five, and eight months of exposure. Although the test environment was not the same as typical service conditions, the test provided a means for a quick examination of the effectiveness of the epoxy coating in a severely corrosive environment. Figure 1.6 shows the test setup. The immersion study is discussed in greater detail in Report No. 1265-1 [21] and Reference 20.

1.3.4.2 Macrocell Study

Triplicate macrocell specimens in each group consisted of fabricated, coated bars linked electrically to uncoated bars and placed inside concrete prisms, as shown in Figure 1.7. All test bars were companion specimens of those bars used for the immersion study described earlier. Salt water was ponded in a cyclic wet and dry regime to contaminate the concrete with chlorides. Test variables included the amount of coating damage, repaired vs. unrepaired damage, bar size, and bar deformation (Table 1.1). Control specimens with uncoated bars were included. Corrosion currents flowing from coated bars to uncoated bars were monitored over a period of sixty 28-day cycles (4.5 years). The corrosion rates of coated and uncoated bars were measured and compared. Forensic examinations were conducted on each triplicate at 1, 2, and 4.5 years to relate corrosion measurements to physical bar condition. The chloride content per unit weight of concrete was measured at different depths during each autopsy. Details of the test setup and results of the autopsies after one and two years were discussed in Reference 20. The 4.5-year autopsy was discussed in detail in Reference 27. A comprehensive summary of the macrocell study including all three autopsies is presented in Report No. 1265-3.[23]

Table 1.1 Summary of study variables for immersion and macrocell studies, Series A (#4 bent bars) and B (#8 bent bars).

Group	Bar Deformation Pattern		Epoxy Coating Damage Level[a]					Damage Condition	
No.	Parallel Ribs	Cross Ribs	Spots >6x6mm	Spots > 2%	Cracks < 1%[b]	Spots < 2%	Pinholes < 1%[c]	Patched	Not Patched
1	●		Control Specimens - Uncoated Bars						
2	●		●					●	
3	●		●						●
4	●			●				●	
5	●			●					●
6	●				●				●
7	●					●			●
8		●	Control Specimens - Uncoated Bars						
9		●	●					●	
10		●	●						●
11		●					●		●

a: Refers to either the size of damaged spots or percentage of damaged area to bar surface area embedded in concrete.

b: Hairline cracks along the transverse ribs on the outside of bends.

c: Fine intermittent tears or pinholes along the rib bases on the outside of bends.

Figure 1.6 Test setup for immersion study.

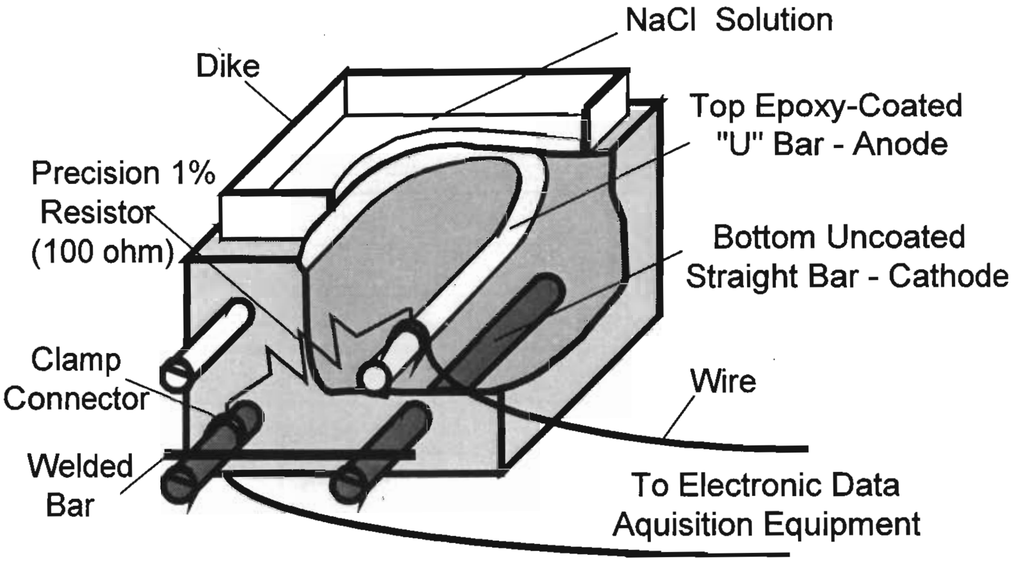


Figure 1.7 Macrocell specimen model.

1.3.4.3 Beam Study

Duplicate concrete beams were reinforced with unlinked coated and uncoated bars. Salt water was irrigated over the middle portions of beams in a cyclic wet and dry regime over a period of 112 fourteen-day cycles (4.3 years). Various arrangements of longitudinal bars, stirrups, and splices were considered. Test variables included the condition of the coating (as received or 3% damage), and repaired vs. unrepaired bars. Some beams were uncracked while others were cracked and either unloaded or kept under load to maintain cracks at a specified maximum crack width. A summary of study variables is shown in Table 1.2. Cyclic loads were applied on cracked beams during wet and dry periods. Corrosion activity of each test bar was monitored by corrosion potential measurements. Beam condition and changes in crack width were observed during exposure. Forensic examinations were conducted on each duplicate after 1 and 4.3 years to relate corrosion measurements to actual bar condition. The chloride content per unit weight of concrete was measured at different depths during each autopsy. The effects of concrete cracking, loading condition, and coating condition on the performance of coated bars were examined. A typical beam specimen is shown in Figure 1.8 and a view of the test setup is illustrated in Figure 1.9. Details of the test setup and results of the one-year autopsy was previously reported in Reference 20. The 4.3-year autopsy was discussed in detail in Reference 27. A comprehensive summary of the beam study including the two autopsies is presented in Report No. 1265-4.[24]

Table 1.2 Summary of study variables for beam study.

Group No.	Description of coating condition	Cracking and loading condition		
		Uncracked, unloaded	Cracked, unloaded	Cracked, loaded [a]
I	As-received [b]	●	●	●
	3% damage, not patched	●	●	●
	3% damage, patched		●	
II	As-received, not patched [c]	●	●	●
	As-received, patched	●	●	●
	3% damage, patched		●	
III	3% damage, patched [d]		●	
	Cut ends (splice) and 3% damage (stirrup), patched		●	●

a: Imposed loads causing bending about strong axis and to open cracks to 0.33 mm.
b: No visible damage
c: No patch on bends
d: 3% damage (patched) on both longitudinal bar and stirrup
Group I: Longitudinal bar monitored
Group II: Stirrup monitored
Group III: Both longitudinal bar and stirrup monitored. Splice bars in several beams.

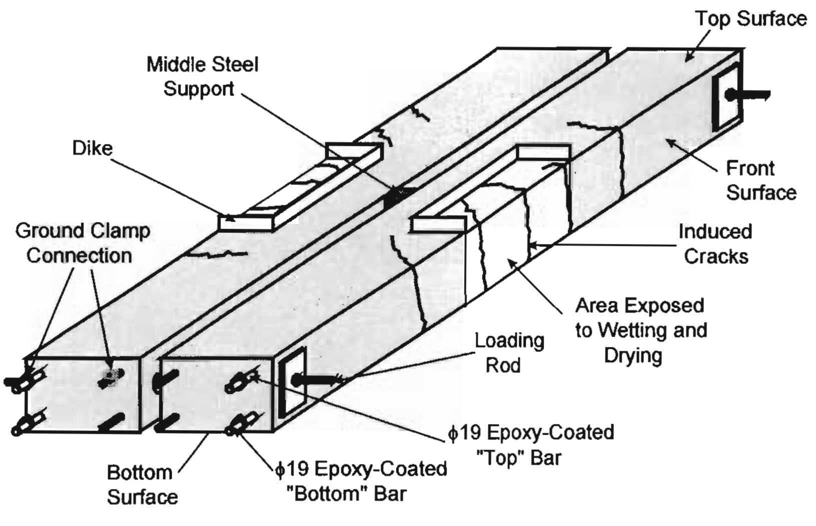


Figure 1.8 Model of beam exposure test specimens.

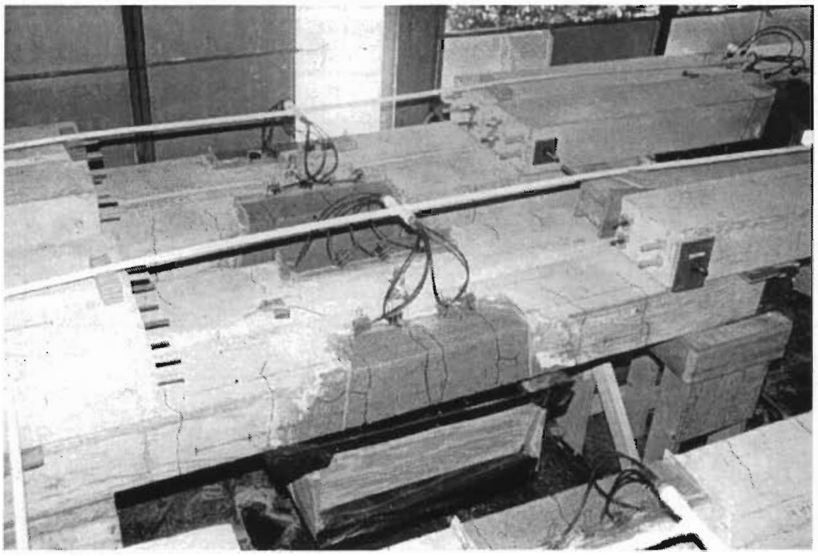


Figure 1.9 Overview of test setup.

1.3.4.4 Coating Repair Study

A pioneering experimental study of repair of coating damage was performed. No research in this area had been previously reported. In this research, the corrosion performance of several patching materials and procedures was investigated. The effect of different bar surface conditions and application procedures was examined. The effectiveness of patching bar cut ends was of particular interest. To evaluate the effectiveness of patching materials and procedures to repair epoxy-coated bars, three major series of experiments were conducted: a) cyclic immersion in NaCl solution, b) electrochemical impedance and polarization resistance, and c) hot water immersion-adhesion tests. In cyclic immersion and electrochemical tests, the corrosion performance of repair materials was studied. In the hot water test, the adhesion quality of patching materials was examined. The coating repair study is discussed in greater detail in Report No. 1265-5 [25] and Reference 27.

1.3.4.5 Cyclic Immersion in NaCl Solution

Cyclic immersion in a 3.5% NaCl solution was conducted on 80 epoxy-coated rebar samples containing 524 patched areas. Samples were subjected to 200 days of exposure in cycles of 7 days (4 days wet, 3 days dry). The following variables were used for cyclic immersion in NaCl solution: Three patching materials (*A*, *B*, and *C*) from different manufacturers were evaluated. The feasibility of an industrial coating (material *D*) for repair of coating damage was also explored. The performance of repaired damaged areas on the bar surface and of repaired bar cut ends was examined. The performance of flame-cut ends was of particular interest because that practice was observed in the field. Fourteen surface preparation procedures were studied, grouped in three categories: i) no surface preparation at all, ii) a specific type of surface preparation, and iii) laboratory-type surface cleaning (control specimens). A summary of study variables is shown in Table 1.3. Observations of the rebar surface condition at repaired or patched areas were taken every other month. Photographs were taken at different stages to record significant changes. Detailed observations were taken throughout the exposure experiment. Patching material at repaired areas was removed to uncover and examine the steel surface underneath. Fusion bonded epoxy coating in the vicinity of patched areas was peeled to inspect the extent of corrosion beyond the repaired zone. A view of all rebar samples in the immersion test set-up is shown in Figure 1.10.

Table 1.3 Summary of study variables for coating repair study (cyclic immersion test).

Patching Material	Surface Preparation	Types of Damaged Area				
		I	II	III	IV	V
A	i) None	•	•	•	•	
	ii) Yes	•	•	•	•	
	iii) Control	•	•	•	•	
B	i) None	•	•	•	•	
	ii) Yes	•	•	•	•	
	iii) Control	•	•	•	•	
C	i) None	•	•	•	•	•
	ii) Yes	•	•	•	•	
	iii) Control	•	•	•	•	
D	i) None			•		

Types of damaged area:

I) Exposed rectangular areas between bar deformations
II) Damaged areas (non-rectangular) on bar deformations
III) Saw-cut bar ends
IV) Flame-cut bar ends
V) Shear-cut bar ends touched up by the coating applicator

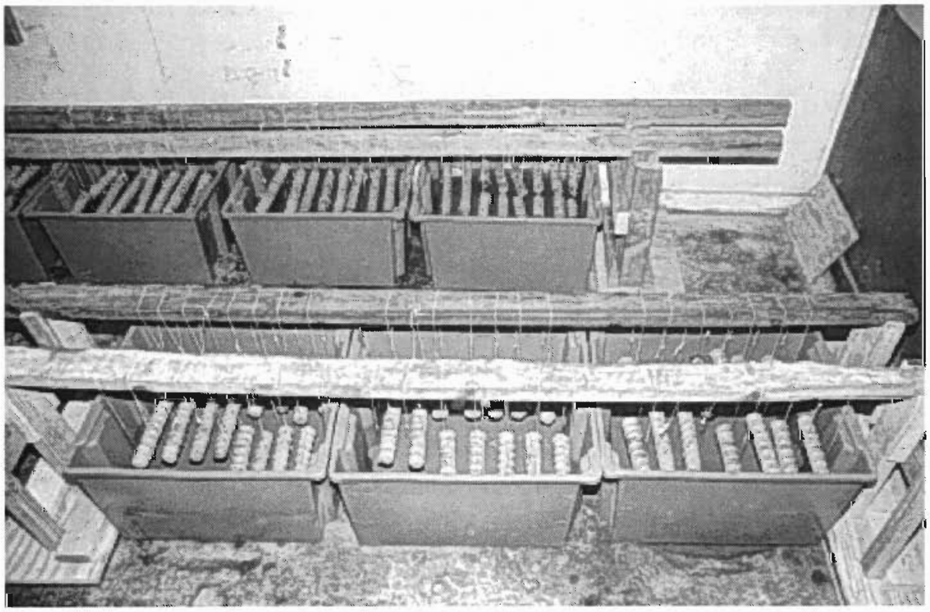


Figure 1.10 Salt immersion test set-up for patched epoxy-coated rebar specimens.

1.3.4.6 Electrochemical Impedance and Polarization Resistance

Electrochemical impedance spectroscopy and polarization resistance tests were conducted on 9 rebar samples coated with patching material and immersed in 3.5% NaCl solution during a 100-day period. Electrochemical measurements were intended to monitor the behavior of patching materials only. Three patching materials and three surface preparation conditions were evaluated. Types of surface preparation were as follows: 1) No surface preparation, 2) wire-brushed surface, and 3) control (near-white finish). The three steel surface conditions can be seen in Figure1.11 and the test setup is shown in Figure 1.12. Measurements were taken at 12 hours, 2, 4, 7, 10, 14 days and at subsequent week intervals until 98 days after immersion. At the end of the experiment, specimens were removed from solution and air-dried. Assessment and photographs of the patch-coating condition were performed. The steel surface condition beneath the coating was examined visually and photographed.

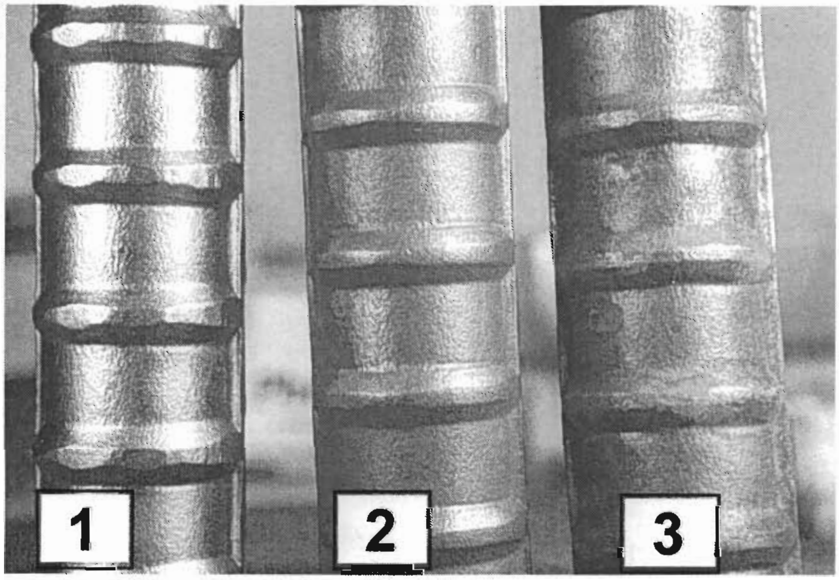


Figure 1.11 Steel surface conditions on specimens: (1) No surface preparation, (2) wire brushed, and (3) control.

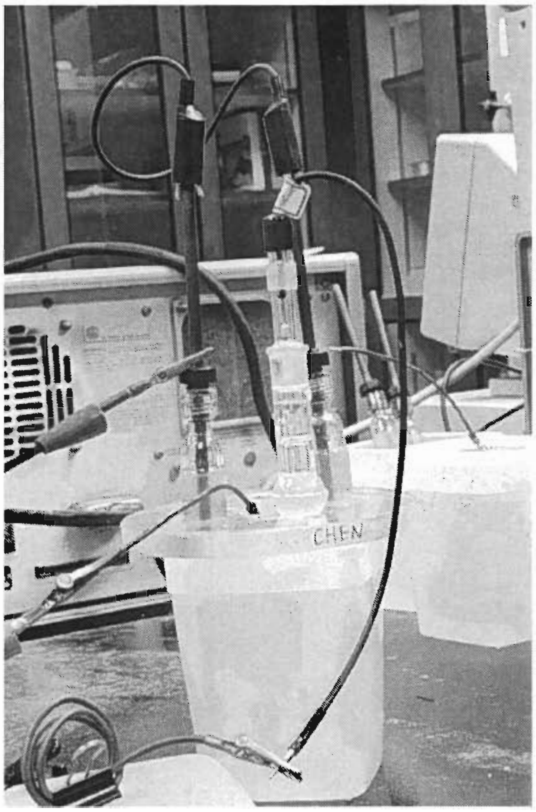


Figure 1.12 Test setup for EIS and polarization resistance tests.

1.3.4.7 Hot Water and Knife Adhesion Testing

A hot water immersion-adhesion test was conducted on patched ECR specimens. The objective was to determine the feasibility of the test to evaluate coating repair materials and techniques quickly and reliably. Seventeen epoxy-coated rebar samples containing 68 patched areas were tested. Samples were prepared and patched using several repair materials and procedures. The coating was damaged at areas between bar deformations. Four patching materials and five repair procedures were used. In two of the repair procedures, no surface preparation was done. Samples were subjected to 24 hours of hot water immersion at a temperature of 75°C. Adhesion tests of the patched areas were conducted.

1.3.5 Part V: Recommendations for Implementation of Results

The overall results and findings from the literature review and experimental research were analyzed and their importance was assessed. Emphasis was placed on analyzing factors that affect the service life performance of epoxy-coated reinforcement. A summary of the study findings and recommendations is presented. Guidelines for design and construction practice using epoxy-coated bars were prepared and included in Appendix A.

CHAPTER 2: EFFECTIVENESS OF EPOXY COATING

2.1 GENERAL COMMENTS

Coated bars performed better than uncoated bars, as evidenced by monitored currents and the observed condition of concrete and bars in the immersion, macrocell, and beam studies. Uncoated bars experienced moderate to extensive corrosion with the formation of several moderate to severe pits (Figure 2.1). Substantial loss of cross-sectional area was evident at crack locations within the wet zone of beams (Figure 2.2). In comparison, although epoxy coating did not completely prevent corrosion of steel reinforcement, none of the specimens with coated bars experienced extensive corrosion cracking, rust staining, delamination, and scaling of the concrete surface, as did specimens with uncoated bars (Figures 2.3 and 2.4). No deep pits or significant reduction of cross-section was observed on the steel surface of epoxy-coated bars (Figure 2.5). Corrosion generally consisted of a uniformly dark surface with shallow pitting. Figure 2.6 shows a comparison of uncoated and coated bars from macrocell specimens after 4.5 years of exposure.

(a) Severe metal loss and pitting at straight leg of #4 uncoated bar.

(b) Pitting at straight leg of #8 uncoated bar.

Figure 2.1 Loss of metal and pitting of uncoated bars from macrocells.

(a) Severe pitting on lower black bar near coated stirrup (beam B23).

(b) Severe pitting on black bars near coated stirrup (beam B23).

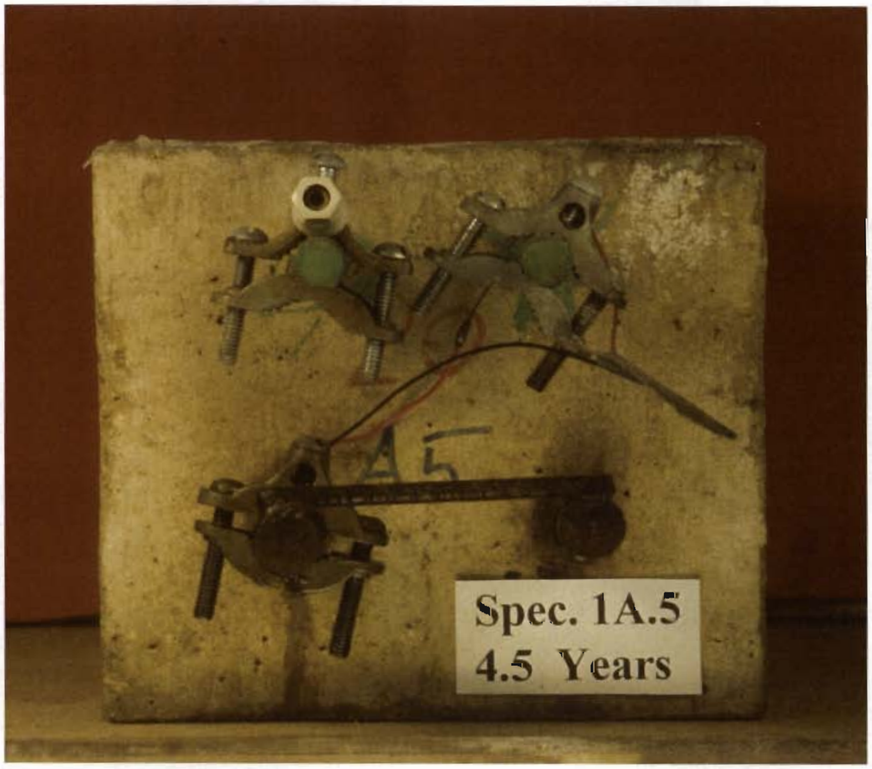
Figure 2.2 Severe pitting and loss of cross section on uncoated bars near crack locations (beam specimens).

(a) Top surface

(b) Perspective view

Figure 2.3 Specimen surface condition of specimen with uncoated bar.

(a) Top surface



(b) Front surface

Figure 2.4 Surface condition of specimens with coated bars.

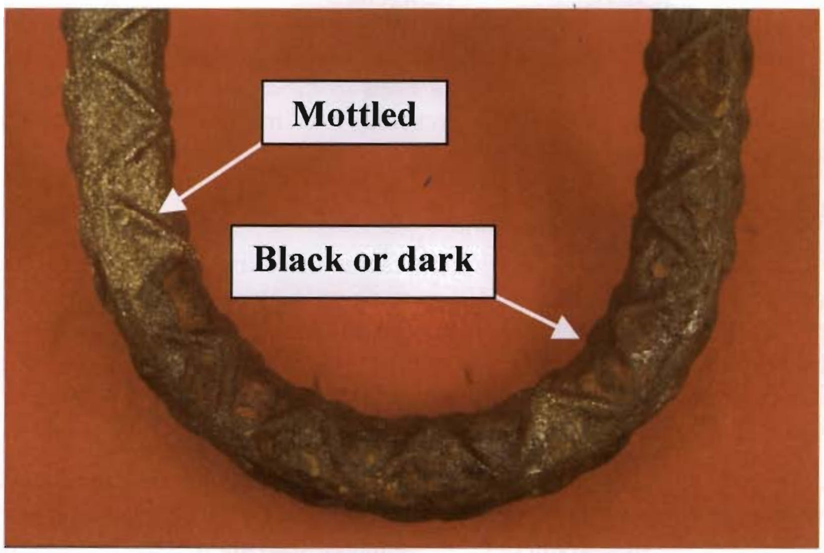


Figure 2.5 Appearance of epoxy-coated bar after removing the coating (macrocell study).

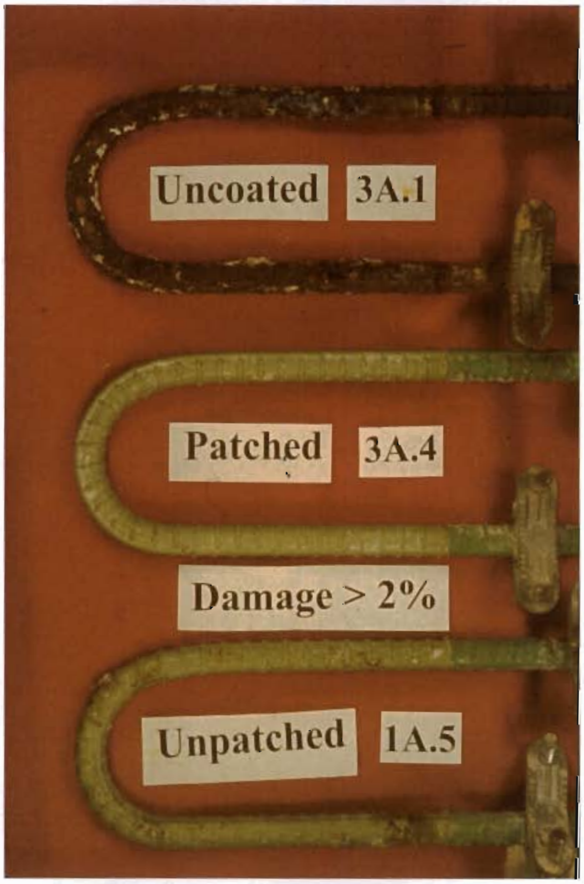


Figure 2.6 Comparative performance of uncoated and coated bars after 4.5 years of exposure (macrocell study).

From the experimental program alone, it was not possible to predict the probable service life of structures with epoxy-coated bars. Field conditions cannot be duplicated in the laboratory and some parameters were selected to accelerate corrosion. The coating used in these studies was manufactured in the early 1990's and was widely used in Texas. Coatings presently used may perform differently under conditions similar to those used in the test program.

2.2 DAMAGE TO EPOXY COATING

Damage to epoxy coating was the most significant factor effecting corrosion performance. Immersion tests,[20] and macrocell[23] and beam[24] studies all led to this conclusion. All tests showed that the greater the size and frequency of damage, the more severe and more extensive the amount of corrosion. The performance of bars from the immersion test showed that corrosion always initiated on any damage to the coating, without exception to the size of the damaged area or its location. Corrosion on small pinholes, cracks, and damaged spots was observed on all of the bars.

Figures 2.7 and 2.8 show the amount of charge flux that was measured for the macrocell specimens. Three observations can be drawn from the charge flux plots: 1) Coated bars performed better than uncoated bars, 2) the greater the frequency of damage, the higher the amount of corrosion, and 3) patching coating damage reduced, but did not completely prevent corrosion. Bars with damaged spots greater than 2% of the bar surface suffered the worst corrosion among coated bars in macrocell specimens. Bars with damaged spots greater than 6x6 mm experienced similar levels of corrosion. The appearance of bars after autopsy confirmed these trends (Figures 2.9 and 2.10). Measured current versus time for macrocell specimens with varying degrees of damage are illustrated in Figures 2.11 and 2.12. The specimens with damage greater than 2% and the specimen with cracks in the coating less than 1% experienced the highest currents. Interestingly, after initial low currents during the first two years of exposure, the specimens with coating cracks and damage less than 1% experienced increasing current at the end of 4.5 years while other damaged specimens seemed to have reached steady-state behavior. Consequently, a large increase in metal consumption occurred during the last 2.5 years of exposure for specimens with coating cracks, and this increase was reflected in the relatively large amount of charge flux after 4.5 years (Figures 2.7 and 2.8). The presence of cracks in the coating may reduce performance of coated bars in the long term. There was good agreement, in general, between monitored currents and observed corrosion attack.

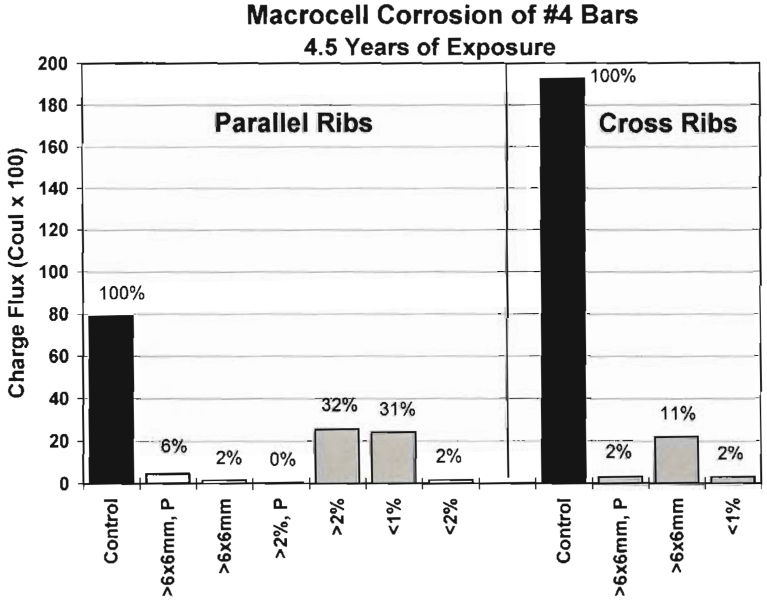


Figure 2.7 Charge flux for all A specimens (#4 bars).

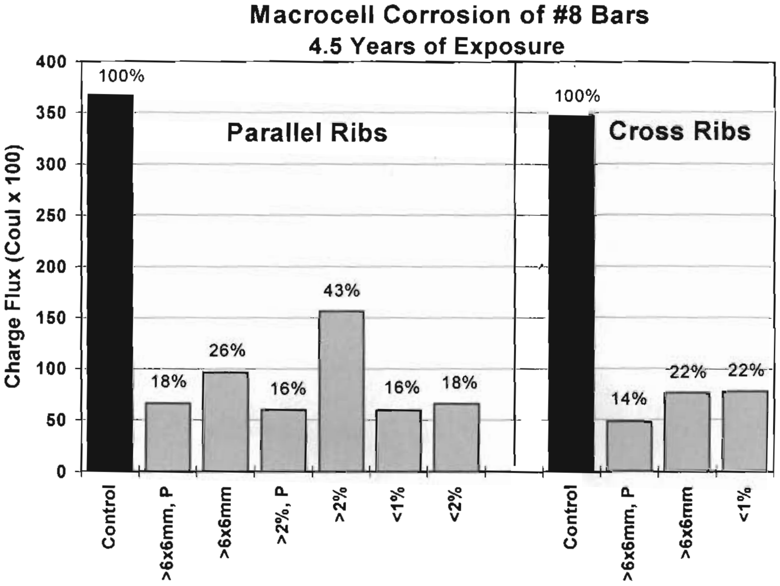


Figure 2.8 Charge flux for all B specimens (#8 bars).

Figure 2.9 Corrosion of damaged areas at outside bend on #8 bar with damaged coating greater than 2%.

Figure 2.10 Corrosion of patched areas at outside bend on #8 bar with damaged coating greater than 2%.

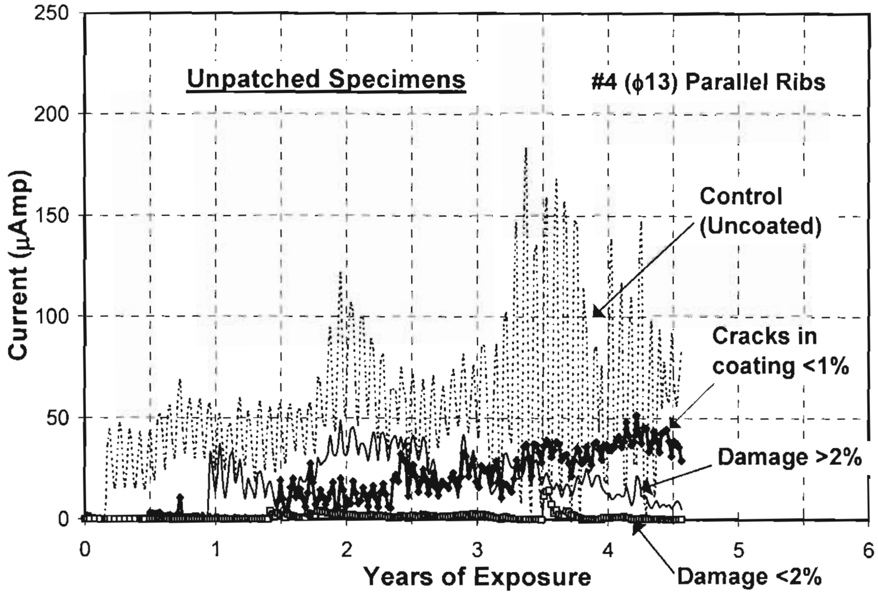


Figure 2.11 Current vs. time of A specimens (#4 bars) with different damage frequency or cracks in the coating (macrocell study).

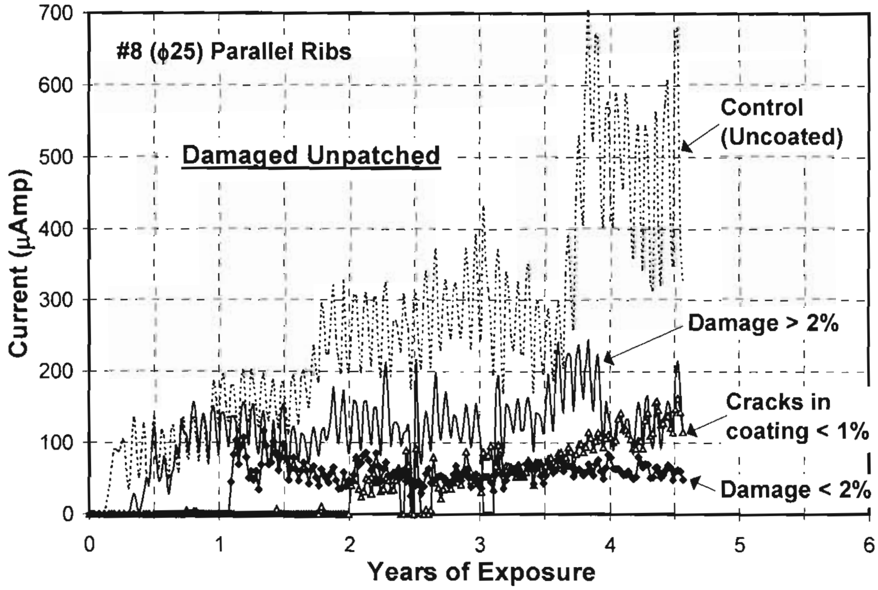


Figure 2.12 Current vs. time of B specimens (#8 bars) with different damage frequency or cracks in the coating (macrocell study).

In beam specimens, epoxy-coated bars in good condition, without any visible damage, remained in very good condition. The coating surface (and steel surface underneath) maintained its original shiny appearance after 4.3 years of saline exposure (Figure 2.13). Only a few spots had a very thin film of reddish rust at mill marks and coating adhesion was preserved throughout most of the bar surface. In contrast, bars with 3% damage in both cracked and uncracked beams showed widespread coating debonding. Extensive bar areas with both mottled and dark corroded surfaces were observed, although some exposed steel areas did not corrode (Figure 2.14). Analysis of corrosion potentials in uncracked beams showed that bars with 3% damage corroded much earlier than bars in as-received condition, but at about 3 to 3.5 years, some corrosion activity was noted on as-received bars (Figure 2.15). The implication of these trends was that bars with larger damaged areas experienced corrosion earlier than as received bars.

Both immersion and macrocell studies showed that corrosion occurred also on the damaged spots introduced during bending on the inside of the bends. Although the coating appears to have been compressed only, the inside portions of bends are as susceptible to corrosion as the outside portions. Damage on the inside of the bend used to be neglected and several specifications do not explicitly address this kind of damage.

Research by others has also shown the detrimental effect of coating damage in corrosion performance.[13,31,32,33] The early failure of Florida Keys' bridge substructures has been partly attributed to presence of damage (within the permissible limits of applicable specifications).[15] Electrochemical impedance spectroscopy (EIS) and polarization resistance tests on bent and straight coated bar samples after 200 days of immersion in 3.5% NaCl solution performed by Chen showed similar findings.[34] Chen concluded that "the most crucial factor affecting epoxy-coated bar performance was the coating integrity." Bar samples with most corrosion were characterized by having a coating of poor quality with numerous damaged areas and pinholes, despite the fact that all damage and defects were patched. Thinner coatings performed poorly, mostly because they were more likely to have weak spots and were more susceptible to physical damage than thicker coatings. Even considering the poorest performance of coated specimens, the corrosion performance of coated bars was always better than that of uncoated specimens.[34]

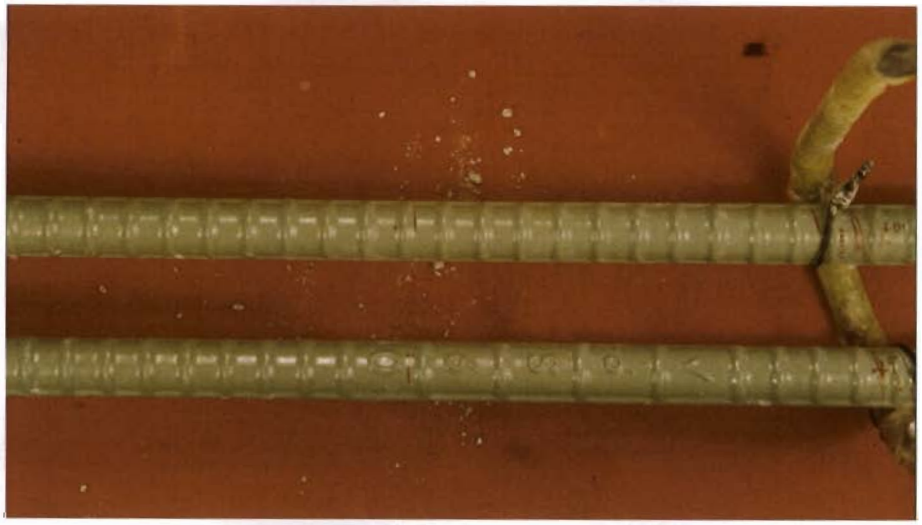
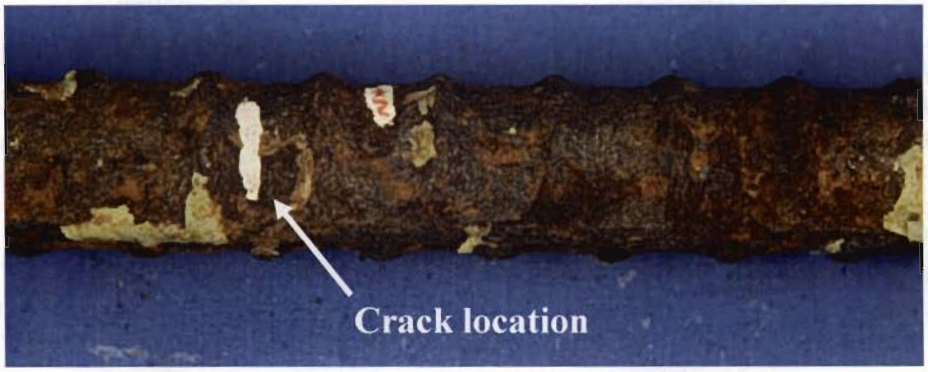


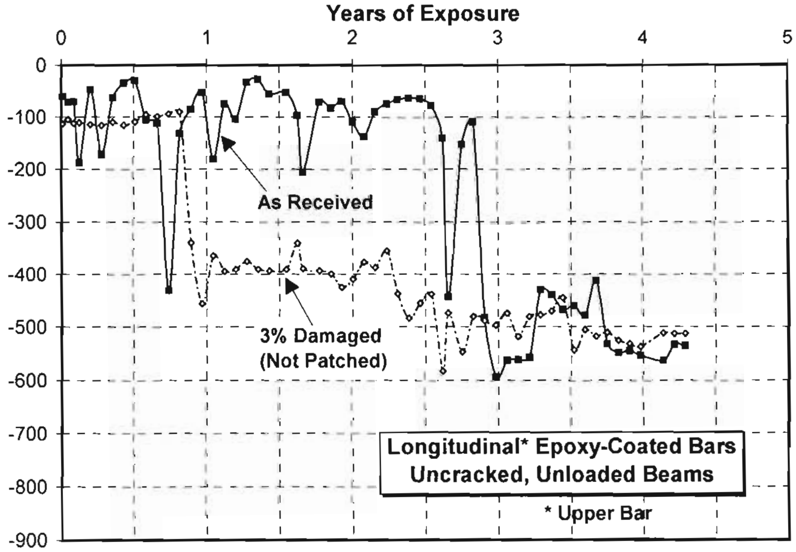
Figure 2.13 Longitudinal coated bars of beam B1 after 4.3 years of exposure.

(a) Rust stains at lower bar of beam B10, portion within the wetted zone. Damaged spot at crack location.



(b) Appearance after removing the coating.

Figure 2.14 Corroded portion on coated bar with 3% damaged coating of cracked, unloaded beam B10 after 4.3 years of exposure.



Upper Bar

Figure 2.15 Comparison of average corrosion potentials (wetted region) of longitudinal bars in uncracked, unloaded beams with different levels of damage.

Research conducted at Sumitomo Metal Industries in Japan with uncoated, galvanized, and epoxy-coated bars embedded in concrete prisms produced very similar results to the present research.[35] The prisms were pre-cracked and loaded to a steel tensile stress of 200 MPa (29 ksi) for two (lab exposure) and three (marine exposure) years. Bars with undamaged epoxy coating in cracked specimens exposed to natural marine environment and to accelerated exposure remained essentially uncorroded, regardless of film thickness and depth of concrete cover. The coating maintained its original appearance, adhesive strength, and scoring and peeling hardness. On the contrary, bars with damaged coating experienced various degrees of corrosion at damaged areas in the vicinity of cracks. Extent and severity of corrosion was dependent on film thickness and depth of concrete cover. Corrosion was more extensive with thinner coatings and shallower concrete covers.[35] In a field survey of four bridge decks in California, the presence of high chloride concentrations (0.7 to 4.6 kg/m^3) at the bar location did not initiate corrosion if there were no defects in the coating, indicating that undamaged epoxy coating provided satisfactory corrosion protection.[13]

Early versions of ASTM D3963 specifications and CRSI guidelines allowed up to 2% coating damage and maximum size of damaged areas of 6x6 mm.[36,37] This and other damage limits allowed by US agencies were based on early research results by the FHWA, where no corrosion deterioration was observed in deliberately damaged bars.[38] Clearly, these limits were not adequate. Specifications for permissible damage should have been more stringent. Findings herein and those of other researchers have caused a continuing revision of acceptable limits on unrepaired damage and patched surfaces. Other specifications (TxDOT, NACE) have set more stringent requirements and lowered the amount of permissible damage. More recently, an ASTM task group approved amending ASTM specification D-3963 to tighten the allowable damage provision. The new specification requires all visible damage to be repaired.[39] Likewise, TxDOT specifications require all visible damage to be patched, with a maximum patched area at the plant of 6 mm (1/4 in) total length in any linear 0.3 m (1 ft) bar length.[40] In the United Kingdom, the limiting damage specified by BS 7295 is 1% of surface area.[41]

2.3 EFFECTS OF FABRICATION AND INSTALLATION

Another factor that influenced corrosion performance was fabrication of coated bars. Fabricated or bent-coated bars tended to perform worse than straight coated bars. Fabricated stirrups in beam specimens performed worse than longitudinal bars. Likewise, bent bars in macrocell specimens and immersion tests corroded more extensively in their bent portions. Performance was compromised because bending coated bars weakens adhesion of the coating to the steel substrate, and may induce coating damage such as cracks, tears, and pinholes. This was observed in the immersion study, where corrosion occurred not only in the damaged areas that had been introduced deliberately but also at the holidays in the coating that were not visible before immersion (Figure 2.16). Most of the holidays existed along the sides of the lugs, where the coating is usually difficult to apply uniformly.

Chen reported that fabricated bars were more susceptible to corrosion because of the higher incidence of damage introduced during bending.[34] In corrosion tests on concrete slabs by Treadaway and Davies, some coating deterioration in the form of underfilm corrosion was observed at ribs on the outside bends of bars. Corrosion was limited to the curved portion of the bar.[33] If the coating at bent areas is damaged, adhesion loss and underfilm corrosion commences at damaged areas and the progression of debonding and corrosion is facilitated by the weak steel-coating interface. The problem is exacerbated by the fact that fabricated bars, such as stirrups or transverse reinforcement, are usually closer to the exterior concrete surfaces. Moreover, in flexural members, coated transverse reinforcement will act as crack inducers, which means that cracks in the plane of the transverse reinforcement will be created. The combinations of all these factors make coated transverse reinforcement particularly vulnerable to corrosion, as was shown in the beam study (Figures 2.17 and 2.18).

Figure 2.16 Corrosion at holidays not detected before immersion in 3.5% NaCl after about 8 months of exposure.

Figure 2.17 Rust staining of stirrup from beam B17.

Figure 2.18 Pitting along stirrup leg surface beneath the coating (beam B27).

Some standards, such as AASHTO M284 suggest that coating cracks without debonding from substrate need not be repaired.[42] Research results from macrocell specimens showed that corrosion progressed and accelerated in the longer term in bars with coating cracks at the outer bend, contrary to AASHTO provisions. As some of the latest standards (TxDOT,[40] ASTM A775-97[43]) specify, all visible damage should be patched, including any cracks in the coating even if the coating does not seem to be debonded. Although coating may not disbond after bending, coating adhesion is usually weakened.

Rigid epoxy coatings that are applied to the bar after fabrication have been developed recently. Since the coating is applied after bars are fabricated, adhesion at bent areas is preserved. Such coatings are also theoretically more resistant to abrasion and scratching than are more flexible coatings. The use of such coatings deserves consideration for fabricated bars. However, corrosion testing in concrete specimens should be performed to assess the effectiveness of these new products. In this project, several samples coated with a rigid epoxy showed poorer adhesion than samples with flexible coatings before and after hot water immersion.

The practice of mixing coated and uncoated bars in the same concrete member may lead to undesirable performance. Any incidental continuity between coated and uncoated bars could establish large macrocells that would be conducive to extensive corrosion, as was shown in the macrocell study. In addition, uncoated bars can be subjected to corrosion regardless of electrical continuity. All uncoated bars in beam specimens underwent severe and extensive corrosion after 4.5 years of exposure. Several of the uncoated, cathodic bars in macrocell specimens started to experience corrosion at the end of 4.5 years of exposure.

CHAPTER 3: COATING PROPERTIES

3.1 REPAIR OF COATING DAMAGE

Immersion tests,[20] macrocell[23] and beam[24] studies, and patching experiments all showed that patched areas are vulnerable to corrosion. Sound fusion-bonded epoxy coating provides much better protection than most patching materials. Patching damaged coating reduced, but did not completely prevent, corrosion in immersion tests and beam and macrocell specimens. Patched bar ends were particularly vulnerable to corrosion. EIS and polarization resistance tests by Chen led to the same conclusion.[34] Corrosion of patched ends has been observed by others.[33] Figures 3.1 and 3.2 show corrosion of patched areas on bars from macrocell and beam specimens. The corrosion mechanism of patched areas is described in Report No. 1265-5[25] and in Reference 27.

Figure 3.1 Corrosion of patched area of #4 epoxy-coated bar (macrocell study).

Figure 3.2 Patch at bar ends of splice bars broke during autopsy, showing a dark corroded surface underneath after 4.3 years of exposure (beam study).

Despite displaying slightly lower currents, the steel surface of most bars with patched coating from macrocell specimens showed levels of corrosion similar to bars with exposed, damaged areas after 4.5 years of saline exposure (Figure 3.3). Corrosion products built up at exposed sites while only very light rust developed at patched areas. However, corrosion spread on the steel surface far beyond patched areas and was not dissimilar from the corrosion observed at bar surfaces beyond exposed areas. There was only one case in the macrocell study where a bar with patched coating presented a substantially improved steel surface condition relative to a bar with exposed areas (small bars with parallel ribs and damaged spots greater than 2% of the bar surface). These observations were in good agreement with measured macrocell currents.

(a) Patched bar 3B.2, outside bend.

(b) Bar 2B.3 with unpatched damage at outside bend.

Figure 3.3 Comparative steel corrosion under the coating at outside bend of bars with damaged coating, with and without repair.

Patching damaged areas on the outside of the bend only was not sufficient. Corrosion also propagated from mandrel indentations at the inside of the bend and at the outside of one straight leg (at point of support for bending operation). Nevertheless, corrosion was more severe on the outside than on the inside of the bends, even if the damage on the outside of bend was patched.

Patched cut ends of splice bars in beam specimens experienced uniform dark corrosion beneath the patch, and coating debonding with underfilm corrosion progressed along the bar up to a distance of about 20 to 24 cm from the patched ends (Figures 3.4 and 3.5). Corrosion spread over the bottom (as in casting position) side of the bars, while the topsides of the bars exhibited a mostly mottled surface. Evidently, bar patched ends are vulnerable to corrosion and, if located at a crack, the situation is aggravated by the availability of chlorides, water, and oxygen. Once bar patched ends start to corrode, corrosion migrates underneath the coating over time.

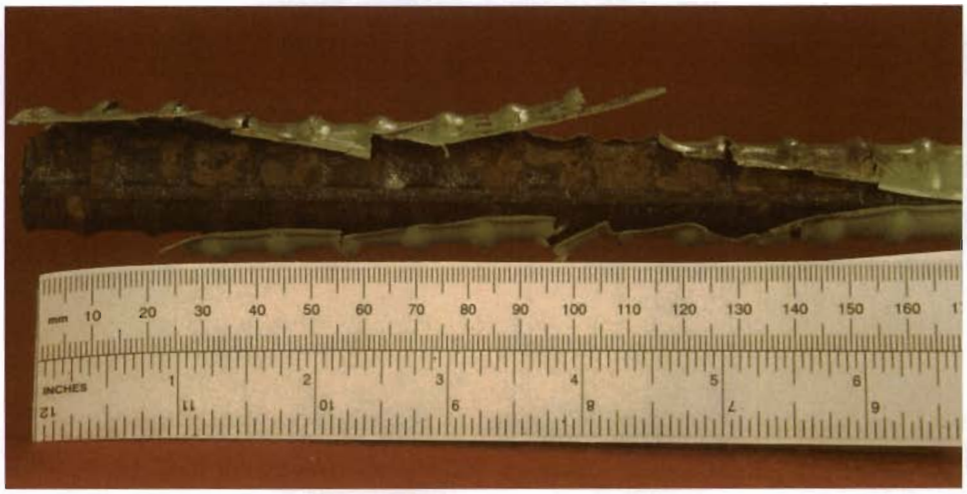


Figure 3.4 Coating debonding of splice bar (beam study).

Figure 3.5 Underfilm corrosion of splice bar after 4.3 years of exposure (beam study).

CRSI guidelines limit the amount of damaged coating, including repaired and unrepaired areas, to 2% of the bar surface area per 0.3 m (1 ft) of bar.[36] ASTM D3963 specifications limit the maximum surface area of patched damage to 5%.[37] Again, these limits are clearly too large. Findings in this research project show that bars with 2% patched damage may undergo significant levels of underfilm corrosion. TxDOT specifications set slightly more restrictive limits, with a maximum patched area at the applicator of 6 mm (1/4 in) total length in any linear 0.3 m (1 ft).[40] However, the precise amount of patched area is not clearly defined, because a variety of sizes could be fit within a 0.3 m length of bar, especially in bars with larger diameter.

Current specifications do not provide adequate guidelines for proper coating repair procedures. The coating repair study shed some light regarding performance of different patching materials and procedures. Manufacturers claim that thorough surface preparation is essential for adequate performance of patching materials. Research performed in this study indicated that the most important factor was the type and properties of the patching material, with surface preparation having little effect. Patching materials of sufficient viscosity to produce a thick coating provided the best protection. Figures 3.6 and 3.7 clearly show that as patch thickness increased, corrosion performance improved. Diffusion of chlorides through the patch was significantly delayed as patch thickness increased. Thicker patches provided good protection at vulnerable areas such as sharp edges of rebar ends, as shown in Figure 3.8.

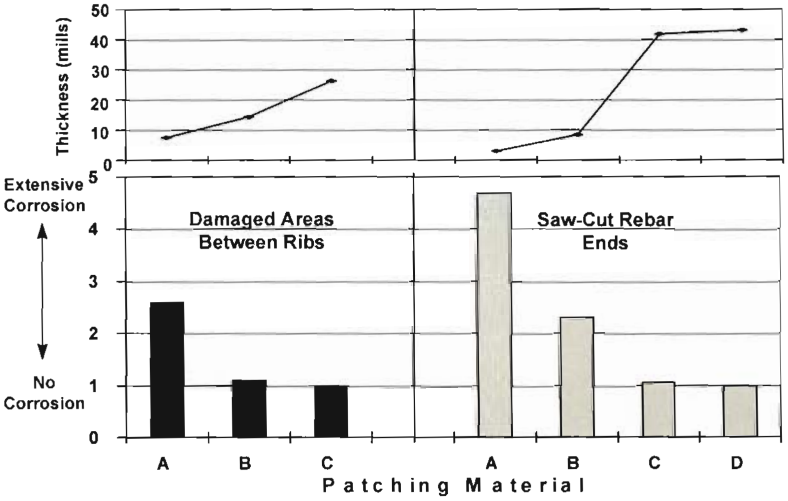


Figure 3.6 Comparative performance between 2 types of specimens repaired with different patching materials.

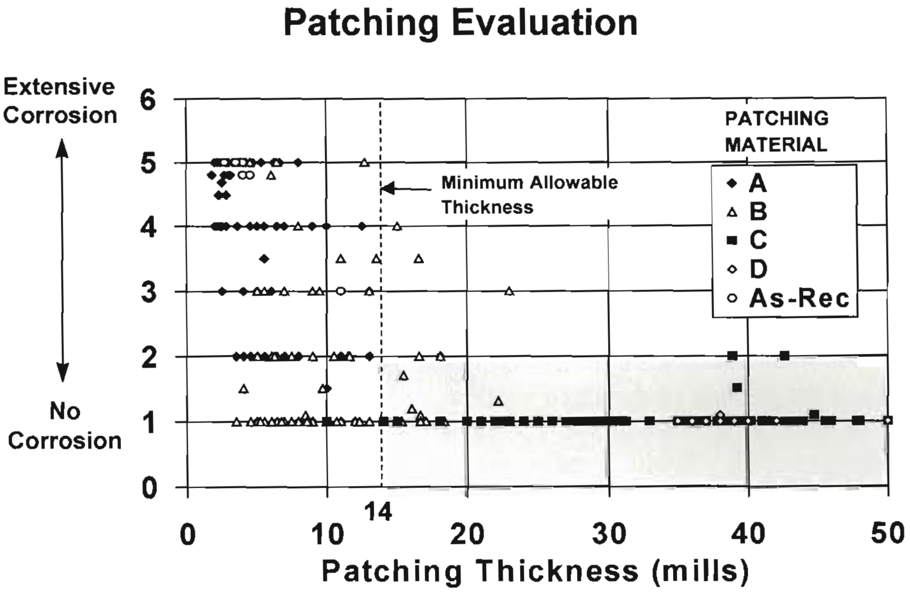


Figure 3.7 Corrosion rating vs. patch thickness of all specimens.

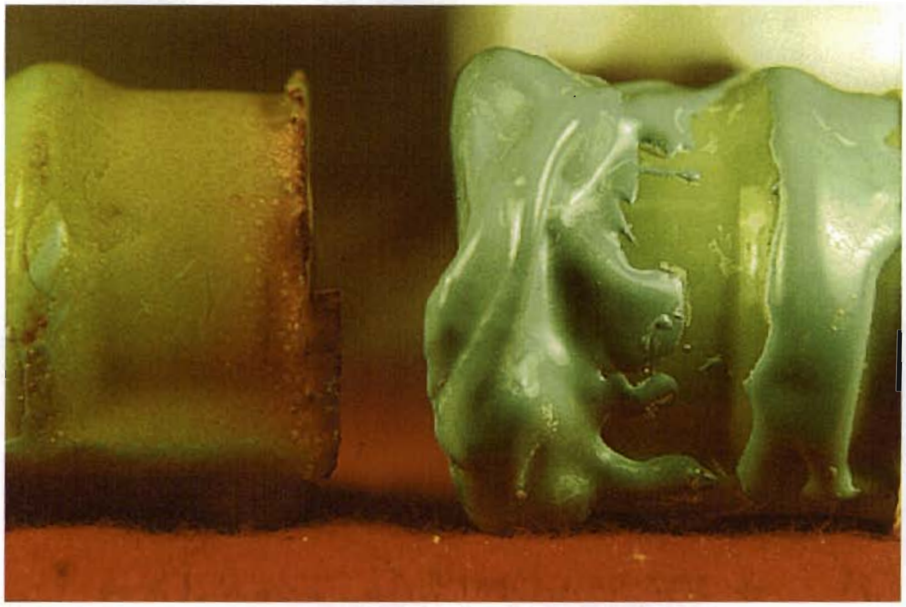


Figure 3.8 Patching material *A* (left side specimen) performed worse than material *C* (right side specimen).

A statistical evaluation showed that 95% of data points in Figure 3.7 with ratings above 2 (deemed as having unacceptable performance) had thicknesses lower than 14 mils. Similarly, only 5% of data points with ratings above 2 had thicknesses greater than 14 mils (Figure 3.7). Based on this database, a minimum patch thickness of 14 mils seems adequate. The region containing data points with thicknesses greater than 14 mils and acceptable performance (ratings lower than 2) is shaded in the graph (Figure 3.7).

There are some disadvantages of thicker patches. Patching materials with a thick consistency have a short curing time and can be very difficult to apply. Epoxy material suppliers need to continue developing new materials that provide improved corrosion protection and are easy to use. Of the materials considered here, material *B* provided satisfactory corrosion protection in many instances and was relatively easy to use. A thick patching material is more important for coating cut bar ends than for repairing damage coating along a bar. Sharp corners and rough-cuts at bar ends were very susceptible to corrosion when thinner materials were used.

Although thickness of the patch was identified as an important factor, the specific properties that make a patching material perform well still need to be identified. The fact that patch thickness was always associated with the type of material seem to indicate that there may be a series of properties, such as rheology, viscosity, flow, percent of solids, modulus of elasticity, flexibility, hardness, and permeability, which may be interrelated and act together to give the material desirable characteristics.

3.1.1 Surface preparation

No clear trend was observed in terms of surface preparation. No improvement in performance was observed with surface cleaning before patching on samples after 200 days of cyclic immersion in 3.5% NaCl (Figure 3.9). EIS clearly showed that performance was dominated by the type of patching material, with surface preparation having little effect (Figure 3.10). The sophisticated surface preparation procedure used in the experiment did not provide improved performance over routine cleaning with a wire brush and a rag. Even some control specimens where the surface was specially cleaned showed poor performance (Figure 3.11). Rounding and smoothing sharp edges at bar ends did not prove successful. Therefore, no sophisticated surface preparation procedures need to be recommended for field application.

Routine cleaning with a wire brush and a clean rag to wipe lose materials and dirt should suffice. Manufacturers' application procedures indicate that proper surface preparation is important for satisfactory performance but this supposition is not supported by results obtained in this study.

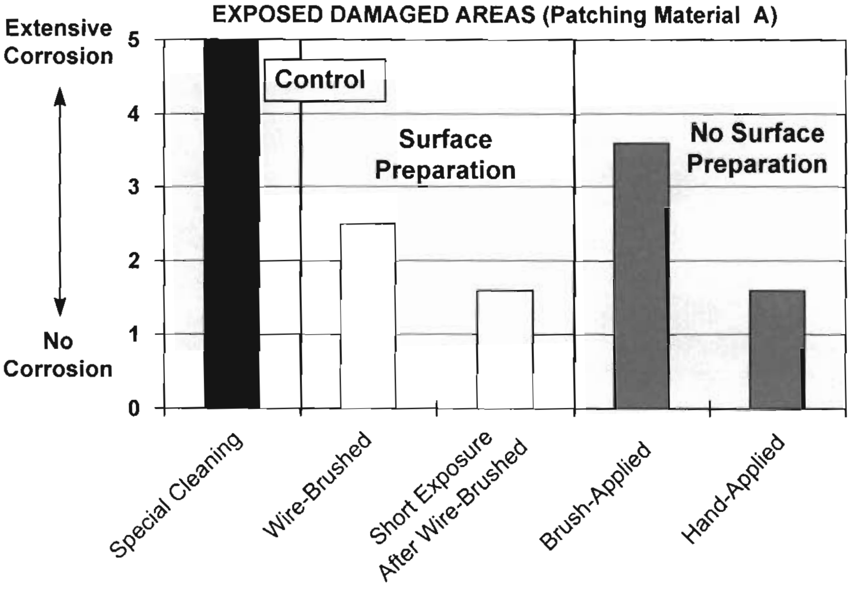


Figure 3.9 Corrosion rating of several coating repair procedures on flame-cut bar ends (Patching material A).

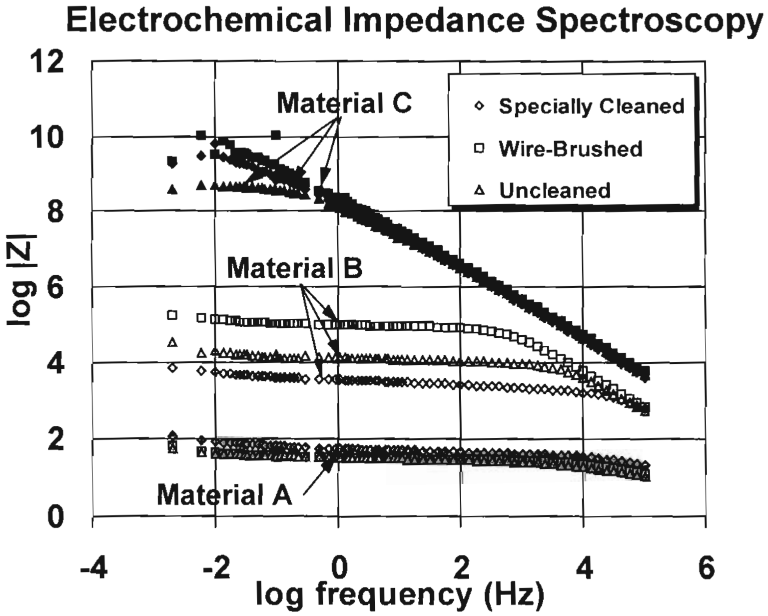


Figure 3.10 EIS results in Bode format (3 patching materials and 3 repair procedures) after 100 days in NaCl solution.

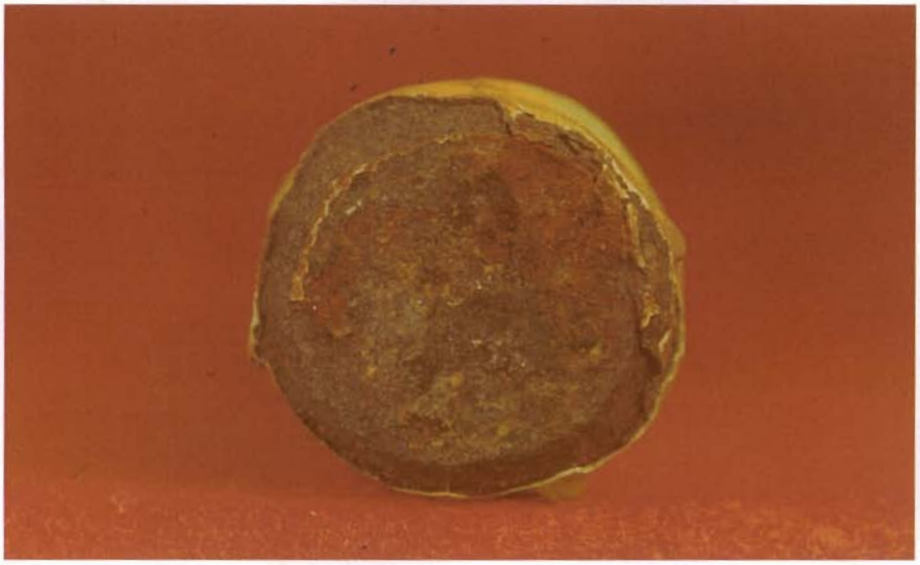


Figure 3.11 Corrosion of bar end surface that was specially cleaned before patch application.

Until recently, ASTM D3963-96 incorporated prequalification tests for patching materials, an area lacking in past ECR standards.[44] The ASTM standard now includes 400-hour salt spray and 28-day, elevated temperature, high-pH solution immersion as prescreening tests for potential patching materials. The tests are performed on repaired areas of coated flat panels. CRSI has developed a separate edge coverage test intended to assess the suitability of patching materials to adequately cover sharp edges at bar cut ends. The test is in the process of evaluation among laboratories to determine its reproducibility.[45] These provisions are steps in the right direction to ensure that adequate patching materials are used.

3.2 COATING ADHESION

The hot water and knife adhesion tests developed in this study proved to be a valuable tool for quality control and for in-depth studies of coating adhesion. Hot water and knife adhesion tests were very useful in discriminating and identifying good from bad quality coatings. The three test procedures that were developed were termed "hot water test," "strip test," and "X-cut test." In the first procedure, adhesion testing of bar samples was preceded by immersion in hot water, while in the "strip" and "X-cut" tests, adhesion testing was performed without previous immersion. The tests were relatively easy to perform and did not require special or sophisticated equipment. Most of the subjectivity involved in earlier tests was eliminated or reduced by the development and use of a calibrated knife (Figure 3.12). Nevertheless, it was shown that the subjectivity of the tests had little or no effect in the detection of coatings with poor adhesion. Test parameters such as knife force calibration procedures, adhesion test method, test operator, type of knife and blade, and test evaluator had little effect on the test results.

The coating adhesion study indicated that sample source was the most influential factor for adhesion strength, revealing that the quality of coating application by different coaters can vary greatly and affects adhesion of the coating (Figure 3.13). An interest finding was the good agreement observed between results from the three knife adhesion test procedures and those from the TxDOT peel test (Figure 3.14). Considering that the TxDOT peel test is simple and quick to perform, the test would be highly recommendable for adhesion evaluation, especially if a calibrated knife is not available. Another important finding was the poor correlation observed between knife adhesion tests and bend tests (Figure 3.15). Bend tests were not reliable indicators of coating adhesion and were more a measure of the coating flexibility. Therefore, the use of bend tests as the only method of testing epoxy-coating adhesion (as proposed in some ECR standards) is discouraged.

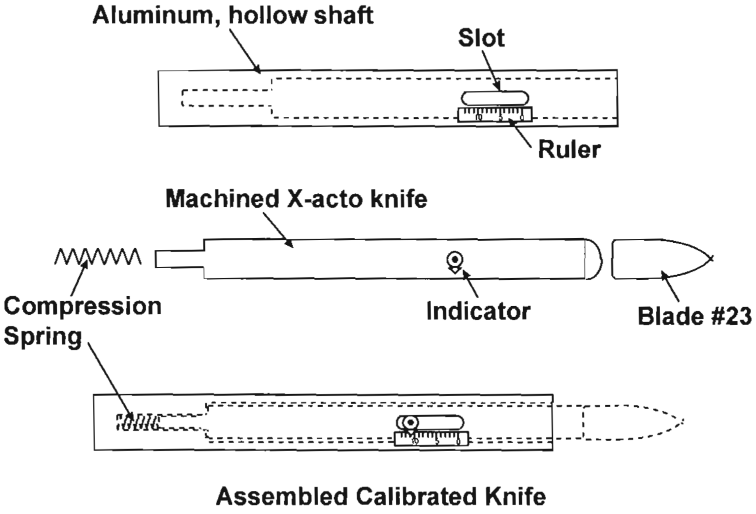


Figure 3.12 Calibrated knife developed for coating adhesion study.

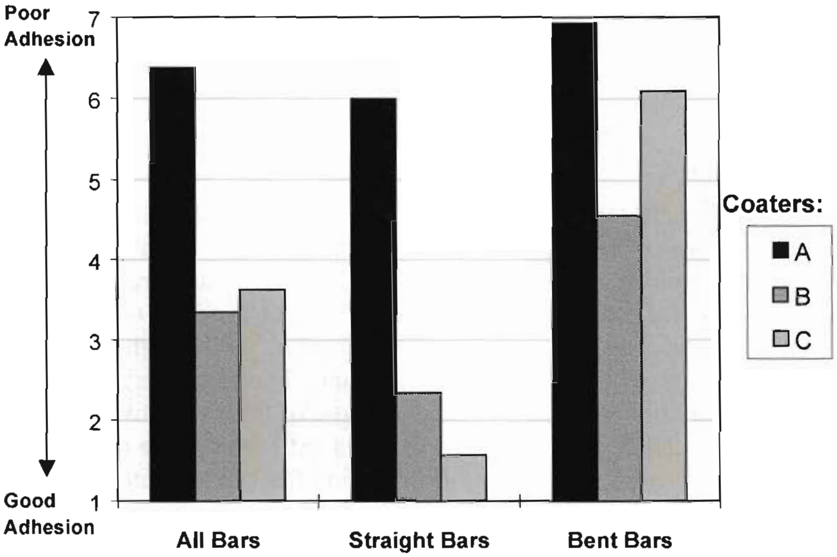


Figure 3.13 Average adhesion ratings of specimens after hot water immersion grouped by coating plant and type of specimen (bent or straight).

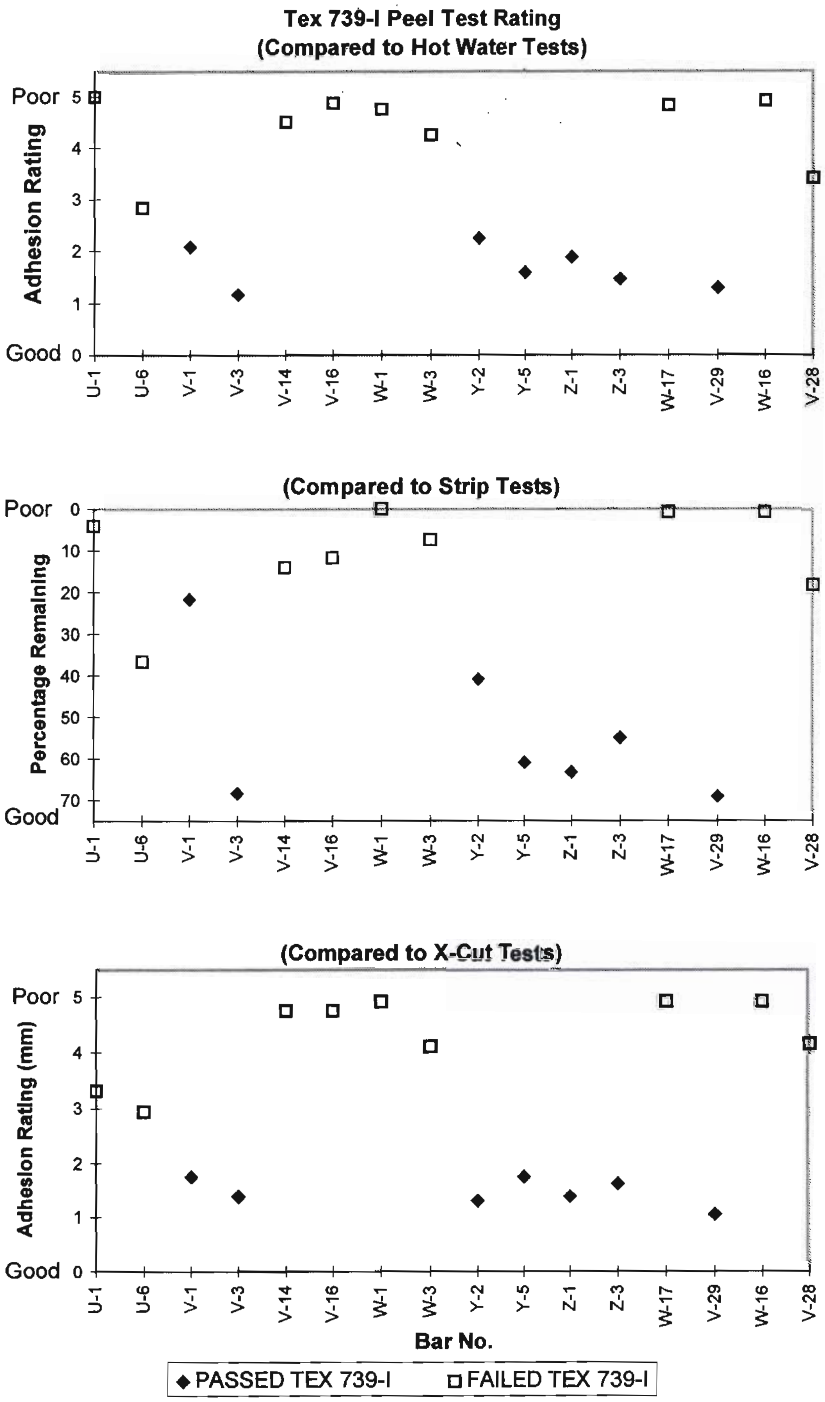


Figure 3.14 Adhesion test results from three test methods compared to TxDOT peel test.

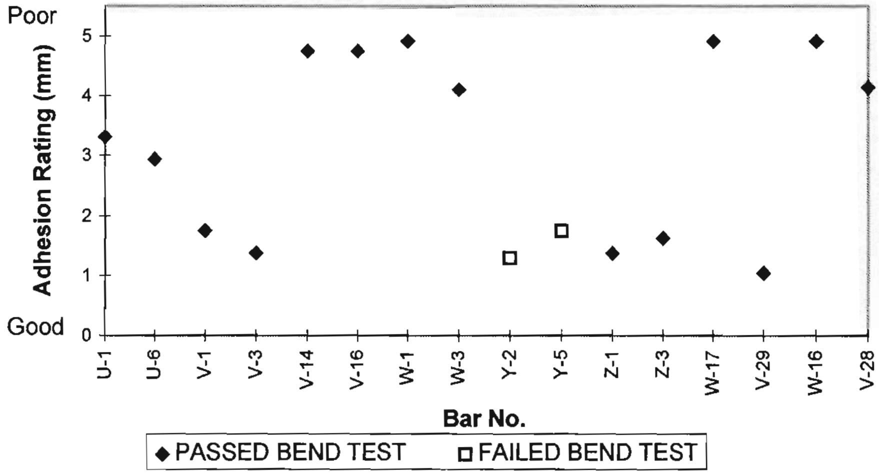


Figure 3.15 Adhesion test results from X-cut method compared to bend test.

The effect of coating adhesion on corrosion protection is not well understood. Coating powder manufacturers and a number of researchers claim that good adhesion is crucial for satisfactory corrosion protection.[18, 46, 47] It is presumed that a poorly adhered coating will allow unrestricted transport of water, chlorides, and oxygen beneath the coating, causing widespread underfilm corrosion. With the exception of one study at the University of Western Ontario, there has not been a careful and systematic study of the effect of coating adhesion in corrosion protection, especially using coated bars embedded in concrete specimens. It has not been clarified whether it is the amount of damage to the coating or the adhesion of the coating to the steel substrate that governs the rate of underfilm corrosion and coating disbondment. In bar specimens immersed in salt water (discussed in Reference 28), it was found that specimens with poor adhesion before immersion showed a smaller corroded area than specimens with better initial adhesion before immersion (Figure 3.16). If the conventionally accepted notion that poor adhesion leads to poor performance is true, then it would be expected that bars with better adhesion before immersion would have corroded less.

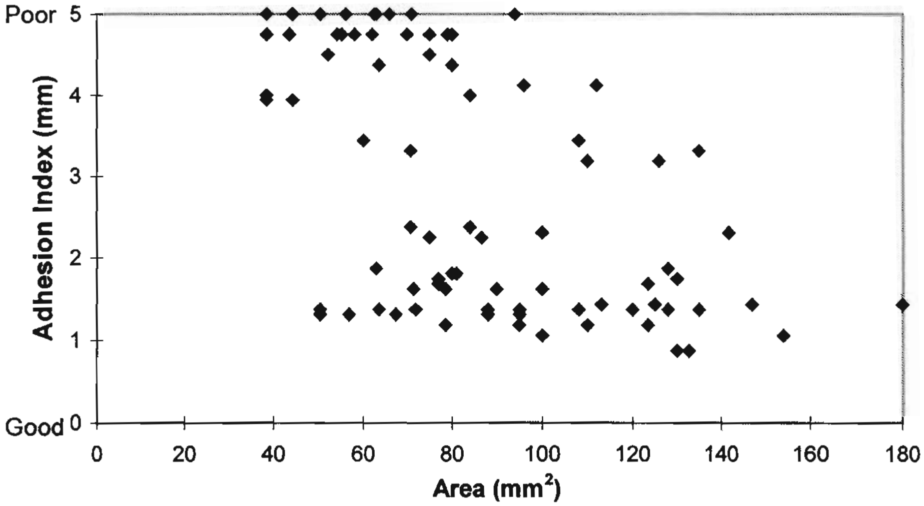


Figure 3.16 Size of corroded area after 12 weekly cycles of immersion in 3.5% NaCl in relation to adhesion index measure before immersion.

Fabrication (bending) of bars weakened coating adhesion. In hot water and knife adhesion tests, straight bars always performed better than bent bars (Figure 3.13). In durability studies, all macrocell specimens showed loss of adhesion at bend portions and adjacent straight legs after 2 and 4.5 years of chloride exposure, regardless of the level of corrosion activity. Likewise, coated stirrups in beam specimens showed widespread adhesion loss after one and 4.3 years (Figure 3.17). On most beams, adhesion loss was slightly more extensive on fabricated bars than on straight bars. Underfilm corrosion was noticeably more extensive on fabricated bars than on straight bars. Weakening of adhesion caused by bar fabrication seemed to be proportional to the observed adhesion loss and underfilm corrosion after chloride exposure. During fabrication, adhesion was weakened at bends in stirrups but was presumably preserved at the straight portions. After chloride exposure, adhesion loss and undercutting progressed from weakened (bend) portions to initially well-adhered (straight) portions. Other factors effecting stirrup performance were discussed in Reference 27.

Figure 3.17 Coating extensively debonded on stirrups (beam study).

The observed corrosion of epoxy-coated bars in the present research reveals that adhesion of the epoxy coating is inevitably lost after a prolonged period of exposure to water and chlorides in concrete (whether bars were fabricated or not). Corrosion experiments and field inspections by others have also provided evidence of various degrees of coating disbondment after chloride exposure in concrete.[13, 15, 16, 32, 33, 48] Kahhaleh suggested that adhesion loss could be beneficial because corrosion would spread along the bar and would not concentrate at certain spots and cause severe localized damage.[20] Longer term exposure showed that this hypothesis may not necessarily be true. Although bar corrosion was less concentrated and severe in coated bars than on uncoated bars, several pits of moderate depth were observed in coated stirrups (beam study).

The degree of adhesion loss after chloride exposure seemed to be affected by differences in coating integrity. Straight bars from beam B1 were in excellent condition with no visible damage before chloride exposure. The bar condition was preserved without signs of corrosion or extensive adhesion loss after 4.3 years of chloride exposure (Figure 3.18). Longitudinal bars in the remaining autopsied specimens had intentional damage, patched or unpatched, and experience adhesion loss within the wetted region with varying degrees of underfilm corrosion (Figure 3.19). Since bars for all beams came from the same lot, it is reasonable to assume that all bars had similar coating adhesion before chloride exposure. Clearly, coating integrity was fundamental in the preservation of adhesion and the protective capabilities of the coating. In addition, it was found that adhesion loss always occurred around areas of damaged coating and was least affected at locations farthest from damaged coating. Similar observations have been made by Sagüés.[15] Visible holidays and coating defects were present on areas that experienced coating disbondment in coated bar segments extracted from four bridge decks in California.[13] This evidence suggests that the agents causing coating disbondment migrated to the coating-substrate interface through coating defects rather than through the bulk of the coating.

Figure 3.18 Coating adhered well throughout most portions of bars from beam B1.

Figure 3.19 Dark corroded surface beneath debonded coating on longitudinal bar with 3% damaged coating within the wetted region (beam B8).

Experiments conducted at the University of Western Ontario showed that the mechanism of adhesion loss appeared to be water permeating the epoxy coating, which displaced the coating from the steel substrate.[38] Nevertheless, electrochemical tests indicated that the effect of adhesion loss in corrosion behavior was directly related to the presence of defects in the coating. If defects were absent, adhesion loss did not change the short-term corrosion behavior. However, if defects were present, corrosion rate was directly related to the adhesion of the coating, i.e. poor coating adhesion resulted in high corrosion rates. The main factors improving coating adhesion identified in that study were an increase in the surface roughness and a decrease in the presence of contaminants.[38]

EIS and polarization resistance tests on bent and straight coated bar samples performed by Chen showed relevant findings regarding adhesion loss and corrosion.[34] Adhesion strength before immersion was similar for both straight and bent samples. After immersion, bent samples experienced more extensive adhesion loss than straight samples did. Extent of adhesion loss was strongly dependent on the coating type and source. There was not a clear correlation between adhesion strength after immersion and extent of corrosion. Several bent samples experienced adhesion loss but no signs of corrosion after immersion in chloride solution. The coating surface in those samples had no visible damage, pinholes, or discontinuities. Even very thin coating at rib bases provided protection as long as the coating had no defects. Chen stated that, "adhesion loss can be the result, and not necessarily the cause, of epoxy-coated bar degradation."[34]

In an attempt to clarify the role of holes in the coating versus coating adhesion, a numerical model was developed at UMIST University.[47] The "Cottis Model" revealed that in the presence of holes in the coating in a low permeable concrete, the bar corrosion rate was governed primarily by the coating adhesion, and not by the relative size of the defects in the coating (Figure 3.20). However, it was not explained whether such a model was validated in actual coated bar specimens, particularly in a real concrete environment.

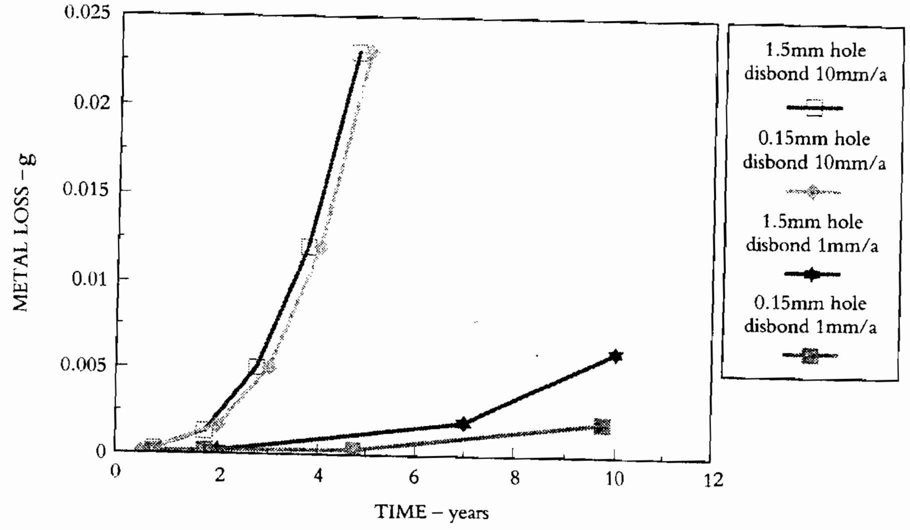


Figure 3.20 Cumulative corrosion with time for epoxy-coated steel in low permeability concrete according to "Cottis Model" [UMIST].[47]

Although coating adhesion was not measured before exposure, some hypothesis regarding the role of adhesion can be drawn from the exposure studies conducted in this study. The effect of adhesion on corrosion performance may be similar to that of flexural concrete cracks. Weakening of adhesion by bar fabrication will accelerate loss of adhesion and underfilm corrosion (similar to the presence of flexural cracks). Adhesion loss and underfilm corrosion will be significantly slowed if there is good adhesion before exposure (similar to the absence of flexural cracks). Nevertheless, in the long term, adhesion loss and underfilm corrosion will progress in bars with initial good adhesion (provided that the coating is damaged) to levels closer to that of bars with initial weak adhesion. The longer the exposure, the more similar the amount of corrosion will be between bars with initially poor or good adhesion.

3.3 COATING QUALITY

The quality of both epoxy material and coating application affect corrosion performance. Experimental research by Chen suggested that quality of coating application may be more important than the type of epoxy material for satisfactory corrosion performance.[34] Sample source (coating applicator) and subsequent handling practices had the most effect on corrosion performance. In a durability study by CRSI on macrocell slabs, bar source was the only variable that correlated with a sudden worsening of corrosion of coated bars when exposure was changed from cyclic salt solution ponding to continuous tap water ponding.[49, 50] In an immersion study by the Building Research Institute (IBAC) in Germany, bars from source B meeting German guidelines exhibited less pitting corrosion and coating debonding than bars from source A meeting ASTM guidelines. It was suggested that the more stringent German guidelines resulted in improved performance compared with those meeting ASTM requirements.[51] The coating adhesion study discussed here also showed that sample source was the most influential factor regarding adhesion strength. Since coating adhesion is an implicit indicator of quality of coating application, it then follows that the quality of coating application is greatly dependent on the sample source (coating applicator).

In addition to poor adhesive strength, the presence of a large number of holidays (i.e. coating discontinuities) is indicative of a coating with bad quality. In a peer review study by WJE of slab specimens with coated bars, it was found that the number of holidays correlated with the development of macrocell corrosion current.[52] Chen obtained similar findings.[34] An excessive number of holidays is detrimental to the corrosion performance of epoxy-coated bars.

It is expected that an improvement in the quality of both the epoxy material and coating application will result in a finished product with better (fewer flaws) coating integrity. In addition to restricting the maximum allowable damage, efforts should be directed to improving the coating properties that reduce damage, such as abrasion and impact resistance, hardness, and flexibility that may occur during all stages of fabrication, shipping, and construction. The production and application of better coatings with improved properties, and the observance of more stringent specifications will undoubtedly lead to improved corrosion performance.

Improvements in the coating quality may involve the optimization of several factors:[47]

- Careful pre-selection of the reinforcement to ensure the supply of a material with consistent quality
- Optimization of the coating process with respect to surface preparation, material preheating, consistency of coating application, and post-curing of the applied coating
- Formulation of the resin system for epoxy coating to provide adequate flexibility while keeping a strong bond to the steel and retaining optimum barrier properties.

Further product development may include chemical pre-treatments to modify the surface of the steel substrate before coating application. The adaptation of pre-treatments in the coating application process by a British coater was claimed to have negligible effect on the overall production cost.[47] Chemical pre-treatments have been used at coating plants in the United Kingdom and Canada.[38, 47, 53]

For optimum corrosion protection, it would be ideal to produce epoxy-coated bars of such quality that the integrity of the epoxy is preserved at all stages of production, transportation, storage, and construction. The less damage to be patched, the better. And if coating repair is needed, patching material should provide adequate thickness and be easy to apply. In addition to achieving good quality control at the coating plant, quality control measures have to be adopted at later stages after the bars leave the plant to minimize the amount of coating damage, and to properly patch damaged coating when needed. Good quality control is more difficult to achieve in the field than in a coating plant. Nevertheless, most quality control measures for epoxy-coated bars involve simple common sense rules that should not be difficult or costly to implement and follow. Observance of such rules requires proper training and field practice.

It should be emphasized that new epoxy coating formulations have resulted in products with improved properties, such as toughness, flexibility, and adhesion. Today's epoxy coating materials are much better than the first formulations used. Today's coating application methods have improved and quality control tests are more stringent than earlier methods. The voluntary certification program for epoxy coating applicator plants launched by CRSI in 1991 established stringent quality control procedures that exceed the basic requirements of most standard specifications.[54] Today's construction practices involving epoxy-coated bars are more conscientious than past neglectful practices. Today's epoxy-coated bar specifications are more comprehensive, stringent, and accurate than those specifications based on overly optimistic interpretations of early research. All these factors combined should result in greater durability of concrete structures reinforced with epoxy-coated bars. Test results from the durability studies performed in this research should be analyzed within this context. Coated bars in the macrocell and beam studies used coating formulations developed in the early 1990's. Coatings developed more recently may perform differently (presumably better) than earlier formulations under similar exposure conditions.

CHAPTER 4: ROLE OF CONCRETE ENVIRONMENT

4.1 CONCRETE CHARACTERISTICS

The concrete environment played a significant role in the corrosion of epoxy-coated reinforcement. There were several concrete characteristics that effected coated bar corrosion: thickness of concrete cover, concrete permeability, concrete consolidation, void and pore structure, moisture content, and presence of cracks. Concrete permeability was not a test variable because all specimens were cast from the same concrete. However, the high water-cement ratio used for the mix made the concrete very permeable. Undoubtedly, performance would have been different if a less permeable concrete mix had been used. The effect of concrete consolidation, and void and pore structure was a very important finding and will be discussed in the following section. The role of cracks is discussed in greater detail in Section 4.3.

It should be emphasized that the concrete environment often played a very complex role in the corrosion of coated bars. Several bars in beam specimens did not corrode at damaged sites, despite being located near cracks, and despite the presence of voids in the surrounding concrete (Figures 4.1 and 4.2). It is possible that concrete voids and pores facing uncorroded sites were locally isolated and not interconnected with the overall pore structure of the concrete. Since concrete is a non-homogeneous material, it is expected that moisture and chloride penetration inside the concrete will be non-uniform and have wide local variations.

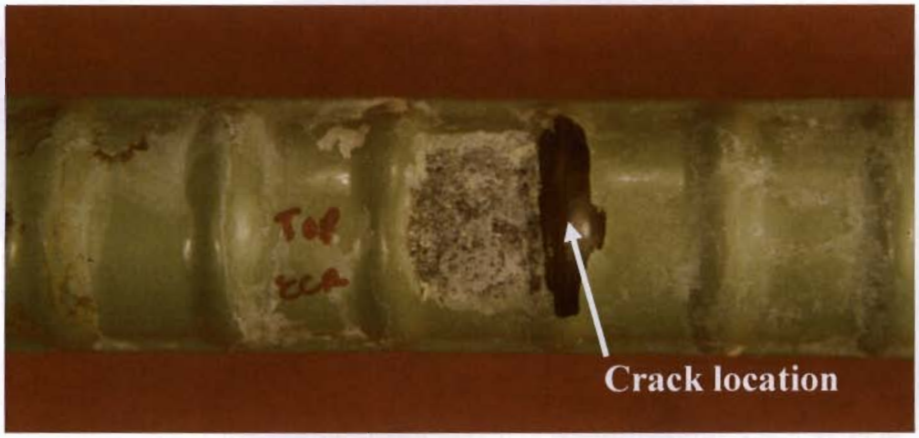


Figure 4.1 Uncorroded damaged spot on coated bar near a crack within the wetted region (beam B10).

The complexity of the concrete environment was evident in polarization resistance measurements in macrocell concrete blocks performed by Chen.[34] Several specimens with uncoated bars had larger corrosion resistance values than some specimens with damaged epoxy-coated bars. In contrast, even though samples from the same-coated bars experienced extensive adhesion loss and poor corrosion performance after 200 days of immersion in 3.5% NaCl solution, uncoated bar samples experienced much more severe corrosion after solution immersion. The concrete used in the study by Chen was of better quality than that used for the present study. Apparently, the improved concrete electrolyte medium protected some uncoated bar specimens.

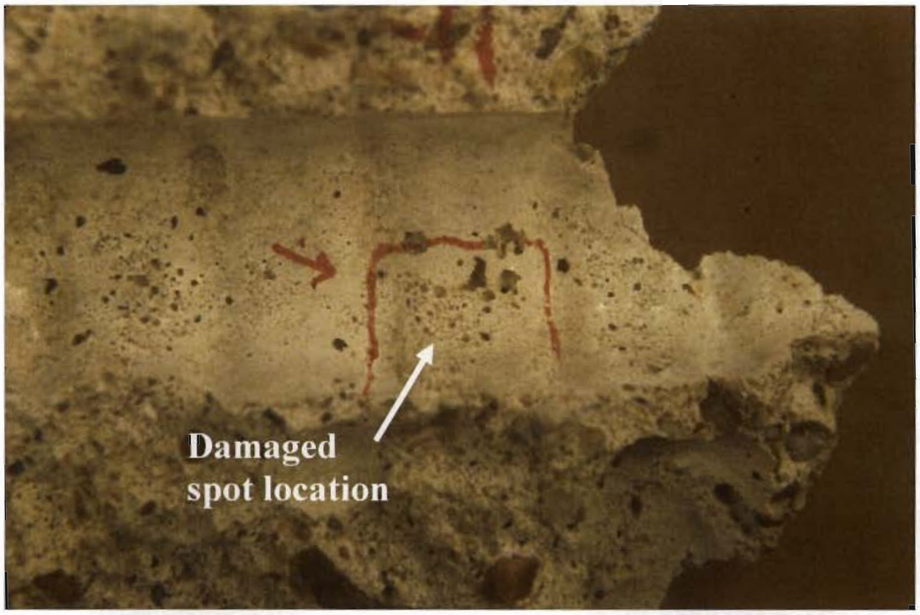


Figure 4.2 Concrete surrounding uncorroded damaged spot within the wetted region (Upper bar of beam B10).

Thickness of concrete cover is one of the most important factors in corrosion of reinforcement. Laboratory specimens and field inspections have consistently shown that a thinner cover leads to more rapid penetration of chlorides and earlier and more widespread corrosion.[33, 48, 55, 56] Cover thickness was not a test variable in the macrocell and beam studies. Nevertheless, the shallow cover of permeable concrete allowed for the relatively early corrosion initiation of macrocell specimens, especially those with uncoated bars.

It is evident that not only is the coating quality important for good performance, but quality of concrete is of equal importance. Concrete of low permeability should be specified and good concreting practices, such as proper placement and consolidation, and adequate curing, should be followed. Concrete cover to reinforcement should be ample. The use of epoxy-coated bars could be questioned when high quality concrete is being used (or vice versa). The severity of the environment should dictate such decisions. If the exposure conditions are particularly severe, high quality concrete and epoxy-coated bars would complement each other and would provide a lines of defense against the damaging effects of chlorides. It should be kept in mind that a low permeable concrete would also be expected to crack, and as was seen in the beam study, concrete cracking leads to early corrosion of reinforcement. If bars were uncoated, the risk of severe pitting corrosion at crack locations would be high. An effective and rigorous crack control method, such as prestressing, would be needed for satisfactory corrosion protection.

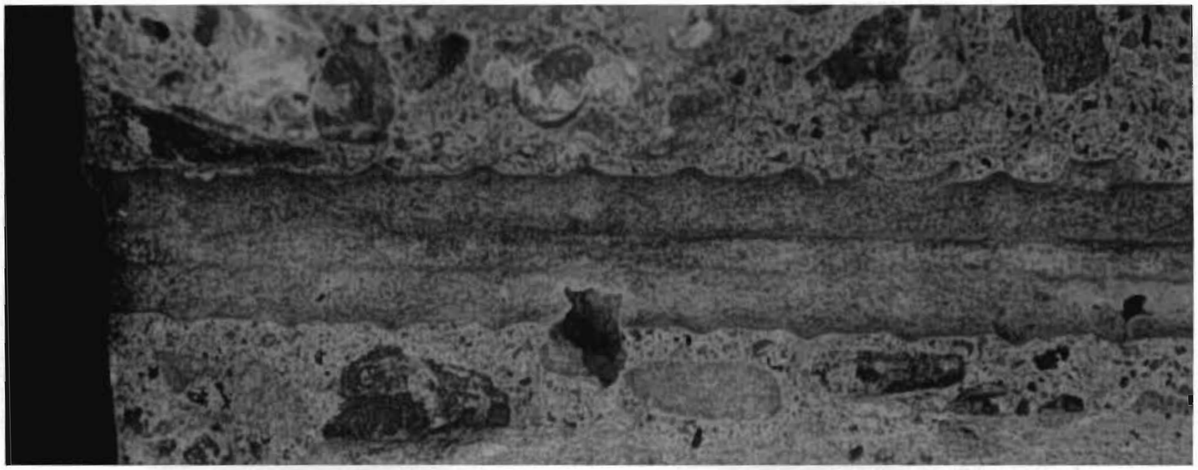
4.2 CONCRETE CONSOLIDATION

The relative position of the surrounding concrete with respect to the bar in the casting position was important in the corrosion performance of epoxy-coated bars. As previously found by Kahhaleh[20] in macrocell and beam specimens, corrosion was more widespread below the bars than above the bars, as shown in Figure 4.3. Due to concrete settlement and the entrapment of air rising to the surface, concrete below the bars was less dense and had more voids than concrete above the bars, and a small gap between the bar and concrete was formed below the bar (Figures 4.4 and 4.5). The presence of this gap and concrete voids provided the space necessary for accumulation of chlorides, moisture, and oxygen, leading to more corrosion at those locations. For this reason, the amount of voids produced during vibration of concrete was qualitatively assessed in the consolidation tests.

(a) Top side.

(b) Bottom side.

Figure 4.3 Comparative performance between top and bottom sides of epoxy-coated bars (macrocell study).



(a) Above the epoxy-coated bar.

(b) Below the epoxy-coated bar.

Figure 4.4 Appearance of bar trace in concrete above and below the epoxy-coated bar (macrocell study).

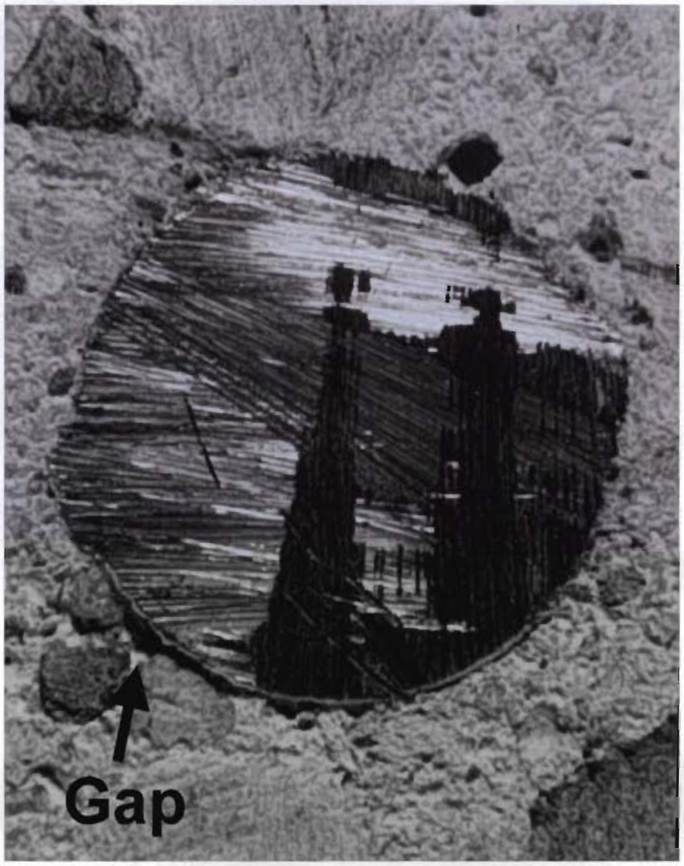


Figure 4.5 Gap between bar and concrete underneath epoxy-coated bar.

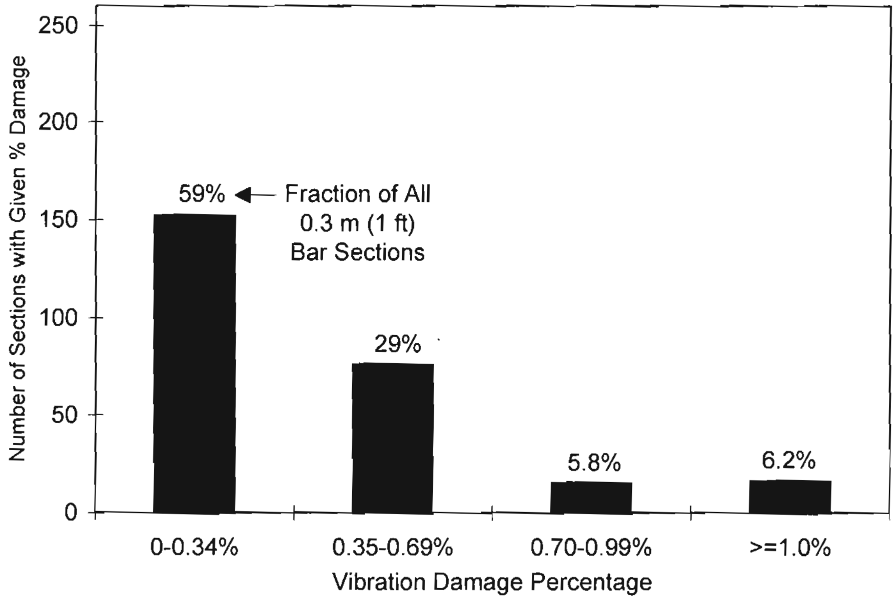
In consolidation tests in concrete, vibrator heads produced considerable damage to coated bars. Typical damage consisted of abrasion and roughening of the surface of the coating (Figure 4.6). Damage to some of the bars was greater than 2% of the total surface area and some bars had damaged spots greater than 6x6 mm, both exceeding the size and percentage of damage limit allowed by some ECR standards. There was greater damage with larger size bars and with small clearances between bars and the forms. Rubber head vibrators caused less damage to epoxy-coated reinforcement than did comparable metal heads (Figure 4.7). As Figures 4.6 and 4.7 show, the metal head vibrator totally removed the coating from a large area of the bar while the rubber head roughened the coating during vibration, but only removed the coating in a few small spots. Under similar conditions and with the same period of vibration, metal heads produced more significant percentages of damage on a coated bar and larger damaged spots than a rubber vibrator head (Figure 4.8). On average, a metal head did almost three times the amount of damage done by a rubber head. In the worst instances, the average damage produced with the metal head was over five times that done with the rubber head. With sufficient periods of vibration and appropriate spacing of insertion points, a rubber head vibrator can satisfactorily consolidate concrete. With both metal and rubber heads, more voids were located under reinforcing bars farther from the point of vibration insertion than were closer to the insertion point, even when the concrete at both locations was adequately consolidated (Figure 4.9). A closer schedule of insertions seems to be required to ensure adequate removal of air voids from beneath reinforcing bars than is required for consolidation of concrete.

Figure 4.6 Damage to coating caused by metal head vibrator on test bar from Phase 1 study.

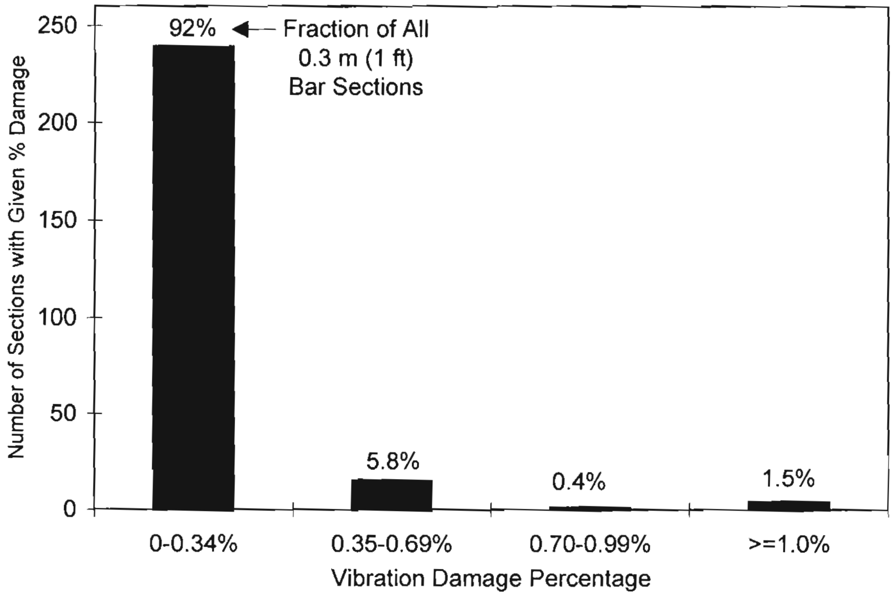
(a) Metal head vibrator.

(b) Rubber head vibrator.

Figure 4.7 Vibration damage to epoxy coating (Phase 2 study).



(a) Metal head.



(b) Rubber head.

Figure 4.8 Histogram of damage percentages for 0.3 m (1 ft) horizontal bar sections from column, footing, and slab specimens.

(a) Air voids close to point of vibrator insertion.

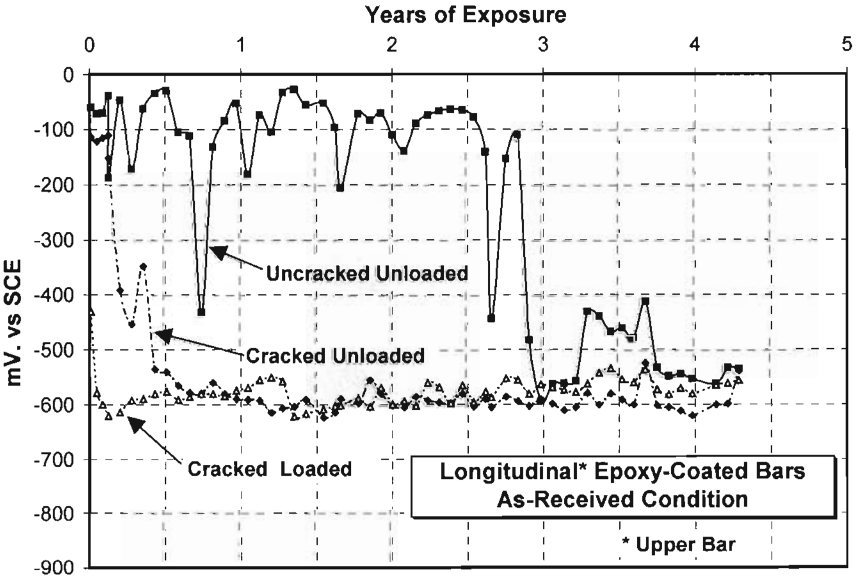
(b) Air voids farther away from point of vibrator insertion.

Figure 4.9 Voids under bars from specimen 20.5 cm (8 in) high consolidated with rubber head vibrator.

4.3 CONCRETE CRACKING

4.3.1 Flexural Cracks

The effect of flexural cracks on corrosion of reinforcement has been debated and was discussed in Reference 27. Some interesting findings arose from the beam exposure study regarding the role of flexural cracks in corrosion. The greatest effect of flexural cracks was in the corrosion initiation of coated bars. Coated bars in cracked members started to corrode much earlier than those in uncracked members. This was indicated by the corrosion potential plots, where uncracked beams had potentials that remained in the region of negligible corrosion (low negative potentials) for a period ranging from about 1 year to 3 years (Figures 4.10 and 4.11). Meanwhile, cracked beams experienced an early drop in the potential to the region of high corrosion (highly negative potentials), as shown in Figures 4.10 and 4.11. As anticipated by the corrosion potentials, the autopsy performed after one year of exposure showed that coated bars in cracked beams underwent more severe and extensive corrosion than bars in uncracked beams. Corrosion was mainly observed in the vicinity of cracks, in close agreement with findings by other researchers.[13, 32, 35, 57, 58] However, as the time of exposure increased, corrosion potentials of uncracked beams suddenly dropped to the same level (region of high corrosion) as bars in cracked beams (Figures 4.10 and 4.11). Autopsies performed after more than 4 years of exposure showed that chloride penetration and corrosion was similar between bars in cracked and uncracked beams. In summary, the absence of flexural cracks in the concrete delayed, but did not prevent the onset of corrosion of coated bars.



Upper Bar

Figure 4.10 Comparison of average corrosion potentials (wetted region) of longitudinal bars with as received condition with different loading conditions (beam study).

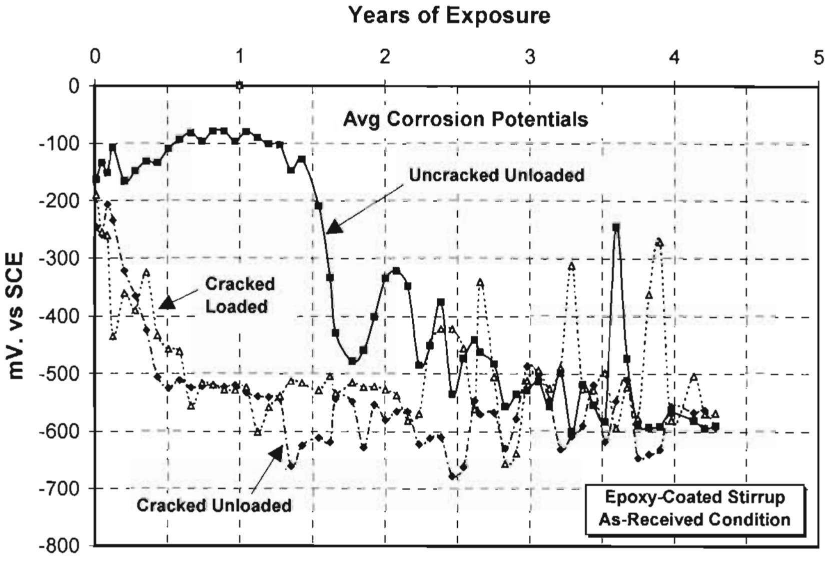


Figure 4.11 Comparison of potentials of stirrups in as-received condition and different loading conditions (beam study).

There was no clear correlation of degree of corrosion with crack width. The effect of flexural cracks was more detrimental to uncoated bars, where very severe pitting occurred at crack locations. Pitting corrosion was so severe that the structural integrity of uncoated bars was adversely effected (Figure 4.12). The most severe pitting in uncoated bars occurred at locations with wider cracks.

(a) Lower black bar of beam B27.

(b) Lower black bar of beam B23.

Figure 4.12 Very severe pitting and loss of cross section on uncoated bars at crack locations.

The above findings support in part the two main claims regarding concrete cracking and bar corrosion. On the one hand, the lack of cracks improved short-term performance by delaying corrosion initiation, supporting the claims of those who espouse crack control. On the other hand, chlorides will inevitably diffuse through uncracked concrete and bars will corrode in the long term. No significant differences in corrosion of coated bars were observed whether flexural cracks originally existed or not, thus supporting the claims of advocates of increasing concrete cover. The presence of cracks in concrete specimens did not increase corrosion of coated bars after 2 years of exposure in synthetic sea water in an experimental research by Salparanta.[31] Apparently, the cracks healed when calcium hydroxide from adjacent concrete leached into them.

It should be kept in mind that the concrete used in the beam study was highly permeable and of poor quality, which could explain the similarities in bar corrosion between cracked and uncracked beams after more than four years of exposure. The overwhelming evidence found in field structures, though, indicates that coated bars corrode more at crack locations.[13, 32, 35, 57, 58] Undoubtedly, a concrete of medium to good quality slows chloride penetration, while cracks provide a direct path to the reinforcement, regardless of concrete quality. The accelerated nature of the beam study does not simulate field conditions. For this reason, the adverse effect of concrete cracks on the corrosion of coated bars should not be assessed solely on the findings from the beam study.

For the case of uncoated bars, crack control advocates have a valid point. Although it was true that corrosion was mostly localized at crack locations, pitting corrosion was so severe that the structural integrity of uncoated bars was adversely effected. Crack width seemed to have some detrimental effect on the severity of pitting.

The conclusion is that if coated bars are used, there seem to be no significant differences in long-term performance between members with and without flexural cracks. For uncoated bars, flexural cracks can have a detrimental effect in the short and long term.

4.3.2 Plastic Settlement Cracks

Cracks that follow the path of reinforcing bars have frequently been observed in concrete structures with epoxy-coated reinforcement.[10] Theoretically, cracks parallel to coated steel bars are more damaging than cracks transverse to the bars, because large amounts of corroding agents can reach the bar surface.[59] These cracks are usually caused by shrinkage and plastic settlement of concrete and develop during the early stages of curing.

In the present study, there were only three macrocell specimens with plastic settlement cracks, and corrosion-induced cracks propagated from the initially observed cracks. However, based on the total number of corroded specimens, it is obvious that corrosion also occurred in many other specimens that did not have initial plastic settlement cracks. Cracks produced by plastic settlement were very narrow and did not result in greater chloride content than that measured in specimens without initial cracks.

4.4 CHLORIDE PENETRATION IN CONCRETE

In the macrocell study, chloride penetration in concrete over time was monitored by measuring the acid-soluble chloride content in companion concrete prisms at different depths. Chloride content at the bar location vs. time is plotted in Figure 4.13. The chloride contents shown are not the chloride contents in the actual specimens, but give a good indication of chloride penetration with time because the samples were made from the same concrete mix used for the specimens and the exposure cycles were the same. Chloride penetration increased with time, and the penetration was accelerated in the last 2.5 years of exposure. The increase was significant deeper into the concrete. The chloride content at the level of the coated bars was quite high towards the end of the exposure period.

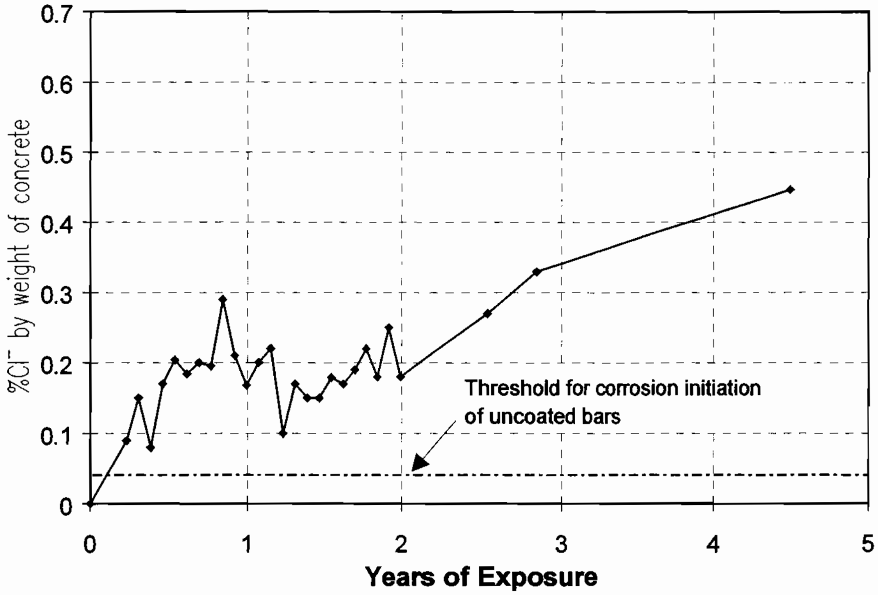


Figure 4.13 Chloride content at the bar location (3.5 cm [1.375 in.] depth) vs. time of exposure. Chloride measurements were taken from concrete blocks cast with same concrete mix as in macrocells.

By comparing the trends of chloride contents and corrosion currents, Kahhaleh estimated that chloride concentrations associated with the onset of corrosion of uncoated bars ranged from 0.08 to 0.12% by weight of concrete.[20] The corresponding average chloride content for onset of corrosion of epoxy-coated bars was estimated at about 0.18%, and it took about 6 months to one year of accelerated exposure to reach that level. In general, it was difficult to find a clear relationship between increases of chloride content and spikes in the corrosion current. The following two observations illustrate this point:

1) The chloride content remained relatively constant from 6 months to 2 years of accelerated exposure (Figure 4.13). Within that period, a number of specimens experienced a gradual increase of current (Figure 2.11 and 2.12). Apparently, the presence of a steady level of chloride ions had a corrosive effect over time.
2) The steady increase of chloride content observed in the last 2.5 years of exposure was not associated with an increase in the amount of current for the majority of the specimens.

The average chloride concentrations in macrocell specimens at the level of the steel was in the order of 0.34% by weight of concrete, while average chloride concentrations in the wet zone of beam specimens (non-crack locations) at the level of upper or lower bars ranged from 0.53% to 0.88% by weight of concrete. Reported chloride thresholds to trigger corrosion of uncoated steel are in the range of 0.02-0.05% by weight of concrete.[20] These numbers give a clear idea of the severity of the exposure conditions for both coated and uncoated bars, especially in beam specimens.

Table 4.1 shows that average chloride contents in beam specimens were higher after 4.3 years than after one year of exposure. In specimens examined at the end of one year, chloride contents tended to be higher at crack locations. However, as can be seen in Table 4.1, the difference in chloride concentrations between crack and non-crack locations within the wet zone after 4.3 years decreased or disappeared, especially in groups I and II. Clearly, chloride diffused and penetrated within the concrete so extensively that chloride distribution was more uniform after more than four years of exposure.

Table 4.1 Average chloride concentration (Percentage by weight of concrete) in beam specimens in the wet zone at two depths from the top surface, after 1 and 4.3 years of exposure.

Group No.	Depth * (mm)	Wet Zone		At Crack in Wet Zone	
		1 Year	4.3 Years	1 Year	4.3 Years
I	50 - 75	0.114	0.53	0.39	0.69
	127 - 152	0.154	0.59	0.43	0.55
II	50 - 75	0.302	0.57	0.595	0.56
	127 - 152	0.356	0.60	0.505	0.53
III	50 - 75	0.59	0.82	0.795	0.95
	127 - 152	0.55	0.88	0.75	1.08

Upper and lower bar location

CHAPTER 5: CORROSION AND SERVICE LIFE

5.1 CORROSION MECHANISM

The precise corrosion mechanism of coated bars inside chloride-contaminated concrete is still not well understood. The mechanism proposed in Reference 27 was based on a re-construction of possible sequences of events that best conformed to the observed deterioration pattern of the bars at the end of exposure. Previously proposed mechanisms by others,[20, 46, 60] and the corrosion process of coatings described in the literature,[61] were taken into account. The corrosion pattern and products observed in both macrocell and beam studies were similar to those found in other studies.

Perhaps the most important implication of the corrosion mechanism is the role of coating defects and damage on corrosion initiation of coated bars. Another aspect is the observed adhesion loss that may be produced by cathodic reactions and moisture action. As a result, the importance of reducing or eliminating coating imperfections and damage, and of improving coating adhesion strength has been emphasized. Undoubtedly, if coating integrity and adhesion are deficient, the epoxy coating will not satisfactorily protect reinforcing bars from corrosion.

Opponents to the use of epoxy coating have stated that even perfectly coated and flawlessly handled reinforcing steel will begin to fail once salt penetrates the concrete and reaches the rebar. This is due to the inability of existent epoxy coatings to achieve long-term adherence to the rebar, according to detractors of epoxy coating.[39] The opponents to ECR conclude that since the epoxy coating will be debonded from the steel when chlorides arrive, the epoxy coating will provide no additional service life. Some researchers have based their conclusions on the observation that "when the coating has debonded, the rate of underfilm corrosion is faster than [that of] bare steel in concrete." Such observation has been based on research results performed by Sagüés.[46]

The experimental evidence of the study reported herein does not support the above assertions. Although underfilm corrosion of epoxy-coated bars is a common phenomenon documented in several studies, including this study, underfilm corrosion tends to be more uniform, less severe, and progresses more slowly than pitting corrosion in uncoated steel. Epoxy coatings generally start to disbond at discontinuities or imperfections. It would take a much longer time for a coating without defects and adequate thickness to disbond, since water would have to penetrate through the bulk of the coating. Evidence provided by scanning electron microscopic examination of some epoxy chips from bars in chloride-contaminated concrete indicated that chlorides did not penetrate the epoxy coating, but reached the steel surface through breaks in the coating.[52] In addition, the rate of corrosion when chlorides reach the steel substrate would be low, because of the very limited oxygen availability provided by the "flawless" coating. Any potential macrocell action would be significantly hampered by the electrical isolation and resistivity provided by the "perfect" coating. Research by the University of Western Ontario demonstrated that reduced adhesion does not compromise corrosion performance providing that the coating remains intact.[38] In a short immersion test discussed in Report No. 1265-6, samples with poor adhesion before chloride arrival did not corrode any faster than those with better initial adhesion.[26]

5.2 FIELD PERFORMANCE OF EPOXY-COATED REINFORCEMENT

Florida DOT's decision to discontinue the use of epoxy-coated reinforcement[62] and the controversy stirred by Clear's statements questioning the effectiveness of epoxy-coated reinforcement[5] was a shock to the epoxy coating industry. Consequently, recommendations made by the Federal Highway Administration (FHWA) led state DOT's around the USA and Canada to re-evaluate the existing infrastructure with epoxy-coated reinforcement.[48] Field and laboratory studies from 92 bridge decks, two bridge barrier walls, and one noise barrier wall were summarized in Report No. FHWA-RD-96-092. The age of the bridges was from 3 to 20 years. The main conclusions are summarized in the following paragraphs.[48, 63]

The majority of inspected bridge decks had an overall good condition. Very few decks had delaminations and/or spalls, and most were not associated with epoxy-coated reinforcement. Concrete cracking was prevalent but did not appear to be corrosion-related. The chloride content at the rebar level for most bridges was equal to or greater than the corrosion threshold for uncoated steel. No signs of corrosion were found on 81% of extracted bar samples despite chloride concentrations above 3.8 kg/m^3. More corrosion was found on bars at crack locations and than at uncracked locations. Coated bars did not corrode at uncracked locations even with high chloride contents of up to 7.6 kg/m^3. Corrosion was also more prominent at areas with shallow concrete cover. Moisture and a high chloride concentration were the principal agents for corrosion of coated bars. Coating disbondment was observed at both corroded and non-corroded areas, and was the result of prolonged exposure to moisture. Coating adhesion decreased with time of exposure. The number of coating defects and the amount of disbondment influenced corrosion performance. Corrosion and coating disbondment typically occurred at locations of visible holidays or bare areas. The overall conclusion was that "epoxy-coated reinforcement has reduced, if not completely eliminated, the deterioration of deck concrete resulting from corrosion of reinforcing steel."[48, 63]

In general, the main conclusions from the macrocell and beam studies reported herein are very similar to findings observed in field bridge decks. Regarding the role of concrete cracks, conclusions from field observations agreed closely with the findings after one year of exposure of beam specimens. Less agreement exists after 4.3 years of exposure of beam specimens (corrosion was similar for bars in both cracked and uncracked beams). Differences in concrete permeability and the accelerated nature of the experiment could account for the change. Concrete for beam specimens had a high water-cement ratio and the cyclic exposure was very severe and continuous. Chloride content at bar location in uncracked beams was as high as 11.8 to 13.8 kg/m^3, versus 7.6 kg/m^3 measured in uncracked field concrete, and 9.5 to 16 kg/m^3 for cracked field concrete. It is possible that with longer times of exposure, uncracked portions in field structures would start to show signs of corrosion as additional chlorides diffused. The drawbacks of laboratory specimens designed for accelerated exposure which lead to their inability to reflect field service life are highlighted by such comparisons.

Two particular cases are worth mentioning. In California field decks, corrosion did not occur when there were no defects in the coating, even with high chloride concentrations of up to 4.6 kg/m^3.[48] This finding closely agreed with what was observed for coated bars in beam specimens, emphasizing that the measured chloride content in the respective beam was significantly higher (12.2 kg/m^3). In contrast, no significant corrosion was observed in Virginia decks despite the presence of numerous holidays and bare areas in the coating.[48] This phenomenon was similar to the lack of corrosion at several damaged areas frequently observed in beam bar specimens.

Another field survey of 18 bridge decks in 14 states was reported by CRSI.[64] All of the inspected decks first used epoxy-coated bars in the 1970's, and each was the first known installation of coated bars in its state. All bridges were located in the areas of freeze/thaw where deicing chemicals were used. The survey was completed in 1993 and repeated in 1995-1996. State inspection records of bridges included a rating from 0 to 9.9 developed by the FHWA, with the top grade reserved for new condition. Ratings of 8, 7, 6, and 5 represent deck conditions from very good to satisfactory, in descending order. All decks were rated from satisfactory to very good, as illustrated in Table 5.1.[64]

Table 5.1 Bridge deck condition based on FHWA ratings. Ratings of 9 indicate new condition. Ratings of 8, 7, 6, and 5 indicate very good to satisfactory condition in descending order.[64]

State	*Mat*	*Year Opened*	*Initial Grade - Year*	*Latest Grade - Year*	*Deck Maintenance*
Iowa	Top	1975	8 - 1975	7 - 06/95	0
Illinois	Top	1977		7 - 12/95	0
Indiana	Top & Bottom	1976	7 - 1976	6 - 01/96	0
Michigan	Top & Bottom	1976	8 - 1980	7 - 10/95	0
	Top & Bottom	1976	8 - 1980	7 - 08/94	0
	Top & Bottom	1976	8 - 1980	7 - 08/94	0
Kansas	Top	1977	8 - 1977	7 - 1995	0
Minnesota	Top	1973	8 - 1973	8 - 08/95	0
Nebraska	Top	1976	N/A*	8 - 1996	0
	Top	1975	9 - 1975	7 - 1996	0
Wisconsin	Top	1976	9 - 1976	8 - 08/95	0
	Top	1976	9 - 1976	8 - 08/95	0
Maryland	Top & Bottom	1974	9 - 1974	7 - 07/96	0
Kentucky	Top	1975	7 - 1981*	7 - 06/95	0
Pennsylvania	Top	1973	6 - 1989*	5 - 07/95	0
Missouri	Top	1974	9 - 1973	7 - 12/95	N/A
Ohio	Top	1974	8 - 1985*	7 - 03/96	0
West Virginia	Top	1973	9 - 1973	6 - 02/96	0

Initial grade unknown** **n/a= not applicable** **Data compiled 11/26/96

Another study of 19 parking ramps built with epoxy-coated reinforcing steel from 1980 to 1985 was conducted by CRSI.[65] The ramps were located in Wisconsin, Minnesota, Michigan, Nebraska, and South Dakota. Although first used during the 1970's, epoxy-coated steel was not used in parking ramps until 1980. Therefore, the ramps surveyed were the first built with ECR. Twelve ramps were visually inspected. Ramp owners and engineers were interviewed, and supporting documentation reviewed for all 19 ramps. Limited corrosion with epoxy disbonding was noted in only one ramp and was attributed to inadequate concrete cover and construction errors. The study concluded that all ramps were performing adequately, with little or no damage since construction. In contrast, three parking garages with uncoated bars in Minnesota experienced extensive steel corrosion and delaminations, requiring extensive patching or replacement.[65]

It should be pointed out, though, that many of these parking structures had other protective measures, such as concrete with low water/cement ratios, corrosion inhibitors, microsilica concrete, and concrete sealers. In addition, chloride levels in most cases were below the threshold value for corrosion initiation, and most slab systems were postensioned to reduce concrete cracking. Therefore, it is difficult to assess the specific contribution of epoxy-coated steel in the overall performance of the structures. The three garages with uncoated reinforcement were older (built in 1979, 1974, and 1963) and no mention was made of any other protective measures.

5.3 CORROSION MONITORING

Measurement of corrosion current for macrocell specimens was very useful and correlated well with observed corrosion. Corrosion potentials were useful in monitoring the performance of coated bars in beam specimens in three aspects: 1) assessing the likelihood of bar corrosion, 2) pinpointing zones of high probability of bar corrosion, and 3) detecting shifts in behavior from passive to active conditions. The main limitation in interpreting corrosion potentials was that, as expected, they gave no indication of the rate, severity, and extent of corrosion. Potentials shifts to more negative values indicate that corrosion cells were operating and not necessarily that more rust is accumulating.

Average current densities versus average corrosion potentials for all macrocell specimens are plotted in Figure 5.1. All specimens with potentials between -200 and -300 mV versus SCE had average current densities smaller than 0.015 $\mu A/cm^2$. Bars with corrosion potentials between -300 and -400 mV versus SCE had average current densitites between 0.025 $\mu A/cm^2$ and 0.194 $\mu A/cm^2$. Corrosion potentials in the range of -400 to -500 mV versus SCE correlated with average current densities of 0.115 $\mu A/cm^2$ and 0.314 $\mu A/cm^2$. Finally, control specimens, which had corrosion potentials between -500 to -550 mV versus SCE, experienced average current densities between 0.418 $\mu A/cm^2$ and 1.02 $\mu A/cm^2$. With this limited data, corrosion potentials between -200 and -300 mV versus SCE correlated with negligible corrosion, potentials from -300 to -500 mV versus SCE related to low to moderate corrosion, and potentials more negative than -500 mV versus SCE correlated with severe corrosion.

The correlation between potentials and corrosion was not as clear in the beam study as it was in the macrocell study. Figure 5.2 illustrates the relation between corrosion activity and steel potential for epoxy-coated and black bars from tests in the beam study. Data from beams autopsied after one and 4.3 years were used for the correlation. Although there was a tendency for readings to become more negative as corrosion performance in the potential range of -300 to -550 mV SCE. For black bars, the overlap of bars with varying corrosion performance was in the potential range of -255 to -535 mV SCE. However, if the two bars showing the most negative potentials in uncorroded zones are excluded, the overlap drastically reduces [see Figure 5.2(b)].

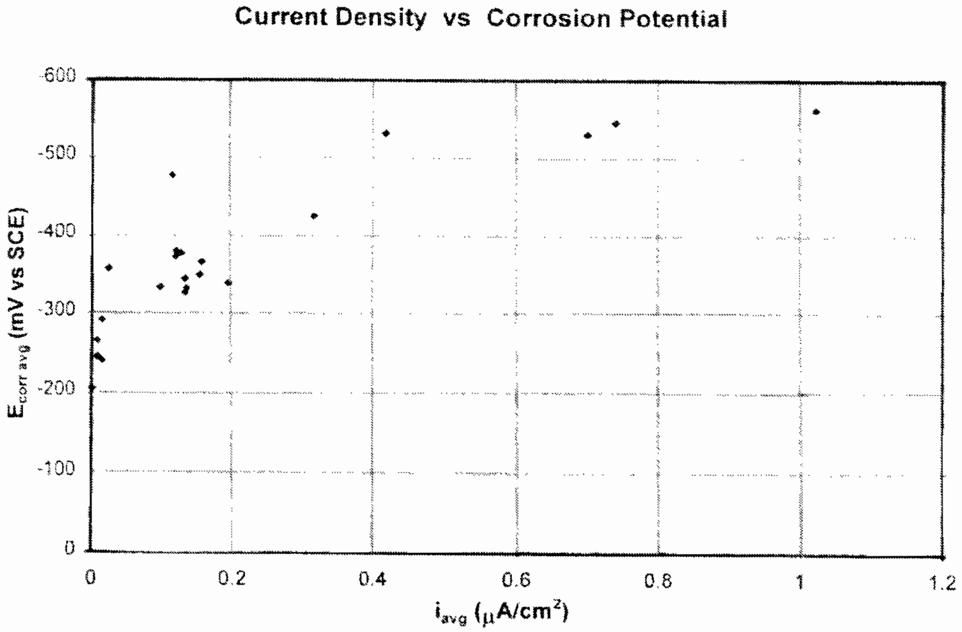
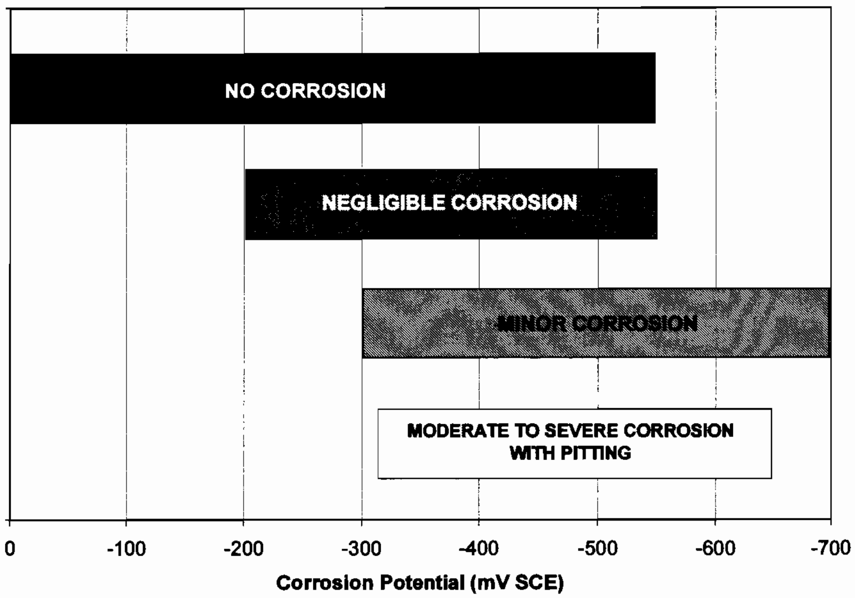
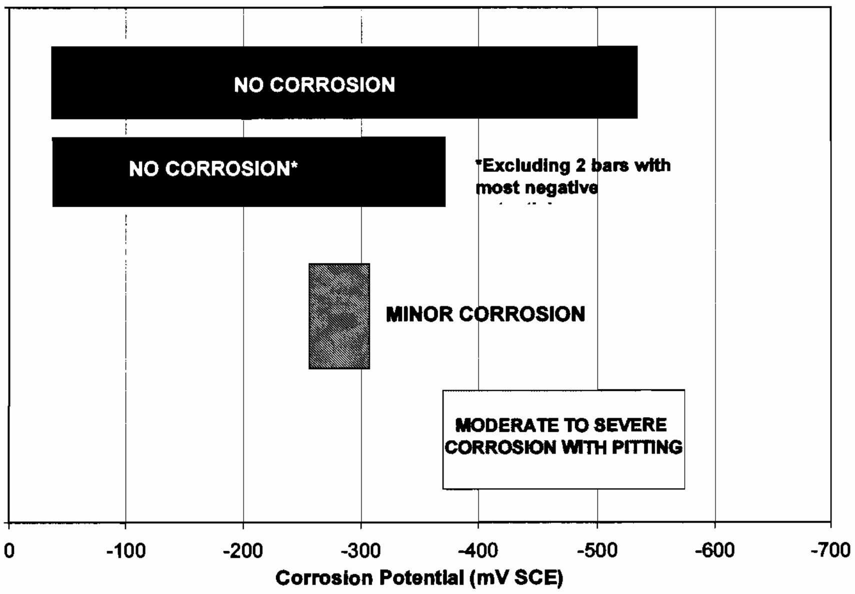


Figure 5.1 Average current densities vs. average corrosion potentials for macrocell specimens



(a) Epoxy-coated bars



(b) Black bars

Figure 5.2 Relation between corrosion activity and steel potential from tests in this study (beams autopsied after one and 4.3 years of exposure).

Measured potential regions that correlated with minor, moderate, or severe corrosion (without overlapping with the "no corrosion" range) for coated bars in the beam study were -550 mV SCE or more negative. This range was more negative than the respective potential range that ASTM C876 suggests as indicating high probability of corrosion for uncoated bars (-273 mV SCE or more negative). Coated bars in macrocells, with corrosion in the -300 to -500 mV SCE range were closer to the ASTM C876 range for high probability of corrosion. Interestingly, uncoated bars tended to have potentials (-375 mV SCE to -570mV SCE) less negative than those for uncoated bars in macrocells (-500 to -550 mV SCE). Treadaway and Davies found more negative potentials in coated than uncoated bars. Their finding was somewhat in agreement with the tendency observed in the beam study, but in disagreement with what was observed in the macrocell study. The highly negative potentials of epoxy-coated bars suggests that corrosion was cathodically controlled in those bars.[33] The presence of the coating significantly reduced diffusion of dissolved oxygen to the steel surface, and the reduction process became diffusion of dissolved oxygen to the steel surfance, and the reduction became diffusion or concentration controlled.

In a field study on bridge decks in Minnesota, there were many areas without corrosion and with potentials more negative than -350 mV CSE (-273 mV SCE). In general, areas with potentials more negative than -400 to -500 mV CSE (-323 to -423 mV SCE) often underwent severe corrosion of coated steel.[32] Hededahl and Manning reported high negative potentials (in the range of -450 to -463 mV SCE) on coated bars without visual evidence of corrosion activity.[66] In general, corrosion potential ranges that are associated with coated bar corrosion varies among different studies. One reason for such differences is the difficulty in relating bar corrosion assessments made by different researchers. Frequently, assessments of bar corrosion are rather subjective, making comparisons difficult. A bar that looks "severely corroded" to one researcher may look "slightly corroded" to another researcher.

Unlike the findings after one year of exposure, maximum potential gradients after 4.3 years did not prove to be very useful nor reliable indicators of corrosion severity of coated or uncoated bars in beam specimens. Overall, maximum potential gradients above 200 mV did not seem to be associated with any particular level of corrosion activity in epoxy-coated bars after 4.3 years of exposure. Corrosion in such bars varied from negligible to moderate. For uncoated bars, maximum potential gradients above 300 mV seemed to be conducive to severe pitting corrosion. Interestingly, Sharp et al. reported a survey where the assessment of potential differences and the rate of potential change gave a reliable diagnosis of corrosion rather than any absolute value of potential.[67] However, after monitoring potentials on beam specimens for up to five years, the pattern of surface potentials was found quite unrelated to the corrosion state, as opposed to their earlier work. In all cases, corrosion potential values had little correlation with corrosion condition.[67]

The ASTM C876 test method was developed for measuring half-cell or corrosion potentials of uncoated reinforcement in concrete. Therefore, care and judgment are needed when measuring and interpreting corrosion potentials in structures with coated reinforcement. The development of a unified criterion for adequate interpretation of potentials for coated reinforcement is needed. For adequate assessment of corrosion, it is recommended that other corrosion monitoring techniques be used along with corrosion potentials. Three-electrode linear polarization resistance and electrical resistivity measurements have been used in field structures.[32, 48, 66, 67] Electrochemical impedance spectroscopy (EIS) has been used in the laboratory but seems to be too complex and sophisticated for field applications.[34]

Corrosion potential, linear polarization, and EIS measurements were conducted in a field study on bridge decks in Minnesota.[32] Overall, polarization resistance and impedance testing were found ineffective for locating areas of bar corrosion or poor coating, and were deemed unsuitable for routine field surveys. In general, areas with low resistance exhibited coating damage but there was significant scatter of data. Corrosion potential, polarization resistance, and EIS tests taken in the field produced significantly different results than tests taken at cores in the laboratory, although the relative performance between specimens was maintained. Presumably, field measurements are affected by factors such as concrete resistance, uncoated bottom reinforcement, areas of bar damage away from core locations, and area effects. In addition, there was poor correlation between resistance as measured by AC impedance and corrosion potential data. The study recommended that future refinements to linear polarization and EIS were needed before widespread implementation of these techniques on decks containing epoxy-coated steel.[32]

5.4 TEST CONDITIONS AND SERVICE LIFE

The durability studies on macrocell and beam specimens were intended to be accelerated. The type of exposure regime was very aggressive and consisted of uninterrupted wet and dry cycles of ponding or irrigation of a highly concentrated chloride solution that resulted in high chloride contents inside the concrete at the end of exposure. It is difficult to determine how the selected test exposures relate to more realistic environments in the field, but it is expected that the test exposures are much more severe, especially when comparing the chloride content of the lab specimens with typical chloride contents reported in field investigations.

In addition to an aggressive test environment, the following characteristics were selected in the design of the specimens to promote early corrosion: concrete with high permeability, shallow concrete cover, and little curing of concrete. For macrocell specimens, a large cathodic (bottom) steel area was coupled to a small anodic (top) steel area to produce a large corrosion driving force, and the distance between anode and cathode was reduced to facilitate ionic flow. For beam specimens, weekly loading and unloading was intended to increase the flow of chlorides and oxygen towards the bar location.

The aggressive nature of the test exposure and the characteristics of the specimens created a somewhat artificial condition that made it difficult to correlate the length of the exposure during the test with an equivalent time of service in the field. The macrocells were subjected to a total of sixty 28-day cycles of wetting and drying during the 4.5 years of exposure, and the beams were subjected to 112 14-day cycles during 4.3 years. The years of exposure reported herein are not the same as years during service conditions, and it would be expected that the adverse effects produced under the test conditions during one year of cyclic exposure would be equivalent to the effects produced after a greater number of years under field exposure conditions. The precise relationship between the effects produced by test and field conditions will only be determined by monitoring the performance of companion laboratory and field specimens.

CHAPTER 6: SUMMARY OF FINDINGS FROM THE STUDY

6.1 HOLIDAY DETECTION [21]

- Holiday detectors are not reliable for detecting voids or pinholes in the epoxy coating. Inconsistent results were produced by varying sponge moisture and operator.
- The slower the speed of detection, the higher the number of responses obtained.
- The number of responses obtained can only indicate possible defects in the coating, but not the location and size of existing defects.

6.2 IMMERSION TEST OF BENT EPOXY-COATED BARS [21]

- Corrosion initiated at any damage to the epoxy coating, such as pinholes, cracks, and large exposed areas. Corrosion progressed under the coating from damaged areas and holidays.
- All patched areas showed corrosion activity after a few weeks of immersion.
- Corrosion on damaged spots introduced during bending on the inside of bends was as severe as on the outside.
- Properly equipped mandrels greatly reduced the amount of coating damage and subsequent corrosion of bent bars on the inside of bend.
- Smaller bars (#4) were more susceptible to hairline cracking when bent to a smaller radius than larger bars (#8).

6.3 COATING ADHESION [26]

- Hot water and knife adhesion tests can be used to evaluate coating adhesion of epoxy-coated reinforcement. The usefulness of such tests in discriminating and identifying good from bad quality coatings (quality control) was demonstrated in this study. The methods do not require special or sophisticated equipment and reduce the subjectivity inherent in prior tests.
- There was poor correlation between adhesion tests and bend tests. Bend tests were not reliable indicators of coating adhesion and were more a measure of coating flexibility.
- There was good agreement between results from the more controlled and objective hot water and adhesion tests and those from the more subjective TxDOT peel test. Because of its simplicity and quickness to perform, the TxDOT peel test seems to be a good option and is recommended, especially if a calibrated knife is not available.
- Test results from immersion in salt solution were inconclusive. No clear correlation was found between adhesion strength and size of corroded area. Additional long-term research is needed to determine the effect of adhesion strength on corrosion protection of epoxy-coated reinforcement. Presently, there is no clear understanding of the relationship between these two properties.

6.4 COATING REPAIR [25]

- Performance of patching materials was greatly dependent on their consistency and texture. Materials of greater viscosity and shorter curing time produced patches of greater thickness. Thicker patches performed better than thinner patches.
- Patching materials that provided the best performance had poor workability and were difficult to use.

- Patched bar ends were very vulnerable because of difficulty in patching sharp bar end edges. Presence of burrs and slag also impaired patch effectiveness.
- Flame-cut and patched bar ends had the worst corrosion performance.
- Bar ends patched by the coating applicator showed very poor performance.
- There was no clear effect of the cleaning and application procedures and size of damaged area on the patch material performance.

6.5 CONCRETE CONSOLIDATION [21, 22]

- Epoxy coating can be substantially damaged during placement and consolidation of concrete by internal vibrators.
- The use of rubber-head internal vibrators significantly reduced the amount and size of damage in the coating.
- Vibration tests in fresh concrete showed that the metallic head vibrator imparts slightly better consolidation to the concrete than the rubber head vibrator. Greater horizontal acceleration, larger radius of influence, and 10% higher frequency were achieved with the metal head.
- More concrete voids next to the coated bar surface were observed at greater distances from the point of insertion of the vibrator.
- Both metallic and rubber head vibrators can provide good concrete consolidation if good practice is followed.
- Concrete voids were always observed, even when concrete was considered to be well consolidated. Typical radii of influence used on construction may not remove voids beneath bars.

6.6 MACROCELL CORROSION [23]

- Coated bars performed much better than uncoated bars. Based on the measured charge flux, the worst coated bar performed about 2.3 times better than an uncoated bar.
- Bars with greater and more frequent damage tended to perform worse. Exposed areas played an important role in the corrosion initiation and mechanism of coated bars.
- The combination of bar fabrication and coating damage was detrimental to corrosion performance. Corrosion in most bars spread from the outer and lower bends towards the inner bend and straight bar legs.
- Regardless of the level of corrosion, the epoxy coating extensively debonded from the steel substrate, especially at the bent portion.
- Patching coating damage slightly reduced but did not prevent corrosion in most specimens. Corrosion in bars with exposed areas tended to be slightly more severe and corrosion in bars with repaired areas tended to be more widespread. The patching material used in the macrocell study had a very thin consistency and is no longer produced.
- Patching damaged areas on the outside of the bend only was not sufficient. Corrosion also propagated from mandrel indentations at the inside of the bend and at the outside of one straight leg.
- Bars with coating cracks and exposed areas less than 1% experienced increasingly higher corrosion currents at the end of 4.5 years.

- Larger bars experienced higher corrosion than smaller bars. Possible factors included differences in the concrete environment caused by the bar size, influence of concrete cover to bar diameter ratio, and discrepancies in the metallurgy between the two bar sizes.
- No clear trend was found in the performance of bars with different deformation (bar lug) patterns.
- Quality and consolidation of the surrounding concrete influenced the corrosion of epoxy-coated bars. More corrosion was observed at surfaces surrounded by less dense, very porous concrete with more and larger voids (bottom side of coated bars).
- The practice of mixing coated and uncoated bars in the same concrete member may lead to undesirable performance. Any incidental continuity between coated and uncoated bars could establish large macrocells that would be conducive to extensive corrosion. Uncoated bars can corrode regardless of electrical continuity conditions.

6.7 BEAM CORROSION [24]

- Both coated longitudinal bars and stirrups underwent less severe corrosion than uncoated bars within the same specimen.*
- Uncoated bars experienced severe pitting with substantial loss of cross-sectional area at crack locations.
- Greater coating damage led to more corrosion. In straight bars, epoxy coating with no visible damage provided excellent protection, while bars with 3% damage to coating underwent moderate underfilm corrosion. As-received and patched stirrups performed better than stirrups in the as-received condition.
- Patching damaged coating slightly improved performance but did not completely prevent corrosion.
- Patching bar cut ends was ineffective. Underfilm corrosion spread from patched ends.
- The main influence of concrete cracking and the loading producing cracks was on the time to corrosion initiation. Coated bars in cracked specimens corroded much earlier than those in uncracked beams, but in the long term, corrosion of coated bars from cracked and uncracked beams was similar. The absence of cracks delayed but did not prevent the accumulation of significant amounts of chlorides at bar locations.
- The effect of concrete cracking was particularly detrimental to uncoated bars. Severe pitting corrosion was observed in several uncoated bars at crack locations.**
- Coated bars tended to corrode slightly more when surrounded by less dense, more porous concrete.
- Measured corrosion potentials did not correlate with rate and severity of corrosion. Potential difference between wetted and dry regions did not accurately reflect corrosion severity.

---

[*] As stated in Report No. 1265-4 [Reference 24], there were no control beam specimens completely reinforced with black bars that allowed a direct comparison of the performance of coated vs. uncoated bars. The comparison presented herein should be cautiously interpreted.

[**] Uncoated bars were in the compression side of the beams, away from the wet portion. The effect of cracks on the performance of black bars located within the wetted region of the beams would likely have been worse.

CHAPTER 7: IMPLEMENTATION – GUIDELINES AND RECOMMENDATIONS

7.1 GENERAL

Damage to epoxy coating was the most significant factor affecting corrosion performance in Project 1265. Bars with coating in good condition, without any visible damage, performed best. Epoxy-coated bars can provide satisfactory corrosion protection but proper quality control measures and proper design and construction practices have to be implemented to preserve the integrity of the epoxy coating. Proposed guidelines for design and construction practice of epoxy-coated reinforcement are included in Appendix A. Many of the recommendations in the guidelines were based on the findings from this study. Relevant provisions from ASTM,[43, 44] TxDOT,[40] CRSI,[36] and other documents from the literature were incorporated. Suggested guidelines are based on a compilation from such documents complemented by results from this research. The proposed guidelines should serve as an aid to TxDOT engineers involved in the specification, design, construction, inspection, and maintenance of concrete bridge and other transportation structures.

7.2 IMPLEMENTATION BY TEXAS DEPARTMENT OF TRANSPORTATION

The Texas Department of Transportation (TxDOT) uses approximately 18 million pounds of epoxy-coated reinforcement annually. The main use is in bridge structures with additional uses in concrete pavements and retaining walls.[68] TxDOT has been satisfied with research results of the present project and believes that epoxy-coated reinforcement can ensure satisfactory performance of highway structures in Texas. During the course of the present study, TxDOT has continually improved its Standard Specifications based on preliminary research findings. TxDOT specifications for epoxy-coated bars have been in some respects more stringent than ASTM specifications, especially before recent changes were introduced by ASTM. The specifications require coating applicators to be approved and "quality monitored" by the Materials and Test Division when furnishing epoxy-coated bars for TxDOT projects.[68] Although subjective, TxDOT has one of the few specifications that incorporated a knife adhesion test (termed "peel test") for bar elements too small for the bend test. Another aspect of this study was the development of a reliable and practical test to assess the adhesion strength of the epoxy coating. Such tests should be performed quickly, repetitively, and economically at the coating plant and should produce results that can be objectively interpreted. A proposed knife adhesion test is included in Appendix A of Report 1265-6.[26]

TxDOT has a policy termed "belt and suspenders" approach for the corrosion protection of the Texas highway infrastructure where increased durability is desired, which consists of the use of multiple corrosion protection measures in addition to epoxy-coated reinforcement. Such measures include increased concrete cover, use of type II cement, high quality concrete with decreased permeability, penetrating concrete sealers, and the use of prestressed members. TxDOT estimates that the use of all these measures increases the total cost of the structure by approximately 5% for an anticipated 25-year increase in service life to 75 years.[68,69] Based on research results that were discussed in this report, TxDOT encourages the use of epoxy-coated reinforcement throughout the same member. Epoxy coating increases the cost of the reinforcement by 25% to 50%. Epoxy-coated reinforcement was used throughout both the superstructure and substructure of the Redfish Bay and Morris and Cummings Cut bridges near Corpus Christi, Texas.[68, 69] The total bridge cost in these structures increased to about 1.8%.[68]

One of the main thrusts of the project was the implementation of research findings for field operations. Research findings are often presented in research reports that few people read and the findings are not implemented. With this in mind, TxDOT has developed a series of posters that contain the most relevant research recommendations in terms of field practice. The objective is to place these posters at visible locations on the job site, so that construction workers can read them and become aware of the proper procedures to handle and repair coated bars. These posters are similar to those produced by the CRSI in technical content, but were artistically designed in a more appealing form using down-to-earth language to attract attention of construction workers. Both English and Spanish version posters will be produced in recognition of the large presence of Spanish-speaking workers in the Texas labor force.[70]

7.3 FUTURE RESEARCH

The following recommendations are made for consideration by TxDOT in identifying where additional research is needed regarding corrosion of reinforcement in concrete and is developing research objectives.

Additional research is suggested in the following areas:

- Future research efforts should be aimed at defining the relationship between parameters from accelerated tests (adhesion strength, impedance, corrosion currents, etc.) and expected service performance. Companion laboratory and field studies are needed.
- More research is needed to clarify the role of coating adhesion in the corrosion protection of reinforcing bars inside chloride-contaminated concrete. It is suggested that for future corrosion studies, epoxy-coated bar samples be obtained from the same bars used for durability experiments, and be tested for assessing their adhesion strength. Adhesion loss and bar surface condition after exposure could be compared with the adhesion strength before exposure.
- Improved coating formulations that provide resistance to undercutting especially in the vicinity of damaged areas should be researched and developed.
- Better patching materials that provide adequate film thickness and that are easy to prepare and apply need to be developed. For this purpose, the engineering properties that make a patching material perform well need to be defined. Pre-qualification tests for patching materials need to be investigated.
- The effect of cracking on the corrosion performance of structures with high-performance concrete and uncoated bars needs to be investigated. Although high-performance concrete has low permeability, relatively wide cracks may form. As was evidenced in this research, uncoated bars can corrode severely at crack locations.

Consideration should be given to the following points in conducting future research efforts:

- Control specimens completely reinforced with uncoated bars should always be available in durability studies. The lack of such specimens hindered a more meaningful assessment of the performance of coated bars in the beam study.
- Ideally, bars should not protrude outside the concrete. The preventive maintenance of protruding bar ends was cumbersome and tedious. However, chloride corrosion at wire connections could be a problem if bar ends do not protrude. A good alternative would be to coat protruding bars ends with a thick layer of industrial epoxy coating.
- Both corrosion potentials and corrosion currents (or corrosion rates) should be monitored in any durability study. This would allow for a better understanding of the corrosion behavior of the specimens and of the relationship between two corrosion parameters.
- Samples for chloride analysis should be obtained from the test specimens during various stages of the experiment (for instance, after a few cycles, halfway through the exposure, and at the end). This would enable a better estimation of the chloride content that triggers corrosion of epoxy-coated bars. If possible, additional companion specimens could be opened for examination at

different time periods to assess the condition of the reinforcement that is associated with a certain chloride content.

- Chloride contents should be measured at a range of depths: Shallower to the bar location, at the level of the bar location, below the bar location, and deeper inside the member. In macrocell specimens in particular, chloride measurements should be taken at the level of the bottom (cathodic) bars.

APPENDIX A

PROPOSED GUIDELINES FOR DESIGN AND CONSTRUCTION PRACTICE OF EPOXY-COATED REINFORCEMENT

A.1 QUALITY CONTROL

Epoxy coating should be of good quality to satisfactorily perform its function. Desired characteristics include adequate flexibility, adhesion, abrasion resistance, thickness, and integrity, among others. This research has shown that among these properties, coating integrity is likely to be the most important characteristic for satisfactory corrosion performance. Coating integrity refers to the condition where the coating does not have discontinuities, such as flaws, pinholes, cracks, damage, or other areas where the metal substrate is exposed. While other coating properties may contribute to performance, quality control efforts at the coating plant should emphasize the manufacture of a final product free of defects.

A.1.1 Coating Integrity

The coating should be free from holes, voids, cracks, contamination, and damaged areas discernible to the unaided eye. Holiday detectors have been used to verify the coating integrity by detecting coating discontinuities. These devices were found to be somewhat reliable in this study, and detector responses were affected by test operator, sponge moisture, and speed of operation. Their use is cautiously recommended. The general quality of the coating can be evaluated by holiday detection but always accompanied by careful visual inspection. For more accurate results, the sponge should always be wet and it is suggested that the detector be passed at a low speed. Holiday detectors at the production line are useful for internal quality control of the coating operation, but independent holiday detection with a portable detector should be performed on random samples for acceptance purposes. The number of holidays per linear meter (or linear foot) should not exceed the maximum allowable of applicable standards [Six per linear meter (two per linear foot) in TxDOT specifications].

All visible coating damage should be patched. At the production line (before transportation), the amount of damage to be patched should not be larger than 0.5% of the bar surface. The research in Project 1265 showed that larger amounts of damage, even if patched, are vulnerable to corrosion. In addition, bars are likely to undergo additional damage during later stages of transportation, handling, and placement.

Bending of bars should be performed with properly equipped mandrels to avoid damage at the inside of bends and outside of straight leg. Protective sleeves on mandrels should be used for that purpose. Coated bars should not be bent tightly unless required by structural design. Hairline cracking occurs on the outer surfaces of tight bends of smaller diameter bars. The macrocell study showed that corrosion propagated over the long term on specimens with this type of damage. Any hairline crack in the outer bent surface should be repaired.

Proper handling and storage practices should be followed at the coating plant and in the field to minimize the amount of damage on the bars.

A.1.2 Coating Adhesion

The relevance of coating adhesion and its relationship to corrosion performance could not be conclusively proved in the present study. Nevertheless, quality control measures to ensure adequate adhesion should be implemented. The rationale is that there are several factors during the coating process that effect adhesion of the final product. Such factors include surface cleaning and preparation, anchor pattern, quality of base steel, temperature during application, and curing time. Poor coating adhesion before the bars are placed in service is usually related to poor application of the coating at the plant.

Adhesion of the epoxy coating can be evaluated with hot water immersion followed by knife adhesion testing. A recommended procedure for hot water-adhesion testing is outlined in Appendix A of Report No. 1265-6.[26] Until additional research on adhesion tests substantiates hot water procedures, acceptance criteria will have to be judiciously established. Since the effect of adhesion strength on corrosion protection is not clearly understood, a very stringent acceptance criterion may not be justified. The TxDOT Peel Test[72] is recommended for quick pre-screening and detection of poorly applied coatings, and does not require hot water immersion. This research indicated that the TxDOT Peel Test, which is very subjective, yielded results similar to those of more objective tests. If possible, the use of a knife calibrated to produce uniform forces is desirable to eliminate possible variances by the test operator.

The use of bend tests as the only method of evaluating epoxy coating adhesion should be discouraged, as has been proposed in some standards. A combination of bend tests with adhesion tests will enable a better evaluation of the coating quality, assuring good coating flexibility and adequate adhesion strength.

A.2 DESIGN AND CONSTRUCTION PRACTICE

To minimize the amount of damage to the epoxy coating, proper procedures for handling, transportation, storage, assemblage, and installation of coated bars should be followed. In essence, those procedures are aimed at avoiding any form of operation or handling that may chip the coating and expose the steel substrate.

A.2.1 Prejob Meeting[55]

For successful implementation of proper construction guidelines and procedures, the roles and responsibilities of all parties involved with the coated bars should be established and clarified before construction. Specifications, construction practices, and inspection procedures should be reviewed. Reinforcement delivery schedules and storage sites should be discussed. The owner's representative should clearly communicate the intent and mechanisms to enforce these provisions established.

A.2.2 Handling and Transportation[20, 55]

Proper practice for handling and transportation should be aimed at avoiding any form of impact or violent abrasion with bars or other hard surfaces that may chip the coating. At the coating plant, bars should be bundled and banded with padded materials to protect the bars during handling and transportation. Equipment for handling coated bars should have protected contact areas. For this purpose, nylon strings, padded straps, or padded wire rope slings can be used.[37, 55, 73]

During transportation, bars should not be skidded from the truck bed. Instead, power-hoisting equipment should be used to move the bars. If a hoist is not available, smaller bar units or individual coated bars should be carefully unloaded by hand. Bundled bars should be lifted with a strong back, a platform bridge, or a spreader beam with multiple lifting points to prevent sagging of bundles during lifting. Spreader cables with at least two point lifting can be used in the absence of a spreader beam.[20, 37, 73] Wood cribbing helps to minimize damage.[73] The use of chains or cable chokers should be forbidden. Bundles should be smaller than those typically used for uncoated bars. A sufficient number of wood blocks can be placed on the truck to prevent sagging of the bundled bars during shipping. Nylon straps need to be tightened across the trailer load at several intervals to reduce vibration during transportation.

During unloading, bars should be inspected for coating damage. If damaged bars are found, the carrier and fabricator should be notified. Bars with extensive coating damage that can not be repaired at the job site should be rejected. Bars with slight damage should be repaired.

A.2.3 Storage [20, 55]

Outside storage of epoxy-coated bars should not be prolonged because of possible detrimental effects when exposed to an adverse environment. It has been reported that exposure to ultra-violet rays, heating/cooling cycles, and salt water spray can degrade the protective qualities of the coating.[47, 63, 74] CRSI guidelines recommend outdoor exposure be limited to 30 days.[75] To avoid long-term storage, delivery of coated bars should be coordinated with schedule of bar placement.

Bars should be stored in conditions hat are adequate to prevent physical damage by impact from other objects and to protect them from adverse environmental agents. Suitable protective materials, such as opaque polyethylene sheeting, should be used to cover the bars and allow adequate ventilation. For stacked bundles, the protective covering should be draped over the sides of the bundle and around the perimeter of the stack. It is important to allow air circulation around the bars to prevent condensation under the cover.

Bars should be stored away from traffic and equipment, and close to final position of installation. Coated bars should be grouped in small manageable bundles and arranged so any group of bars can be accessed without having to dislodge or move others. Coated bars should never be stocked in large entangled piles directly on the ground. Instead, bars should be stocked in ordered bundles on wooden blocks or other protecting cribbing above the ground. Spacing of supporting blocks should be close enough to prevent sags in the bundles. Non-metallic tags should be used to identify the bars.

A.2.4 Assemblage and Installation [20, 55]

Coated bars should be handled with special care during the assembly of the reinforcing cage and positioning in concrete forms to avoid or minimize the amount of coating damage. Coated bars should never be dragged to their final locations. Walking on or moving of heavy equipment over coated bars should be minimized. Heavy objects or tools should never be dropped on the bars. Plastic-covered tie wires should be used to assemble reinforcing cages to minimize cutting of the wire into the bar coating and avoiding electrical continuity. To avoid electrical contact between bar layers or the potential corrosion at contact points, bar chairs and supports can be protected by epoxy or plastic coating, but the use of plastic bar chairs is preferable. Chairs supporting the top coated bars should rest on the formwork instead of the bottom reinforcing bars. If splicing or coupling systems are used, the installed splice should be epoxy coated, including steel splice sleeves, bolts, and nuts.

Cutting, fabrication, and welding of coated bars should be minimized and well controlled. Field cutting must be authorized by the engineer. Project specifications should cover field cutting and require coating of bar cut ends with proper patching material. Flame cutting should be forbidden. Shear and saw cutting are acceptable, but shear cutting may create a rougher end surface with more sharp edges, especially with bars of larger diameter that are difficult to cut. Field bending or straightening should be avoided if possible. If bending or straightening are performed, any damaged coating should be repaired. Welding or mechanical coupling of coated bars should not be permitted except when specified by design. TxDOT specifications include procedures for surface preparation and coating before and after welding.[41]

Coated bars in reinforcing cages should be carefully inspected before placing concrete to detect and repair any visible damage. All damaged areas and bar cut ends should be patched with a suitable repair epoxy.

A.2.5 Repair of Damaged Coating [25]

All visible damage and bar cut ends should be patched. Coating damage should be repaired with patching materials that provide a uniformly thick coating layer, especially at sharp edges and slag ridges on bar cut ends, and surfaces facing downwards. Minimum patch thickness should be 14 mils. Patching materials of high viscosity and thick texture provide excellent protection but are difficult to use. The use of materials with medium viscosity (pot life of about 2 hours) may provide good corrosion protection and are relatively easy to use. Discontinuities on the patch surface should be avoided. Slag and burrs should be removed from bar cut ends. Epoxy-coated rebar should not be flame-cut and patched. Research results from Project 1265 demonstrate the difficulty of repairing flame-cut ends and their poor corrosion performance. For surface preparation, loose particles (mud, dirt) and grease should be removed with a wire brush and/or a rag. Very thorough or sophisticated surface preparation is neither practical nor warranted, as was shown in Project 1265. The patch should be allowed to cure before further handling of bars or placing concrete over the bars. If coating damage exceeds the limits allowed by project specifications, the bars may have to be replaced. Clearly, repair of damaged coating is tedious, time-consuming, and expensive. Avoiding coating damage in the first place is always more effective and less costly.[55]

A.2.6 Concrete Placement [21, 22, 55]

Concrete placement operations should be performed to minimize coating damage. Equipment used for placement of concrete should be maneuvered properly to minimize physical impact on bars. Runways for concrete buggies and pump hoses should be set up. Runways should be supported and moved carefully to minimize coating damage and to avoid displacing the bars. Concrete should not be dropped from a high position. Whenever possible, consolidation of concrete by external vibration is preferable. If internal vibration is performed, vibrators with a soft (rubber-encased) head should be used to reduce abrasion and damage of the epoxy coating. The research study proved the viability of rubber head vibrators in significantly reducing coating damage. Operators should not deliberately contact coated reinforcement with either metal or rubber heads, and they should avoid cursory contact between the vibrating head and reinforcing bars. The vibrator should not be dragged over coated bars, and pounding of the vibrator head between the rebar cage and formwork should be avoided, since this can introduce significant damage to the coating.

The procedure to consolidate concrete should not only be aimed at minimizing coating damage but at producing well consolidated concrete with very few voids. Poorly consolidated concrete with large voids around damaged areas of the coating can lead to corrosion of reinforcement as was observed in Project 1265. Construction project specifications should include a proper procedure for consolidation of concrete with epoxy-coated bars. ACI recommended procedure for consolidation of concrete provides valuable guidance. When using rubber head vibrators in particular, points of insertion of the vibrator head should be closely spaced, and time of vibration should be long enough to permit all trapped air to escape. For both metal and rubber vibrator heads, the area of influence for removing air voids should be 75% of that required for adequate consolidation.[22]

A.2.7 Design Issues

The use of coated and uncoated bars in the same concrete member should not be specified. Macrocell corrosion may develop at any incidental continuity between layers of coated and uncoated bars. In addition, uncoated bars may be subjected to severe corrosion, especially at members with flexural cracks. If feasible, bars coated after fabrication should be specified. The maximum amount of total coating damage (patched and unpatched) should be clearly specified. Based on the present research, maximum patched damage should not be greater than 1% of bar surface area.

For severe environments, good quality concrete should be specified. A low water-cement ratio, adequate cement content, control of aggregate size and grading, and possible use of mineral admixtures will help to obtain a concrete of low permeability. Concrete should be properly consolidated and cured. Minimum concrete covers should be equal to or larger than recommended for the design exposure conditions. A maximum permissible crack width may be specified. Although a direct correlation between crack width and corrosion of coated bars was not found, specimens with severely pitted uncoated bars were observed in beams that had wider cracks. Proper concrete cover will be more beneficial for corrosion control than trying to limit crack widths by changing cover dimensions. ACI Committee 201 provides useful guidelines for producing durable concrete.[60]

For structures where long-term durability is essential, provisions for cathodic protection could be made. Cathodic protection may provide an ideal supplement to coated bars, because the impressed current concentrates more effectively at damaged, exposed areas and at coating imperfections. Current requirements are thus significantly reduced to more practical levels. Cathodic protection would be very practical for cases where there is electrical continuity through the entire reinforcement assembly, such as epoxy-coated welded wire fabric.

REFERENCES

1. "Salt Flattens Old Garage." *Engineering News-Records* 14 June 1984: 11.
2. Brown, Robert P. "Corrosion of Metals in Concrete: It Costs Money." *Materials Performance* (Dec. 1987): 78.
3. Alidi, Saleh H. "Concrete Deterioration in Saudi Aramco Facilities." *Civil Engineering in the Environment of Saudi Arabia*. American Society of Civil Engineers -- Saudi Arabia Section. Proceedings of the First Annual Seminar. Saudi Arabia, 1992: 30-43.
4. ACI Committee 222. "Corrosion of Metals in Concrete." In *ACI Manual of Concrete Practice*. Part I. Detroit: American Concrete Institute, 1996. 5 vols.
5. Clear, Kenneth C. "Effectiveness of Epoxy-Coated Reinforcing Steel." *Concrete International* (May 1992): 58-62.
6. Clifton, J.R., H.F. Beeghly, and R.G. Mathey. *Nonmetallic Coatings for Concrete Reinforcing Bars*. U.S. Department of transportation. Federal Highway Administration. Report No. NBS BSS-65. Washington, 1975.
7. Baldwin, W.R. "An Update on Epoxy-Coated Reinforcing Steel." *Solving Rebar Corrosion Problems in Concrete*. National Association of Corrosion Engineers. Paper no. 7. Seminar Reprints. Houston, 1983.
8. Munjal, S.K. *Evaluation of Epoxy-Coated Reinforcing Steel in Bridge Decks*. Maryland State Highway Administration. Interim Report No. FHWA-MD-82/03. Brooklandville, 1981.
9. Read, J.A. *FBECR-- The Need for Correct Specification and Quality Control*. Paper presented at Symposium on FBECR at Sheffield University, 1989.
10. Andrade, C., J.D. Holst, U. Nürnberger, J.D. Whiteley, and N. Woodman. *Protection Systems for Reinforcement*. CEB Bulletin D'Information no. 211. Switzerland, 1992.
11. Gillis, Henry J., and Mark G. Hagen. *Field Examination of Epoxy-Coated Rebars in Concrete Bridge Decks*. Minnesota Department of Transportation. Materials Research and Engineering. 1994. Reprinted in Concrete Reinforcing Steel Institute, *CRSI Research Series – 4*. Schaumburg: CRSI, 1995.
12. Hasan, Hendy O., Julio A. Ramírez, and Cleary B. Douglas. "Indiana Evaluates Epoxy-Coated Steel Reinforcement." *Better Roads* 65, no. 5 (May 1995): 21,25.
13. Reis, Robert A. *In Service Performance of Epoxy Coated Steel Reinforcement in Bridge Decks*. California Department of Transportation. Report No. FHWA/CA/TL-96/01-MINOR. Sacramento, 1995.
14. Yeomans, S.R. "Performance of Black, Galvanized, and Epoxy-Coated Reinforcing Steels in Chloride-Contaminated Concrete." *Corrosion* 50, no. 1 (January 1994): 72-81.
15. Sagüés, Alberto A. *Corrosion of Epoxy Coated Rebar in Florida Bridges*. University of South Florida. Final Report to Florida DOT WPI No. 0510603. Tampa, 1994.

16. Griggs, Ray D. "Use of Epoxy Coated Concrete Reinforcement Steel in Georgia Highway Construction and a Limited Field Evaluation of the Performance of Epoxy Coated Reinforcement Steel as Corrosion Protection System in Coastal Georgia Bridge Construction." Unpublished report. Georgia Department of Transportation, 1993.

17. Clear, Kenneth C., William H. Hartt, Jack McIntyre, and Seung Kyoung Lee. *Performance of Epoxy-Coated Reinforcing Steel in Highway Bridges.* National Research Council. Transportation Research Board. NCHRP Report 370. Washington: National Academy Press, 1995.

18. Weyers, Richard E., Wioleta Pyc, and Michael Sprinkel. "Corrosion Protection Performance of Bridge Decks and Marine Substructures Constructed with Epoxy Coated Reinforcing Steel in Virginia." *Proceedings of the Seventh International Conference on Structural Faults and Repair.* Vol. 1. Ed. Professor M.C. Forde. Edinburgh: Engineering Technics Press, 1997: 249-261. 3 vols.

19. Weyers, Richard E., and Philip D. Cady. "Deterioration of Concrete Bridge Decks from Corrosion of Reinforcing Steel." *Concrete International* (Jan. 1987): 15-20.

20. Kahhaleh, Khaled Z. *Corrosion Performance of Epoxy-Coated Reinforcement.* 3 vols. Ph.D. Diss., The University of Texas at Austin, 1994.

21. Kahhaleh, K.Z., H.Y. Chao, J.O. Jirsa, R.L. Carrasquillo, and H.G. Wheat. *Studies on Damage and Corrosion Performance of Fabricated Epoxy-Coated Reinforcement.* The University of Texas at Austin. Bureau of Engineering Research. Center for Transportation Research. Research Report No. 1265-1. Austin, 1993.

22. Herman, Reagan S., and James O. Jirsa. *Consolidation of Concrete with Epoxy-Coated Reinforcement.* The University of Texas at Austin. Bureau of Engineering Research. Center for Transportation Research. Research Report No. 1265-2. Austin, 1997.

23. Kahhaleh, Khaled Z., Enrique Vaca-Cortés, James O. Jirsa, Harovel G. Wheat, and Ramon L. Carrasquillo. *Corrosion Performance of Epoxy-Coated Reinforcement – Macrocell Tests.* The University of Texas at Austin, Bureau of Engineering Research, Center for Transportation Research. Report No. 1265-3. Austin, 1998.

24. Kahhaleh, Khaled Z., Enrique Vaca-Cortés, James O. Jirsa, Harovel G. Wheat, and Ramon L. Carrasquillo. *Corrosion Performance of Epoxy-Coated Reinforcement – Beam Tests.* The University of Texas at Austin, Bureau of Engineering Research, Center for Transportation Research. Report No. 1265-4. Austin, 1998.

25. Vaca-Cortés, Enrique, Henching Chen, James O. Jirsa, Harovel G. Wheat, and Ramon L. Carrasquillo. *Corrosion Performance of Epoxy-Coated Reinforcement.* The University of Texas at Austin, Bureau of Engineering Research, Center for Transportation Research. Report No. 1265-5. Austin, 1998.

26. Vaca-Cortés, Enrique, Miguel A. Lorenzo, James O. Jirsa, Harovel G. Wheat, and Ramon L. Carrasquillo. *Adhesion Testing of Epoxy Coating.* The University of Texas at Austin, Bureau of Engineering Research, Center for Transportation Research. Report No. 1265-6. Austin, 1998.

27. Vaca-Cortés, Enrique. *Corrosion Performance of Epoxy-Coated Reinforcement in Aggressive Environments.* 2 vols. Ph.D. Diss., The University of Texas at Austin, 1998.

28. Lorenzo, Miguel A. *Experimental Methods for Evaluating Epoxy Coating Adhesion to Steel Reinforcement.* M.S. Thesis, The University of Texas at Austin, 1997.

29. Chao, Heng-Yih, *Determination of damage to epoxy coating of reinforcement during construction and fabrication.* M.S. Thesis, The University of Texas at Austin, 1992.

30. Herman, Reagan Sentelle. *Consolidation of Concrete with Epoxy-Coated Reinforcement.* M.S. Thesis, The University of Texas at Austin, 1995.

31. Salparanta, Liisa. Corrosion Prevention of Concrete Reinforcement by Epoxy Coating. *Nordic Concrete Research.* No. 7, 1988: 250-258.

32. Krauss, Paul D., David B. McDonald, and Matthew R. Sherman. *Corrosion Investigation of Four Bridges Built Between 1973 and 1978 Containing Epoxy-Coated Reinforcing Steel.* Minnesota Department of Transportation. Report No. MN/RC-96/25. St. Paul, 1996.

33. Treadaway, K.W.J., and H. Davies. "Performance of Fusion-Bonded Epoxy-Coated Steel Reinforcement." *The Structural Engineer.* 67, no. 6 (Mar. 1989): 99-108.

34. Chen, Hengching. *Performance of Epoxy-Coated Reinforcing Steel in Saline Media.* Ph.D. Diss., The University of Texas at Austin, 1996.

35. Satake, J., M. Kamakura, K Shirakawa, N. Mikami, and N. Swamy. "Long-Term Corrosion Resistance of Epoxy-Coated Reinforcing Bars." *Corrosion of Reinforcement in Concrete Construction.* Ed. A.P. Crane. Great Britain: Ellis, 1983: 357-378.

36. Concrete Reinforcing Steel Institute. *Guidelines for Inspection and Acceptance of Epoxy-Coated Reinforcing Bars at the Job Site.* Schaumburg, Ill: CRSI, 1986.

37. American Society for Testing and Materials. *Standard Specification for Epoxy-Coated Reinforcing Steel.* ASTM D3963-87. Philadelphia: ASTM, 1987.

38. Manning, David G. "Corrosion Performance of Epoxy-Coated Reinforcing Steel: North American Experience." *Construction and Building Materials.* 10, no. 5 (July 1996): 349-365.

39. Flynn, Larry. "Epoxy-Coating Controversy Spurs New Materials Research." *Roads & Bridges.* 31, no. 11 (Nov. 1993): 44-45.

40. Texas Department of Transportation. *Standard Specifications for Construction of Highways, Streets and Bridges.* Item 440. Austin: TxDOT, 1993.

41. Hartley, Jeremy. "Corrosion Protection with Epoxy Coated Reinforcement." *Steel Times.* 224 (Jan. 1996): 23-24.

42. American Association of State Highway and Transportation Officials. *Standard Specification for Epoxy-Coated Reinforcing Bars.* AASHTO M284-87. From *Standard Specification for Transportation Materials and Methods of Sampling and Testing. Part 1 – Specifications.* Washington: AASHTO, 1995.

43. American Society for Testing and Materials. *Standard Specification for Epoxy-Coated Reinforcing Steel Bars.* ASTM A775/A775M-97. West Conshohocken, PA: ASTM, 1997.

44. American Society for Testing and Materials. *Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Reinforcing Steel Bars.* ASTM D3963-96. West Conshohocken, PA: ASTM, 1996.

45. Lampton, Robert D. Jr., and Dieter Schemberger. "The Evolution of Epoxy-Coated Steel Reinforcing Bar Standards: 1987 to 1997." Unpublished paper. Distributed at Conference on Understanding Corrosion Mechanisms of Steel in Concrete (A Key to Improve Infrastructure Durability), MIT, 1997.

46. Sagüés, A.A. *Mechanism of Corrosion of Epoxy-Coated Reinforcing Steel in Concrete -- Final Report.* University of South Florida. Report No. FL/DOT/RMC/0543-3296. Tampa, 1991.

47. Hartley, Jeremy. "Improving the Performance of Fusion-Bonded Epoxy-Coated Reinforcement." *Concrete.* 28, no. 1 (Jan./Feb. 1994): 12-15.

48. Smith, Jeffrey L., and Yash Paul Virmani. "Performance of Epoxy-Coated Rebars in Bridge Decks." *Public Roads.* 60, no. 26 (Autumn 1996): 6-12.

49. Concrete Reinforcing Steel Institute. *CRSI Performance Research: Epoxy-Coated Reinforcing Steel.* Interim Report. Schaumburg: CRSI, 1992.

50. Sohanghpurwala, A.A., and K.C. Clear. "Effectiveness of Epoxy Coatings in Minimizing Corrosion of Reinforcing Steel in Concrete." *Transportation Research Record No. 1268.* National Research Council. Transportation Research Board. Washington, 1990: 193-204.

51. Schieβl, Peter, and Carola Reuter. "Epoxy-Coated Rebars in Europe: Research Projects, Requirements and Use." *Transportation Research Circular: Epoxy-Coated Reinforcement in Highway Structures.* No. 403. National Research Council. Transportation Research Board. Washington, 1993: 29-35.

52. Pfeifer, D.W., R. Landgren, and P. Krauss. "Performance of Epoxy-Coated Rebars: A Review of CRSI Research Studies." *Transportation Research Circular: Epoxy-Coated Reinforcement in Highway Structures, No. 403.* National Research Council. Transportation Research Board. Washington, 1993: 57-65.

53. Ip, Alan. Private communication. Ontario Ministry of Transportation. Research and Development Branch. July 1994.

54. Gustafson, David P., and Theodore L. Neff. "Epoxy-Coated Rebar: Handle with Care." *Concrete Construction.* 39, no. 4 (Apr. 1994): 356-359.

55. Clear, K.C., and Y.P. Virmani. "Corrosion of Non-Specification Epoxy-Coated Rebars in Salty Concrete." *Public Roads.* 47, no. 1 (June 1983): 1-10.

56. "Epoxy-Coated Rebar Doing Well in Indiana after All These Years, Study Finds." *Civil Engineering.* News. 65, no. 5 (May 1995): 19.

57. Poston, R.W. *Improving Durability of Bridge Decks by Transverse Prestressing.* Ph.D. Diss., The University of Texas at Austin, 1984.

58. Kobayashi, K., and K. Takewaka. "Experimental Studies of Epoxy-Coated Reinforcing Steel for Corrosion Protection." *The International Journal of Cement Composites and Lightweight Concrete.* 6, no. 2 (May 1984): 99-116. Quoted in Kahhaleh, Khaled Z. *Corrosion Performance of Epoxy-Coated Reinforcement.* 3 vols. Ph.D. Diss., The University of Texas at Austin, 1994.

59. ACI Committee 201. Guide to Durable Concrete. In *ACI Manual of Concrete Practice*. Part I. Detroit: American Concrete Institute, 1996. 5 vols.

60. Schießl, Peter. "Review of the KCC-Inc. Reports on Effectiveness of Epoxy-Coated Reinforcing Steel." Private communication. Copy of report prepared for C-SHRP. Germany, 1992.

61. Jones, Denny A. *Principles and Prevention of Corrosion.* New York: Macmillan, 1992.

62. Smith, L.L., R.J. Kessler, and R.G. Powers. "Corrosion of Epoxy-Coated Rebar in a Marine Environment." *Transportation Research Circular: Epoxy-Coated Reinforcement in Highway Structures*. No. 403. National Research Council. Transportation Research Board. Washington, 1993: 36-45.

63. Virmani, Yash Paul. "Field Performance of Epoxy Coated Rebars in Bridge Decks." Unpublished paper. Distributed at Conference on Understanding Corrosion Mechanisms of Steel in Concrete (A Key to Improve Infrastructure Durability), MIT, 1997.

64. Concrete Reinforcing Steel Institute. "Survey Updates Epoxy Success in Bridge Decks." *Anti-Corrosion Times*. 14, no. 2 (Spring 1997): 3, 7.

65. Brown, Dan. *Epoxy-Coated Reinforcing Steel in Parking Garages.* Concrete Reinforcing Steel Institute. CRSI Epoxy Report. Schaumburg: CRSI, 1997.

66. Hededahl, P., and D.G. Manning. *Field Investigation of Epoxy-Coated Reinforcing Steel.* Report No. MAT-89-02. Ontario Ministry of Transportation. Research and Development Branch. Ottawa: MTO, 1989. Quoted in Kahhaleh, Khaled Z. *Corrosion Performance of Epoxy-Coated Reinforcement.* 3 vols. Ph.D. Diss., The University of Texas at Austin, 1994.

67. Sharp, J.V., J.W. Figg, and M.B. Leeming. "The Assessment of Corrosion of the Reinforcement in Marine Concrete by Electrochemical and Other Methods." *Concrete in Marine Environment*. Ed. V.M. Malhotra. American Concrete Institute. Proceedings, 2nd International Conference, St. Andrews by-the-Sea, Canada. ACI SP-109-5. Detroit: ACI, 1988: 105-125.

68. Wolf, Lloyd M., and Sarcinella, Robert L. "Use of Epoxy Coated Reinforcing Steel and Other Corrosion Protection Philosophy in Texas: The 'Belt and Suspenders' Approach." Unpublished paper. Distributed at Conference on Understanding Corrosion Mechanisms of Steel in Concrete (A Key to Improve Infrastructure Durability), MIT, 1997.

69. Wolf, Lloyd M., Sarcinella, Robert L., and Jirsa, James O. "Epoxy-Coated Reinforcement in Texas Bridge Structures." *Structural Engineering International*. 6, no. 4 (Nov. 1996): 275-277.

70. Wolf, Lloyd M. Personal communication. Texas Department of Transportation. Bridge Design Division. Oct. 1997.

71. "Sampling and Testing Epoxy Coated Reinforcing Steel." *Manual of Testing Procedures*. Vol. III. Texas Department of Transportation. Materials and Test Division. Test Method Tex-739-I. Austin: TxDOT, 1995.

72. McFadden, B.J. "Application and Fabrication of Epoxy-Coated Reinforcing Steel." *Solving Rebar Corrosion Problems in Concrete*. National Association of Corrosion Engineers. Paper no. 8. Seminar Reprints. Houston, 1983.

73. Canadian Strategic Highway Research Program. *Exposure Study of Epoxy-Coated Reinforcement*. Technical Brief #14. Transportation Association of Canada. Ottawa: C-SHRP, 1996.

74. Concrete Reinforcing Steel Institute. *Voluntary Certification Program for Fusion Bonded Epoxy Coating Application Plants*. Schaumburg: CRSI, 1991.