REPAIR OF EPOXY-COATED REINFORCEMENT

by

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ABSTRACT

Coating damage to epoxy-coated rebars (ECR) in chloride-contaminated concrete may lead to failure of the coating protection system. Damage to epoxy coating can occur during the stages of coating application, handling, storage, transportation, fabrication, assemblage, and/or concrete placement. Epoxy patching materials are manufactured to repair coating damage. In earlier corrosion studies at the University of Texas at Austin, performance of patched damaged areas in chloride contaminated concrete specimens and in ECR samples submersed in NaCl solution was marginal. [Report 1265-1, Kahhaleh] Patching delayed but did not prevent the onset of corrosion. Existing ECR specifications do not adequately describe proper repair procedures with patching materials. No systematic study of the efficacy of patching materials and repair procedures has been reported. In this research, performance of several patching materials was investigated. The effect of different bar surface conditions on the adhesion quality and corrosion performance of patching materials was examined. The effectiveness of patching rebar cut ends was of particular interest. 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.

PREFACE

This report provides the findings of an experimental study on repair materials and procedures for epoxy-coated bars. The study was part of a multi-phase project on the performance of epoxy-coated reinforcement. The objective of the study was to assess the effectiveness of patching materials and procedures commonly used to repair epoxy-coated bars. Patching materials and application procedures that are typically used in construction were considered in the experimental work. Little or no studies have been conducted in this area. Findings are implemented as field recommendations and are incorporated in guidelines for epoxy-coated reinforcement (Appendix A of Report 1265-S). Observance of proposed recommendations will improve the protection provided by the coating repairs.

SUMMARY

The most important factor for adequate performance 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. As thickness of patching material 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. The effect of surface preparation was minimal. No improvement in performance was observed with surface cleaning before patching on samples after 200 days of cyclic immersion in 3.5% NaCl. Rounding and smoothing sharp edges at bar ends did not prove successful. Based on these findings, no sophisticated surface preparation procedures need to be implemented 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 (but undefined) surface preparation is important for satisfactory performance but this correlation is not supported by results obtained in this study.

IMPLEMENTATION

The approach for the evaluation of repair materials and procedures for 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 improve the performance of epoxy coating repairs. Findings are implemented as field recommendations and are incorporated in guidelines for epoxy-coated reinforcement (Appendix A of Report 1265-S).

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CHAPTER 1

Introduction

1.1 PROBLEM STATEMENT

Coating damage to epoxy-coated bars in chloride-contaminated concrete may lead to failure of the coating protection system. Damage to epoxy coating can occur during the stages of coating application, handling, storage, transportation, fabrication, assemblage, and/or concrete placement. In addition, bar ends are left uncoated during the coating process or when rebars are cut. Epoxy patching materials are manufactured to repair coating damage and touch-up bar ends.

Performance of patched damaged areas in chloride contaminated concrete specimens and in ECR samples submersed in NaCl solution was marginal in tests conducted during the early stages of the project.[1, 2, 3] All patched areas were vulnerable to corrosion. Sound fusion-bonded epoxy coating provided much better protection than most patching materials. Beam and macrocell specimens where coating damage was repaired experienced rust staining on the patched surface after 1 and 2 years of exposure, respectively. Nevertheless, they exhibited slightly less corrosion than those specimens where coating damage was not repaired. The overall conclusion was that patching delayed but did not prevent the onset of corrosion. EIS and polarization resistance tests by Chen led to the same conclusion.[4] Figures 1.1 and 1.2 show corrosion of patched areas on bars from macrocell specimens. The corrosion mechanism of patched areas is described in Research Report 1265-3[3] and in Reference 5.

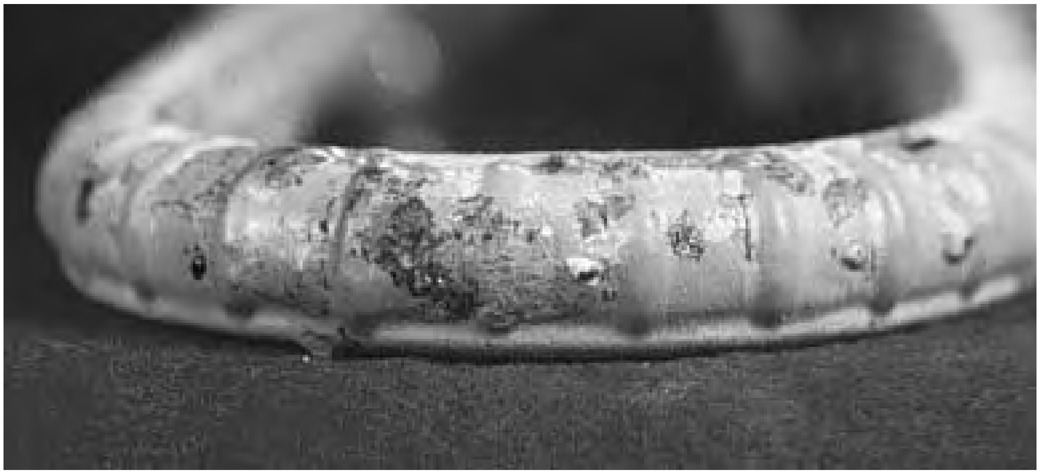


Figure 1.1 Corrosion of patched area of #4 epoxy-coated bar (macrocell study).

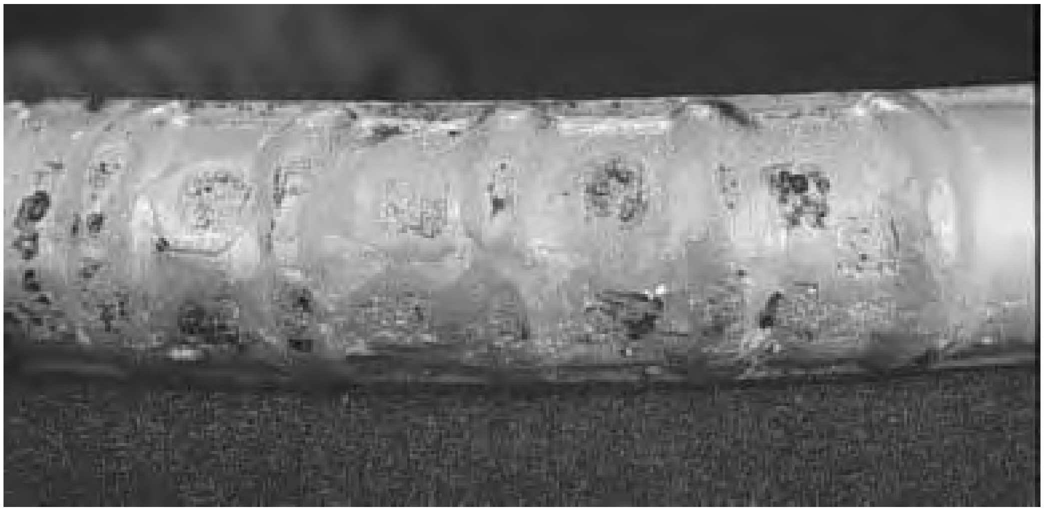


Figure 1.2 Corrosion of patched areas at outside bend on #8 bar with damaged coating greater than 2% (macrocell study).

The ineffectiveness of patching coating damage became more evident with longer times of exposure. Despite displaying slightly lower currents, the steel surface of most bars with patched coating in macrocell specimens showed levels of corrosion similar to bars with damaged, unpatched areas after 4.5 years of saline exposure (Figure 1.3). Corrosion products built up at exposed sites while only a very light rusting 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 unpatched areas of damage. 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.

Patched bar ends were particularly vulnerable to corrosion. Patched cut ends at spliced 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 1.4 and 1.5). When bar patched ends coincided with a crack location, corrosion was initiated and chloride solution penetrated and migrated underneath the coating. Corrosion of patched ends has been observed by others.[6]

Most specifications now require that all coating damage be repaired with patching material. However, some specifications do not have requirements for maximum patched damage. Most importantly, existing ECR specifications do not provide adequate guidelines for proper coating repair procedures. Repair of coating damage with a suitable patching material compatible with the epoxy coating and following the manufacturer's recommendations is the main guideline provided in all ECR specifications. No systematic study of patching materials and repair procedures has been reported.

(a) Patched bar, outside bend.

(b) Bar with unpatched damage at outside bend.

Figure 1.3 Comparison of steel corrosion under the coating at outside bend of bars with damaged coating, with and without repair (macrocell study).

Figure 1.4 Patch at ends of spliced bars broke during autopsy, exposing a dark corroded surface after 4.3 years of exposure (beam study).

Figure 1.5 Coating debonding with underfilm corrosion of spliced bar within the wetted region after 4.3 years of exposure (beam study).

1.2 REPAIR MATERIALS AND PROCEDURES

1.2.1 Patching Materials

Patching materials used for repairing damaged epoxy coated rebars consist of two-component, thermosetting, liquid or viscous epoxy resins. The two components are the epoxy resin (part A) and the curing agent or hardener (part B). The two parts are thoroughly mixed in order for the polymerization of the epoxy resin to take place. Mixing of the two components in incorrect proportions or incomplete mixing of the components will cause improper curing of the coating and the material will remain tacky. Thorough mixing is achieved when a uniform color is obtained.

Some manufacturers provide the two parts in separate cans of the same size and, therefore, mixing of the two parts is done in a separate container. To accurately measure the right amounts of each material before pouring and mixing them in a separate container may not be very practical at a job site. Other manufacturers distribute or sell patching materials with the correct mixing proportions in two cans of different size. This is a more practical solution since it only requires that the component inside the smaller can be poured into the larger can and mixed. The only drawback is that the amount of the produced material may be much greater than needed for a specific application.

Patching materials or compounds are produced by most epoxy coating manufacturers. Patching materials have different characteristics including uncured consistency and viscosity, pot life, color, drying time, curing time, and cured consistency and thickness. Some formulations can be applied right after mixing the two parts or components while other formulations require a standing time period after mixing before application. As with any epoxy, the higher the ambient temperature, the shorter the pot life and drying time. Manufacturers generally specify a minimum ambient temperature for application.

Some trends in the characteristics of different patching material were found during the course of this research. The greater the viscosity of uncured epoxy, the shorter the curing time and pot life. The greater the viscosity, the thicker the coating layer of the patched area. The greater the viscosity, the harder the cured surface. The greater the viscosity, the fewer air voids formed in the patch.

Some ECR specifications mention that patching material should be compatible with epoxy coating on the rebar and should not be harmful to the concrete. In addition, the patch material should conform to the same pre-qualification requirements of all organic coatings.

1.2.2 Repair Procedures

Epoxy coated bar specifications require that repair of coating damage be done in accordance with the manufacturer's recommendations. A typical set of manufacturer recommendations includes the following:

1. *Surface preparation*: Clean and remove loose and deleterious materials such as moisture, oil, grease, dust, scale, rust, and damaged coating from the area to be repaired.
2. *Application*: Patching material may be applied by brush, roller, or spray. For spray application, follow guidelines regarding tip orifice opening and air supply pressure. Special care should be taken to apply the product before its pot life ends. As with all chemical products, special safety precautions should be observed during application of the patching compound.

3. *Post-application handling*: Allow the patching material to dry before handling and storing repaired epoxy coated bars.

There are some practical issues related to surface preparation of a damaged area. Patching manufacturers recommend cleaning of the area to be repaired but do not mention how that task can be accomplished, what specific procedures or tools should be used for adequate cleaning. Options include a wire or wheel brush, sand paper or other types of abrasive paper, or sandblasting. The degree of surface cleanliness that should be obtained is not clearly defined. Degree of cleanliness ranges from removing only loose dirt and materials to thorough cleaning to a bright metal surface or "near white" surface. There is no guidance regarding tolerance in the degree of surface cleanliness.

Damage to epoxy coating on steel rebars usually consists of chipped areas of small size. Most damage occurs due to mishandling of the epoxy coated bars during the various stages from production to placement in the structure. Bars may be abused, dragged, hit, pounded, dropped, stepped on, or scratched. Most of the damage occurs on the bar corrugations but some damage occurs on the valleys between corrugations. Such abuse may produce small chipped off areas, scratches, nicks, tears, and abrasion. Damaged areas are usually of very small size, generally less than 1 cm^2. It is very difficult to clean the metallic surface of such a small area. If a wire brush is used, the relatively large size and bristle spacing of the brush compared to the small area to be cleaned makes it difficult to achieve good surface cleaning of the exposed metal. In addition, the metallic bristles of the brush rub against the epoxy coating around the damaged area and cause abrasion of the coating. Even though a wire brush may not be the most suitable tool for cleaning of damaged areas in epoxy coated rebars, it is the tool typically employed by contractors when surface cleaning is attempted. The development of a small wire brush with closely spaced bristles would be warranted.

The touch up of bar cut ends presents an interesting problem. When a bar is cut, either with shears or with a chop saw, the edges of the bar at the perimeter of the cut section will be sharp. Patching around sharp edges is very difficult. The patching material will tend to flow away from sharp edges in its uncured state, resulting in a very thin layer of coating when the epoxy completely cures. If the epoxy has a very thin consistency, it may be possible that no material is left on some of the sharp edges, mainly at top edges because the material flows down from those edges. The problem may be aggravated if bars are cut with a torch. The high temperatures needed to cut steel with a flame will leave a thick layer of slag at the cut section. The slag layer has a very irregular, rough surface with many sharp ridges throughout.

Several manufacturer's recommendations mention that patching materials can be applied by brush, roller, or spray. From the above discussion regarding the difficulty in cleaning small areas of coating damage, it is evident that applying epoxy materials by roller or spray would be extremely difficult and impractical, and would result in material being wasted. Application with a paint brush is easiest and most practical for epoxies with liquid-like consistency. Spreading patch material with a spatula, tongue depressor, or wood stick is the most viable method for epoxies with very thick consistency.

1.3 RESEARCH OBJECTIVES

As previously mentioned, there is no information about the in-situ effectiveness of different patching materials and repair procedures. There are no specifications for testing procedures to evaluate the effectiveness of a patch on an epoxy coated bar. The objective of this research was to determine the effectiveness of the patching and repair materials and procedures presently approved by the Texas DOT and to develop improved guidelines for repairing damaged epoxy coated bars.

In this research, the corrosion performance of several patching materials 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. In addition to examining repair procedures following manufacturers recommendations, other repair procedures were evaluated. Of special interest was a study of procedures that are currently practiced in the field. From several field visits it was noted that in many instances, contractors did not follow all the manufacturer's recommendations. Most often, repair materials were applied without any surface preparation. In one case, epoxy coated bars were cut using a torch and the cut ends were immediately touched up without any cleaning (Figure 1.6). Flame cutting leaves a very rough end and burns the epoxy coating, making it very difficult to patch the damage.

Figure 1.6 Improper field practice: Epoxy coated bars were flame cut and, immediately thereafter, bar ends are being touched up by hand.

1.4 TEST PROGRAM

To evaluate the effectiveness of patching materials and procedures to repair epoxy coated rebar, three major series of experiments were conducted: a) Cyclic immersion in NaCl solution for 200 days, b) electrochemical impedance and polarization resistance, and c) hot water immersion-knife adhesion tests. In cyclic immersion and electrochemical tests, the corrosion performance of repair materials was studied. In hot water test, the adhesion quality of patching materials was examined.

CHAPTER 2

Cyclic Immersion Test - Methodology

2.1 TEST PROCEDURE

Cyclic immersion in a 3.5% NaCl solution was conducted on 80 epoxy-coated bar samples containing 524 patched areas. Samples were subjected to 200 days of exposure in cycles of 7 days (4 days wet, 3 days dry). Samples were cut from epoxy coated bars as follows:

Table 2.1 Samples for cyclic immersion tests.

Type of Damaged Area	Sample Length	Bar Size	ECR Coating Plant
I	16.5 cm to 17.5 cm	#11	a
II	16.5 cm to 18.4 cm	#11	a
III	14 cm	#10	b
	16.5 cm	#11	a
IV	30 cm	#10	b
		#11	a
V	16.5 to 20 cm	#11	a, b
	27 cm	#10	c

Samples were prepared and patched using a variety of repair materials and procedures as described in the next section. Once cured, patch thicknesses at repaired locations were measured with a Mikrotest thickness gage for each specimen. Average patch thickness for different types of repaired area and patching material are listed in Table 2.2. No attempt was made to control patch thickness for all specimens because it is extremely difficult to achieve a specified thickness. The finished thickness of patched areas was a result of the viscosity of each epoxy material.

Table 2.2 Average patching thickness (mils) of different types of repaired area and patching material.

Patching Material	Types of Damaged Area				
	I	II	III	IV	V
A	7.5	3.9	2.9	3.7	
B	14.3	7.1	8.4	12.9	
C	26.3	24.8	41.9	43.4	38.9
D			43.2		

Patch thickness at rough flame-cut ends was often impossible to measure. The irregular, ridged slag surface was barely covered by a thin film of epoxy at protruding ridge edges. Similarly, attempting to measure patch thickness of very small patched areas was futile. In several cases, thickness of rebar ends patched with epoxy materials *C* and *D* was probably underestimated. The finished coating was thicker than the maximum value of the gage scale (40 mills).

Samples were hung with nylon strings from wooden racks. All bar specimens were enclosed inside large plastic containers holding the 3.5% salt solution. Wooden supports for the racks were built to permit specimens to be immersed in the solution during wet cycles by lowering the racks. The saline solution was periodically changed when it became contaminated by significant amounts of rust. A view of all bar samples in the immersion test set-up is shown in Figure 2.1.

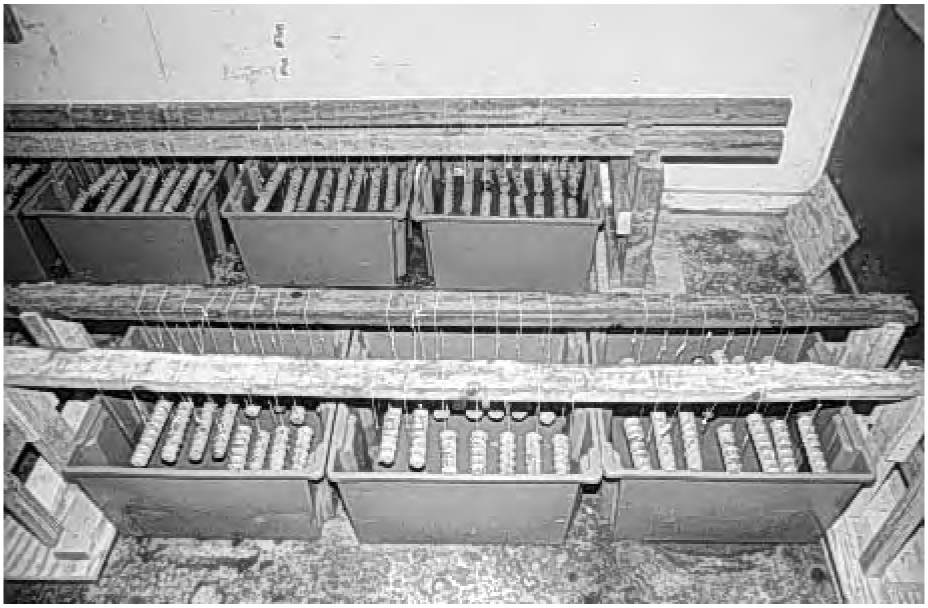


Figure 2.1 Salt immersion test set-up for patched epoxy coated bar specimens.

Observations of the bar surface condition at repaired or patched areas were taken every two months. Photographs were taken at different stages to record significant changes. Detailed observations taken throughout the exposure period are not included because of space limitations. Instead, the most important events are summarized.

Patching material at repaired areas was removed to uncover and examine the steel surface beneath. Patch materials *A* and *B* were removed with a sharp utility knife. Epoxy materials *C* and *D* were so hard that chiseling (using a hammer) was required to remove the patch. Fusion bonded epoxy coating in the vicinity of patched areas was peeled to inspect the extent of corrosion beyond the repaired zone.

2.2 VARIABLES

The following variables were used for cyclic immersion in NaCl solution:

2.2.1 Patching Materials

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 characteristics of each repair material were as follows:

A Material of very thin consistency in its liquid state. Dry to touch at about 5 hours in a small 2 oz. cup at a temperature of approximately 19°C. Its color was light green. Could be applied by brush, roller, or spray.

B Material of viscous consistency in its liquid state. Dry to touch at about 3 hours in a small 2 oz. cup at a temperature of approximately 19°C. Its color was grayish green. Could be applied by brush or roller.

C Material of very thick consistency in its uncured state. Dry to touch at about 10 minutes in a small 2 oz. cup at a temperature of approximately 19°C. Its color was bright green. Due to thick consistency, it could not be applied by brush, roller, or spray. Could be applied by spreading with a spatula, tongue depressor, or wooden stick.

D Material of very thick consistency in its uncured state. Dry to touch at about 10 minutes in a small 2 oz. cup at a temperature of approximately 19°C. Its color was gray. Due to thick consistency, could not be applied by brush, roller, nor spray. Could be applied by spreading it with a spatula, tongue depressor, wooden stick, etc.

General properties of all four epoxy materials are included in Appendix A. Figure 2.2 shows bar ends patched with materials *A*, *B*, *C*, and *D*.

(a) Patching materials *A* (left specimen) and *B* (right specimen).

(b) Patching material *C*.

(c) Epoxy material *D*.

Figure 2.2 Specimens patched with different patching materials.

Damaged Areas

I-Areas between Bar Deformations: Rectangular incisions of 11 x 16 mm and 6 x 6 mm were made through the coating with a sharp utility knife. Coating inside the rectangular incision was removed with a chisel blade mounted on an X-acto knife. Figure 2.3 shows rectangular damaged areas on a typical ECR sample. By controlling area of damage, performance of patched areas could be evaluated by size.

II-Areas on Bar Deformations: Intentional damage of irregular shape was created by subjecting ECR to different types of action, such as dragging, dropping, or hammering, which resulted in damage mainly at bar ribs (both transverse and longitudinal). In many instances, damaged areas were enlarged by chipping with a utility knife. This type of coating damage is similar to that produced in the field. Size of damaged areas ranged from barely visible areas of less than 1 mm^2 up to large areas (90 mm^2). The average damaged area was 13.09 mm^2 and the median value was 2 mm^2. Figure 2.4 illustrates two typical samples with irregular shaped coating damage on bar ribs.

III-Saw-Cut Bar Ends: Epoxy coated bar samples were cut with a chop saw and bar ends were patched. See Figure 2.5 (a, b) for a typical sample.

IV-Flame-Cut Bar Ends: Epoxy coated bar samples were cut with a torch and bar ends were patched. Samples with flame-cut ends were about twice as long as those samples with saw-cut ends because the torch cutting operation burned a significant area of epoxy coating. Although flame cutting epoxy coated rebars is not recommended, it is done in the field and it was felt important to investigate the possible repercussions of such practice. Figure 2.5 (c, d, e) shows samples with torch cut ends.

V-As-Received, Patched, Shear-Cut Bar Ends: Samples in which touching up of bar ends was done by the coating applicator. The use of these samples allowed comparison of the performance of samples patched by the coating applicator against that of samples patched in the laboratory. A bar end patched by the coating applicator is shown in Figure 2.5 (f).

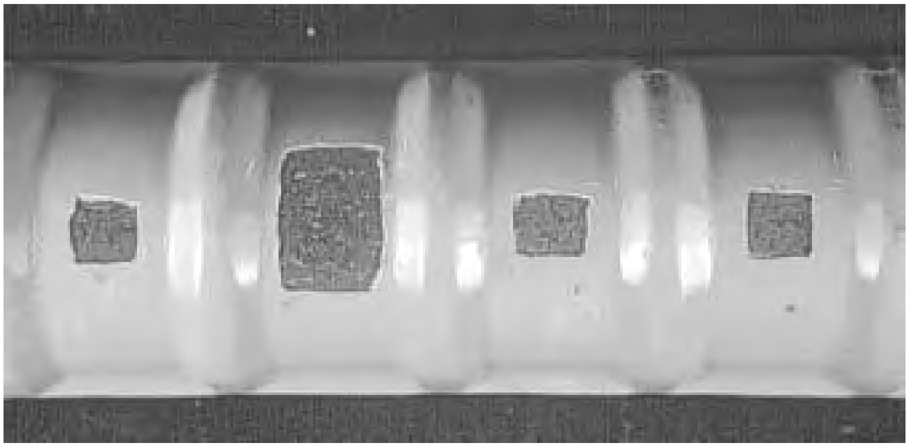
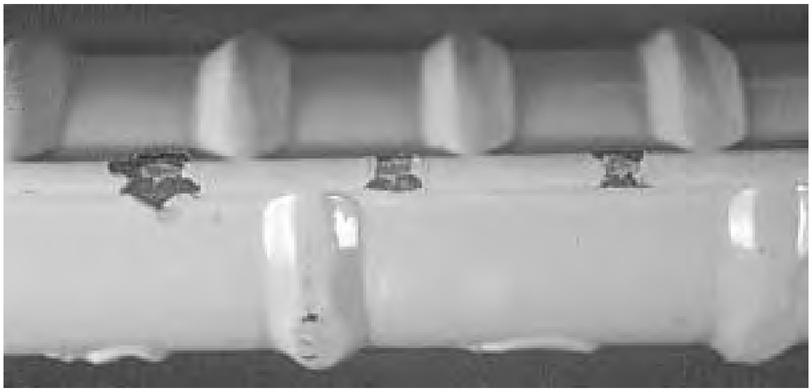
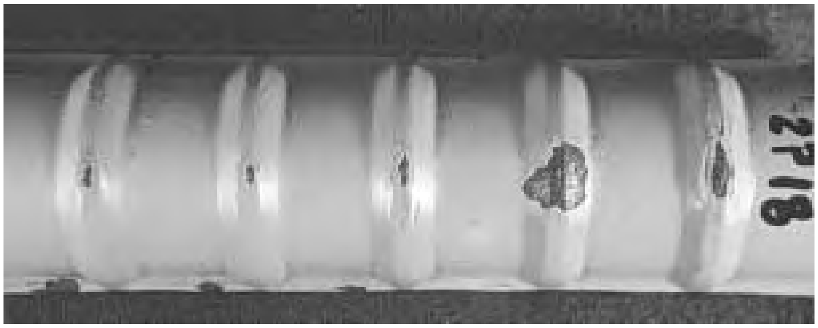


Figure 2.3 Damaged areas (*I*) between bar deformations

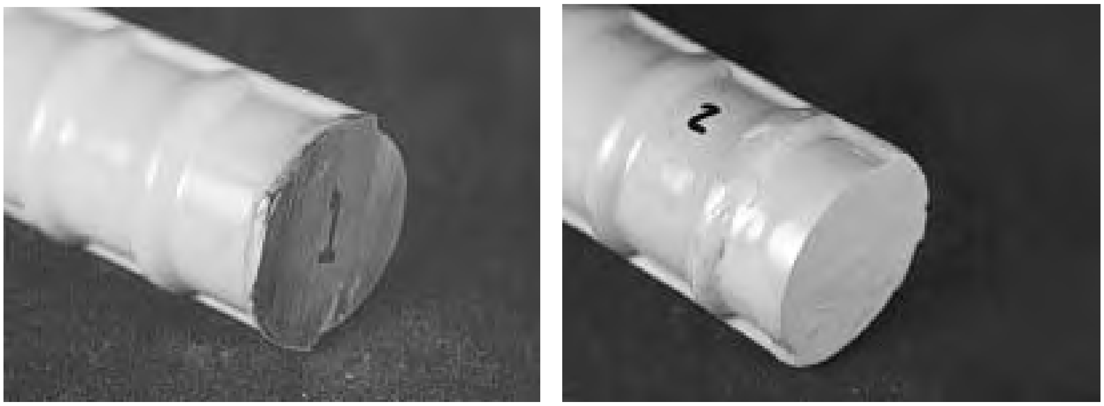


(a) Coating damage on longitudinal rib.

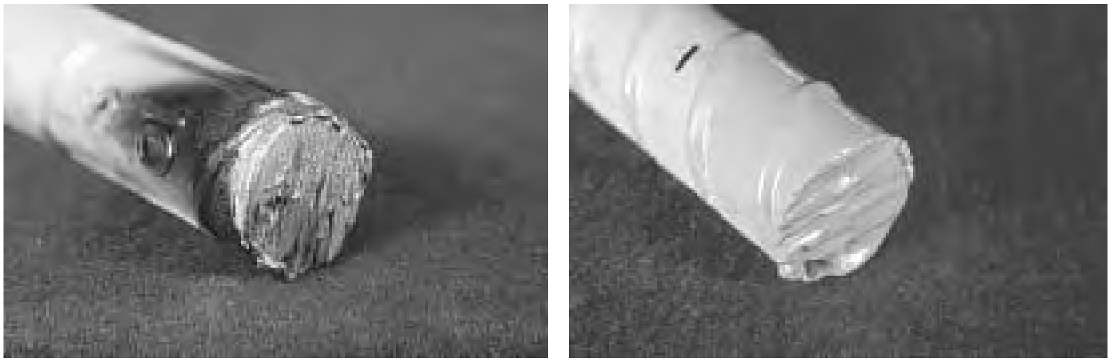


(b) Coating damage on transverse ribs.

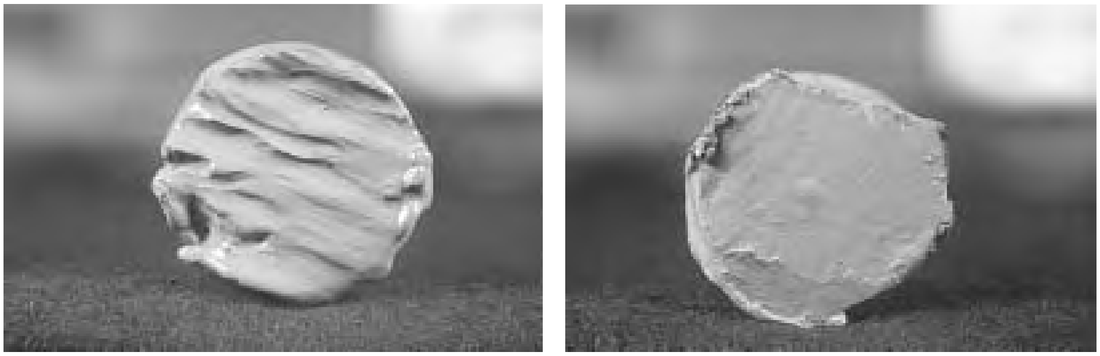
Figure 2.4 Damaged areas (*II*) on bar deformations.



(a) Saw-cut bar end (*II*). (b) Patched bar end (saw-cut)(*II*).



(c) Torch-cut bar end (IV). (d) Patched bar end (torch-cut) (IV).



(e) Patched bar end (torch-cut) (*IV*). (f) Shear-cut bar end patched by coating applicator (V).

Figure 2.5 Condition of cut ends and patches (*III–V*).

Repair Procedures

a Patching immediately applied after laboratory-type surface cleaning

b Patching immediately applied after damage and surface cleaning (wire brush)

c Patching applied on smoothed and cleaned (wheel grinder/brush) bar end (no outdoor exposure)

d Patching applied on wheel brush-cleaned bar end (no outdoor exposure)

e	Patching applied on surface cleaned (wire brush) after outdoor exposure
f	Patching applied after short outdoor exposure of previously cleaned surface (wire brush)
g	Patching applied on smoothed and cleaned (wheel grinder/brush) bar end after outdoor exposure
h	Patching applied after short outdoor exposure of previously smoothed and cleaned bar end (wheel grinder/brush)
i	Brush-applied patching on untreated surface after outdoor exposure
j	Spatula-applied patching on untreated surface after outdoor exposure
k	Hand-applied patching on untreated surface after outdoor exposure
l	Brush-applied patching on untreated surface immediately after saw or torch cutting
m	Hand-applied patching on untreated surface immediately after saw or torch cutting
n	Touch-up of as-received patch

A description of each of the above procedures is included in Appendix A.

Grouped Repair Procedures

Specimens with no surface preparation: The exposed metallic surface at damaged areas and bar cut ends was not cleaned before patching. In several cases, bar samples were subjected to outdoor exposure for 1 or 2 weeks until rust developed on the steel surface. In other cases, patching material was applied on hot bar cut ends immediately after torch or saw cutting. Patching material was applied with a small paint brush, spread with spatula, or spread with glove-covered finger. Procedures *i, j, k, l, m,* and *n* are included in this category. Specimens with no surface preparation are illustrated in Figure 2.6 (a, c, e).

Specimens with surface preparation: The exposed metallic surface at damaged areas and bar cut ends was cleaned either with a wire brush or wheel brush before patching. Some bar cut ends were rounded and smoothed with a wheel grinder. In several cases, bar samples were subjected to outdoor exposure for 1 or 2 weeks before surface cleaning until rust developed on the steel surface. Some specimens were subjected to an additional 24 to 48 hours of outdoor exposure after surface cleaning and before patching application. Patching material was applied with a small paint brush or spread with spatula. Procedures *b, c, d, e, f, g,* and *h* are included in this category. Figure 2.6 (b, d, f) shows various specimens with surface preparation.

Control Specimens (Procedure a)- Patching material applied to specially prepared bar surface for following two cases:

- Bar cut ends [Figure 2.7 (a, b)]: Sharp edges and burrs at cut sections were rounded and smoothed using a wheel grinder and wheel brush. The sharply ridged slag surface in flame-cut rebars was smoothed and rounded as much as possible. The metallic surface was cleaned to a near-white, polished finish with the aid of a wheel brush. All dirt, slag, burrs, rust, coating, and other contaminants were thoroughly removed.

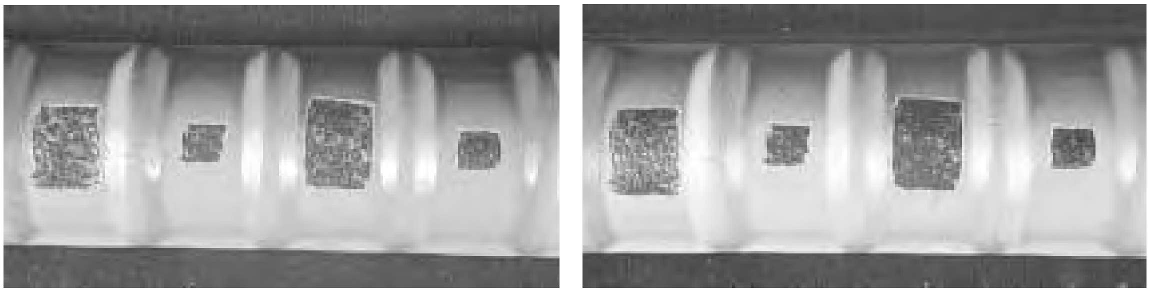
- Bar surface [Figure 2.7 (c, d)]: On an undamaged epoxy coated bar sample, portions of the coating were removed with a wheel brush at the following locations: a) bar surface between ribs (1.4 cm x 2.2 cm), and b) bar deformations or ribs (2.5 cm x 3.0 cm). The uncovered metallic surface was cleaned to a near white, polished finish with the wheel brush.

Prior to patching, any remaining grease and dirt on the surface was removed with acetone to produce a shinning, bright metallic surface.

In all repair procedures, patching material was allowed to cure overnight before any further handling. In samples where areas were patched on both bar sides, patching was applied first on one side, allowed to completely dry, and then turned over to patch the other side.

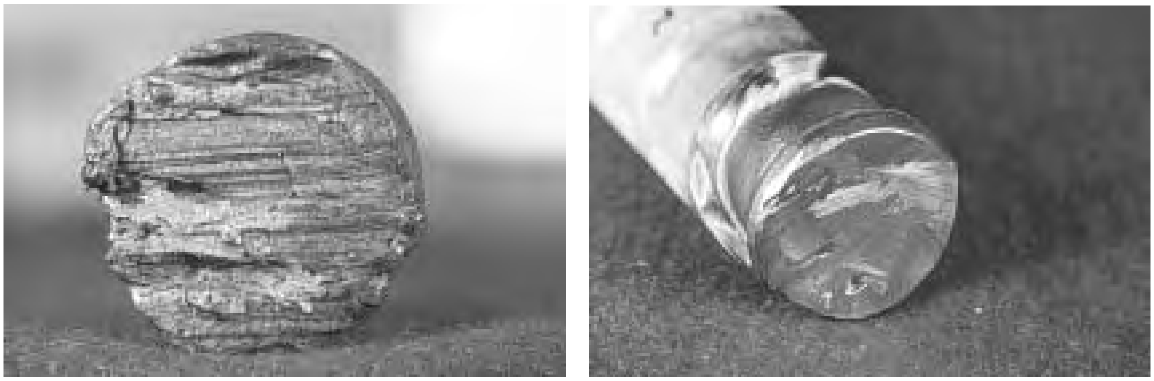
(a) Uncleaned bar end surface after 2 weeks of exterior exposure.

(b) Surface preparation with wheel grinder and wheel brush.



(c) Appearance of damaged areas after two weeks of outside exposure.

(d) Appearance of damaged areas after cleaning with a wire brush.

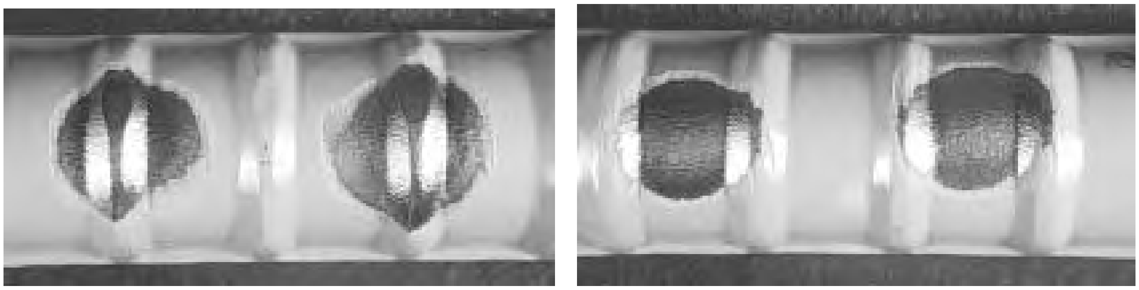


(e) Appearance of torch-cut end after two weeks of exterior exposure.

(f) Appearance of torch-cut end after wheel grinding and wheel brushing.

Figure 2.6 Appearance of specimens before and after surface preparation.

(a) Aspect of specially cleaned bar end. (b) Front view of specially cleaned bar end.



(c) Specially cleaned surfaces on bar deformations. (d) Specially cleaned areas between bar deformations

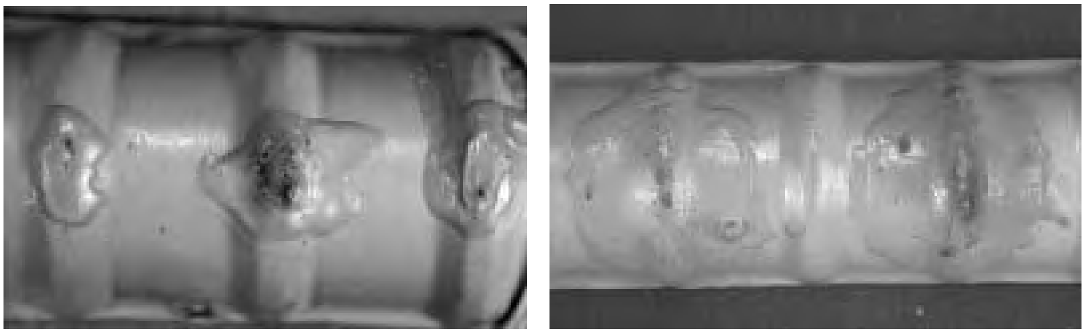
Figure 2.7 Surfaces specially cleaned before patching application (control specimens).

CHAPTER 3

Cyclic Immersion Test–Results and Discussion

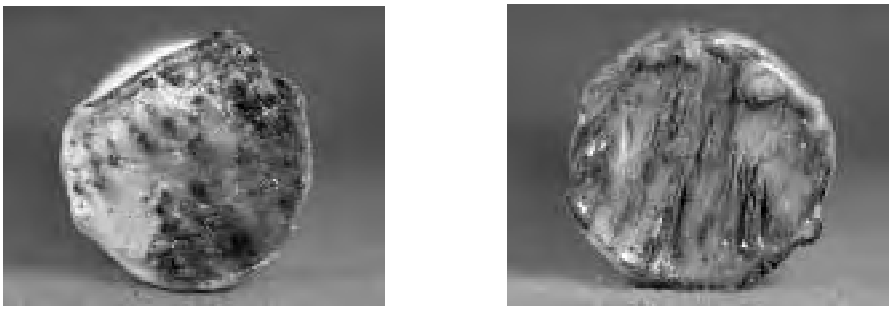
3.1 CORROSION OF SPECIMENS

Corrosion and associated deterioration of patched surfaces was observed in the form of coating blisters, patch softening and debonding, rust spotting and staining, fine rust exudation, and breakage and delamination of patches on bar ends. Rust staining spread beyond patched ends to adjacent bar side surface. A few photos illustrating corrosion on patched surfaces and ends after 200 days of immersion are shown in Figures 3.1 and 3.2. Corrosion on the steel surface beneath the patch produced a uniform black or dark rusted surface combined with areas of reddish-brown (or other tones of brown) rust. There were zones with accumulation of black, reddish-brown, or other tones of brown, fine rust products, especially underneath areas with softened or debonded patches and blisters. Mounds or bulges of accumulated, hardened rust (black or reddish-brown) formed underneath patching blisters. In several bar ends, the dark rusted surface could be removed in large, thick (0.5 mm), flat layers or flakes with a utility knife, leaving behind a uniform layer of fine black rust with scattered reddish-brown rust spots. In cases of most severe corrosion, several shallow pits developed. The steel surface at adjacent non-corroded portions looked dull. A few photos illustrating corrosion on steel surfaces beneath patches are shown in Figures 3.3 and 3.4.



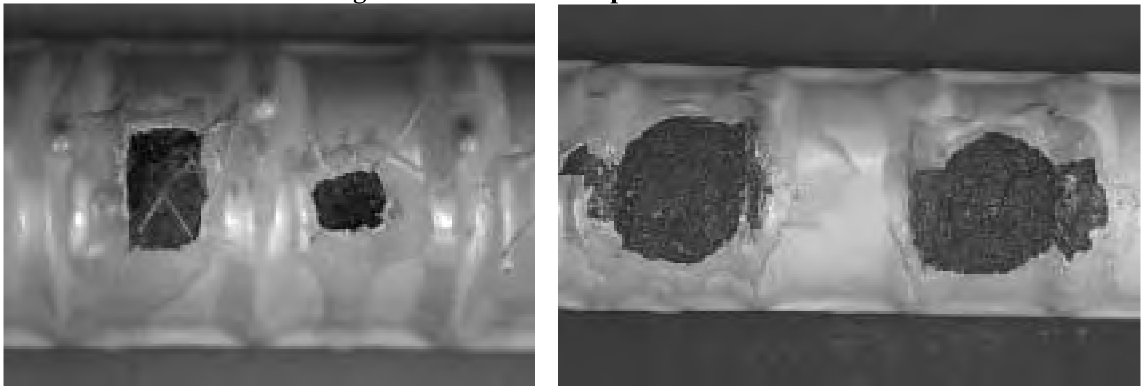
(a) Corrosion of patched area on bar deformation. (b) Rust stains on repaired areas on bar deformations.

Figure 3.1 Corrosion of patched areas on bar surface.



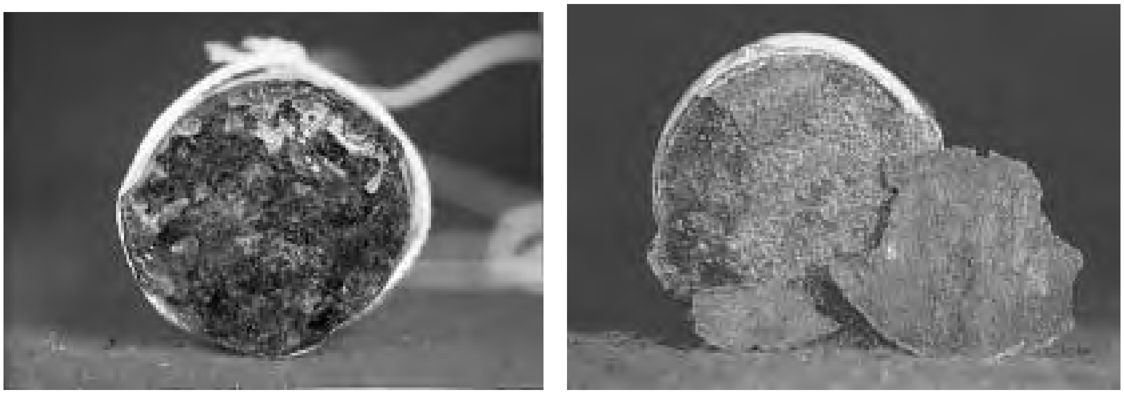
(a) Corrosion of patched end (shear-cut). (b) Corrosion of patched end (torch-cut).

Figure 3.2 Corrosion of patched bar ends.



(a) Corrosion of steel surface underneath patch on damaged areas. (b) Corrosion of steel surface beneath patched areas.

Figure 3.3 Appearance of corroded steel surfaces underneath patched areas.



(a) Corrosion of bar end surface underneath the patch. (b) Rust layer beneath patch.

Figure 3.4 Appearance of corroded bar end surfaces.

From periodic examination of specimens, various corrosion stages for patched, repaired areas were observed:

1. Salt solution permeated through patch layers until patch eventually lost adhesion and slightly bulged at certain areas of small to medium size [Figure 3.5(a)]. Solution seemed to be trapped underneath patch at such areas. This phenomenon is called patch softening in this discussion

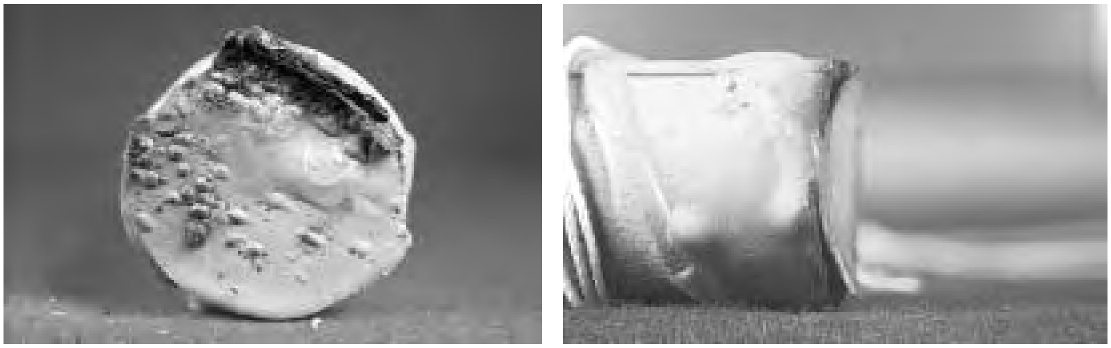
because the patch felt soft at these areas. Small to medium size blisters developed on patched surface. At patched areas on bar sides, rust spotting or staining of small size formed anywhere on the patch surface (around blisters, at patch boundaries, on pinholes, etc.). On patched ends, rust spotting or staining of small or medium size formed preferentially around perimeter of bar end, at burrs, at slag ridges, and around blisters [Figure 3.5(a)].

2. Corrosion progressed with subsequent wet-dry cycles. Debonded, softened patch areas increased in size. More blisters formed and existent blisters enlarged and bulged further. Already present rust spots and stains gradually increased in size and additional rust spotting sometimes appeared, especially around perimeter of ends [Figure 3.5(b)].
3. Patch broke and rust exuded at blister edges (all patched areas) and perimeter edges (bar ends) [Figure 3.5(c)]. More salt solution and oxygen was accessible to steel surface through small zones of patch breakage. Areas of debonded patch material were of medium or large size. Medium to large rust stains were present. There was widespread rust staining around perimeter of bar ends and at sharp, projecting burrs and slag ridges [Figure 3.5(c)]. Rust staining and blistering spread beyond patched end section into adjacent bar side surface.
4. Widespread rust staining spread over the whole patch surface on bar ends (less extensive on other patched areas). Patch continued to break and separate from steel surface at perimeter of bar ends [Figure 3.5(d)]. In a few samples, patch material completely separated and lifted from the steel surface [Figure 3.5(e)]. Uniform corrosion (black or dark with spots of brown rust) developed on steel surface underneath the patch. Extent of uniform corrosion varied from a large portion of repaired area to the full patched area and spreading a few millimeters (centimeters on bar ends) into adjacent surface underneath epoxy coating [Figure 3.5(f)]. Fine reddish-brown (or other tones of brown) rust accumulated at areas where more salt solution was concentrated (softened or debonded patch and blisters). At blistered patch locations, corrosion products accumulated and formed hard mounds or protrusions. In some cases, shallow pits developed.

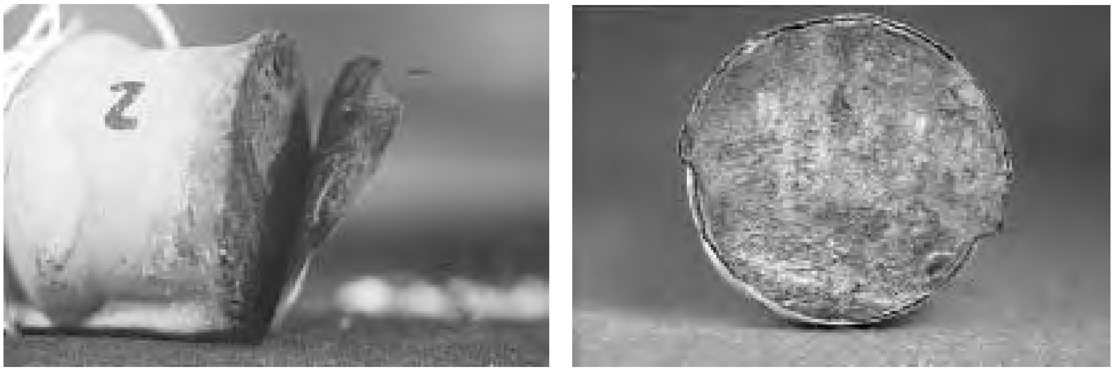
In the corrosion process described, penetration or diffusion of chlorides through the layer of patching material was the necessary first step for corrosion initiation and progression. Therefore, the thickness of the patch layer was an important attribute of the repair material and procedure for success. The thicker the patch layer, the slower the chloride diffusion, and the longer the time to initiation of corrosion.

Rust spotting and staining occurred anywhere within the patched area but appeared more frequently at blisters and near boundaries of patched area and seemed to indicate vulnerable zones for corrosion attack. As the patch swelled to form a blister, the coating eventually broke at the perimeter of the blister. Breaks were small and could be seen only with the aid of a microscope. More chlorides and oxygen entered under the patch and rust products exuded at the breaks. At boundaries of patched area, there may have been microscopic gaps between the patching material and epoxy coating. Chlorides and oxygen could have reached the steel surface through those gaps resulting in debonding and blistering close to the boundary. Rust exuded through the broken patch at blisters and/or through gaps at boundary of the patched areas.

(a) Corrosion stage 1.　　(b) Corrosion stage 2.



(c) Corrosion stage 3.　　(d) Corrosion stage 4.



(e) Corrosion stage 4.　　(f) Corrosion stage 4.

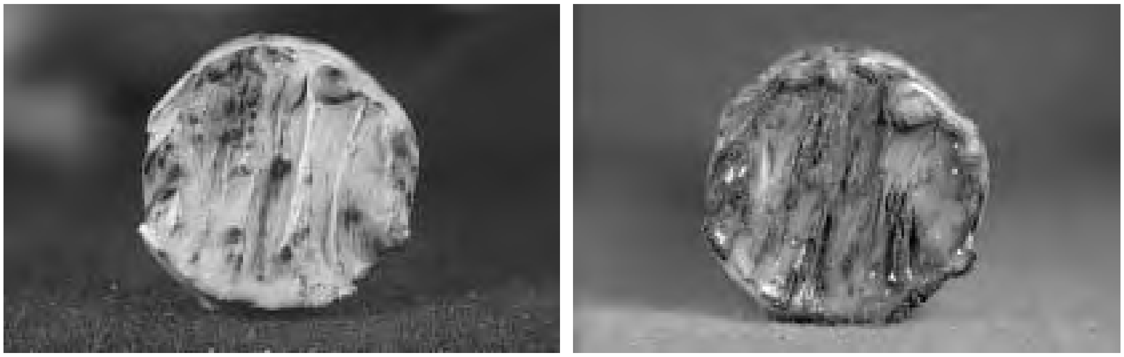
Figure 3.5 Corrosion progression of patched bar ends.

On bar ends, the perimeter was the most vulnerable zone for corrosion attack. Other vulnerable areas were projecting or protruding burrs and slag ridges. These vulnerable zones had one characteristic in common –

sharp edges. If the patching material was of a thin, very liquid consistency, it had a tendency to flow away from sharp edges and resulted in a very thin coating layer. The patch layer was so thin at the perimeter edge of some end surfaces that the steel could be seen (Figure 3.6). It was very difficult to coat sharp edges at rebar ends with patching materials of thin consistency, despite the fact that liberal amounts of epoxy were applied. Chlorides diffused easily to the steel surface through zones of very thin patch thickness. As corrosion progressed, thinner patches offered less resistance to debonding and blistering. Once enough rust accumulated, the patch layer was easily torn at sharp edges where the patch was very thin. Once the patch was broken, chlorides and oxygen directly accessed the steel surface and corrosion accelerated. Therefore, the adverse effect of thinly covered areas was threefold: Initially, it allowed easy diffusion of chlorides; subsequently, as corrosion progressed, it was the weak link for patch tearing; and finally, when the patch tore, chlorides and oxygen had direct access to the steel surface.

Touched-up surfaces cut with a chop saw behaved differently from those surfaces cut with a torch. Saw-cut surfaces were more prone to patch softening and blistering than torch-cut surfaces. Surfaces cut with a chop saw were level and smooth. Once chloride solution permeated, surface smoothness facilitated corrosion undercutting, patch debonding, and patch blistering. Torch-cut surfaces did not show extensive patch debonding and blistering. Instead, they experienced breakage and extensive rust staining at multiple locations along slag ridges (Figure 3.7). Both torch-cut and saw-cut surfaces experienced rusting and patch tearing around perimeter of section. However, patch material could be separated and lifted only from smooth saw-cut surfaces.

Figure 3.6 Visible steel due to very thin patch around perimeter edge on bar end.



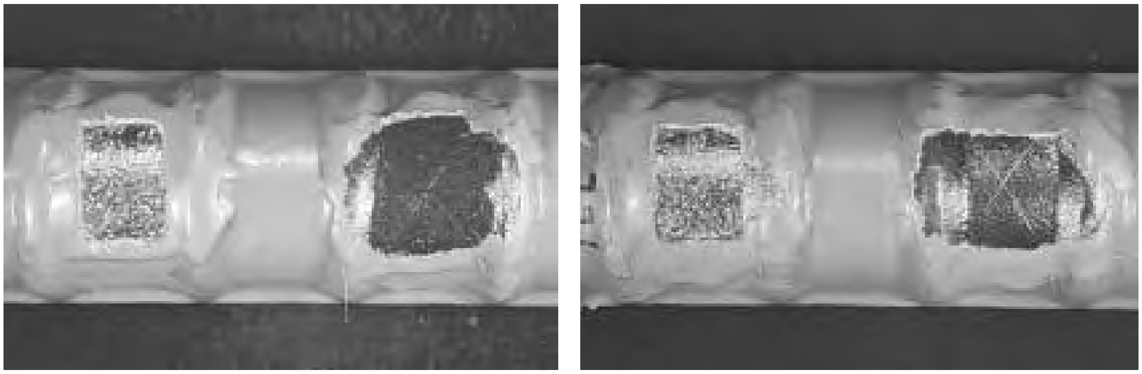
(a) Appearance after 53 days of immersion in 3.5% salt solution. (b) Appearance after 200 days of immersion.

Figure 3.7 Corrosion of flame-cut and patched bar ends.

Depending on the patching material used, several patched areas exhibited relatively good corrosion performance. When corrosion occurred, it was confined to a limited area and was rather superficial, with no appreciable amount of metal loss or pitting. Many specimens with good performance did not experience corrosion at all and the steel surface maintained its original condition (either cleaned or unclean). The assessment of “no corrosion attack” on unclean, patched areas (atmospherically rusted steel surface not cleaned before touching-up) was made only when the pre-existent, thin layer of rust appeared on the steel surface and no evidence of chloride-induced corrosion (dark or black corroded metal combined with reddish-brown rust) was found (Figure 3.8). In fact, the amount of “atmospheric” or original rust was less at the end of the exposure study than at the beginning. Most of the original rust blended with the patching material. Upon removal of the coating, there was only a very superficial layer of original rust left.

Patch adhesion to the steel surface was lost in corroded areas. Patching material could be easily peeled and lifted in large portions with a sharp utility knife. In many cases, rust adhered well to the patch and removal involved cutting through the rust layer. At non-corroded areas, there was inconsistent patch adhesion. In most cases, patch adhesion to steel remained intact and the patch material could only be removed in small chips. Many small chips of patching material remained stuck to the steel surface. However, there were several cases where adhesion to the steel was marginal or poor but no corrosion occurred (Figure 3.9). Patch adhesion seemed to always be lost because of steel corrosion; however, adhesion may not be necessary for corrosion protection.

Figure 3.8 Good corrosion performance of bar end surface uncleaned before patching after 200 days of exposure to 3.5% NaCl solution.



(a) Good adhesion and no corrosion on left area. Poor adhesion with surface corrosion on right area.

(b) Uncorroded areas with good adhesion (left area) and poor adhesion (right area).

Figure 3.9 Patch adhesion after 200 days of exposure to 3.5% NaCl solution of specimens.

3.2 CORROSION EVALUATION

To compare corrosion performance of different coating repair materials, a rating system was developed to evaluate corrosion activity of each patched specimen as described below:

1–None

2–Slight

3–Moderate

4–Moderate to Severe

5–Extensive

Specimens were evaluated both before and after peeling of patching material. A detailed description of each of the above indexes is explained in subsequent paragraphs.

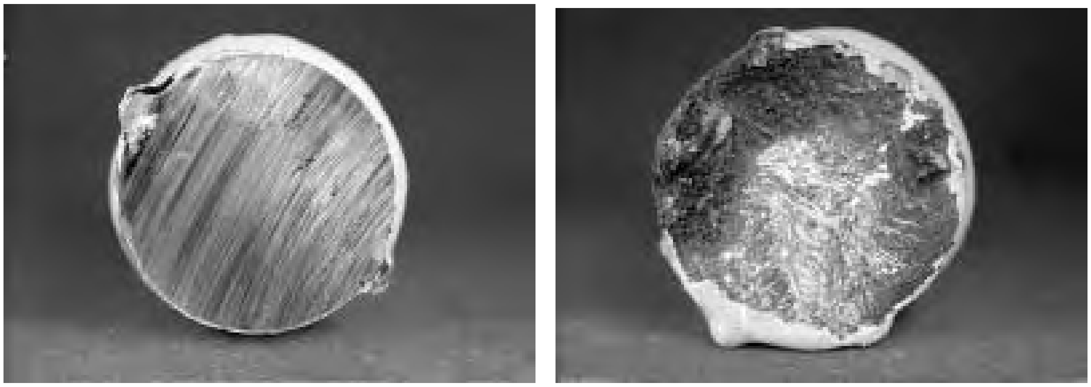
1–None: Patch surface was clean without rust staining, patch softening, or patch blistering. Steel surface underneath the patch remained in the condition noted before patching, that is: a) bright, shiny steel for surfaces thoroughly cleaned before patching, and b) no change in appearance of rust for surfaces not cleaned prior to patching. Patch adhesion ranged from good to poor. See Figure 3.10(a) for an example of a rated 1 specimen.

2–Slight: Corrosion was observed on less than one third of the steel surface area beneath the patch. Surface no longer appeared smooth and showed generally superficial rusting. On patched ends, the corroded portion may have spread on bar side surface several centimeters beyond the cut end section. Adhesion of patch to steel surface was marginal. A few small rust deposits were present on the patch surface. Thirty percent or less of the patch surface area exhibited rust staining. Some blisters were formed. There was partial patch softening and debonding. See Figure 3.10(b) for an example of a rating level 2.

3–Moderate: Corrosion on as much as two thirds of the steel surface area underneath the patch. Corrosion ranged from superficial to loss of smooth appearance. On patched ends, the corroded portion spread on bar side surface several centimeters beyond the cut end section. Substantial rust deposits were present on the patch surface. Rust staining was observed on 30 to 60% of the patch surface area. There was extensive blistering, softening, and debonding of the patch material. The patch started to crack at boundaries or sharp edges. Patch adhesion to steel surface was marginal to poor. See Figure 3.10(c) for an example of a level 3 rating.

4–Moderate to severe: Corrosion spread over more than two thirds of the steel surface area beneath the patch. Mostly superficial rusting but some pitting and accumulation of rust was observed. On patched ends, corrosion spread on the bar side surface several centimeters beyond the cut end section. At other repaired areas, corrosion extended a few millimeters beyond the patched area. Large rust deposits were present on the patch surface. Overall rust staining ranged from 60% to 90% of patch surface area. The patch clearly delaminated and may have broken at sharp edges. Patch adhesion to steel surface was marginal to poor. See Figure 3.10(d) for an example of a rating level 4.

5–Extensive: Corrosion was uniform over the whole steel surface area underneath the patch. Shallow pitting and accumulation of rust layers were observed. On patched ends, corrosion spread on bar side surface several centimeters beyond the cut end section. At other repaired areas, corrosion spread well beyond the patched area. The patch completely debonded from steel surface. Overall rust staining was observed over more than 90% of patch surface area. Patch adhesion to steel surface was poor. See Figure 3.10(e) for an example of extensive corrosion.



(a) Rating 1.

(b) Rating 2.

(c) Rating 3.

(d) Rating 4.

(e) Rating 5.

Figure 3.10 Corrosion rating of patched specimens.

3.3 EVALUATION OF RESULTS AND DISCUSSION

Average and standard deviation of corrosion ratings for different types of damaged areas and patching materials are summarized in Table 3.1.

Table 3.1 Average and standard deviation of corrosion ratings of patched areas after 200 days of exposure.

Patching Material	Type of Damaged Area											
	I			II			III			IV		
	N	Avg	σ	N	Avg.	σ	N	Avg.	σ	N	Avg.	σ
A	44	2.6	1.3	99	2.4	1.8	27	4.7	0.4	20	5	0
B	45	1.1	0.6	119	1.2	0.8	19	2.3	1.3	21	3.1	1.2
C	22	1.0	0	37	1.01	0.08	25	1.06	0.2	10	1.01	0.03
D							30	1.0	0.02			

N: Number of readings
Avg: Average
σ: Standard Deviation

Most patched areas on the bar surface exhibited relatively good corrosion performance with an average corrosion rating of 1.7 (Type I) and 1.6 (Type II) (Figure 3.11). When corrosion occurred, it was rather superficial, with no appreciable amount of metal loss or pitting. Many specimens did not experience corrosion at all and the steel surface maintained its original condition (either cleaned or unclean). However, more specimens with patched ends experienced extensive corrosion, with an average corrosion rating for saw-cut ends of 2.8 and 3.4 for flame-cut ends. Shear-cut ends patched at the coating plant performed very poorly, with an average corrosion rating of 4.3 (Figure 3.11). Poor performance of patched rebar ends was due to the vulnerability of sharp edges as discussed earlier.

Consistently, specimens patched with materials *C* and *D* showed excellent corrosion performance (Figure 3.12). Specimens repaired with material *B* exhibited more corrosion than those specimens patched with materials *C* and *D*. Specimens patched with material *A* performed poorly. Figure 3.13 illustrates the performance of areas type I (patched damage between ribs), type II (patched damage on ribs), type III (saw-cut and patched rebar ends), and type IV (flame-cut and patched rebar ends) repaired with different patching materials. For all cases, patching material *C* performed best and material *A* worst. The average thickness obtained with each patching material is plotted at the top of both figures. Clearly, as patch thickness increased, corrosion performance improved.

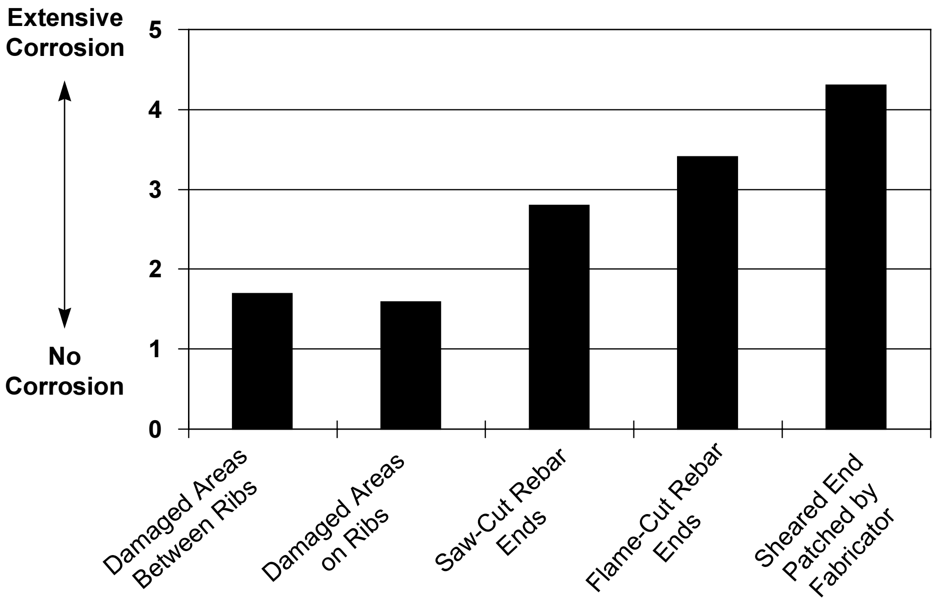


Figure 3.11 Corrosion rating of different damaged areas.

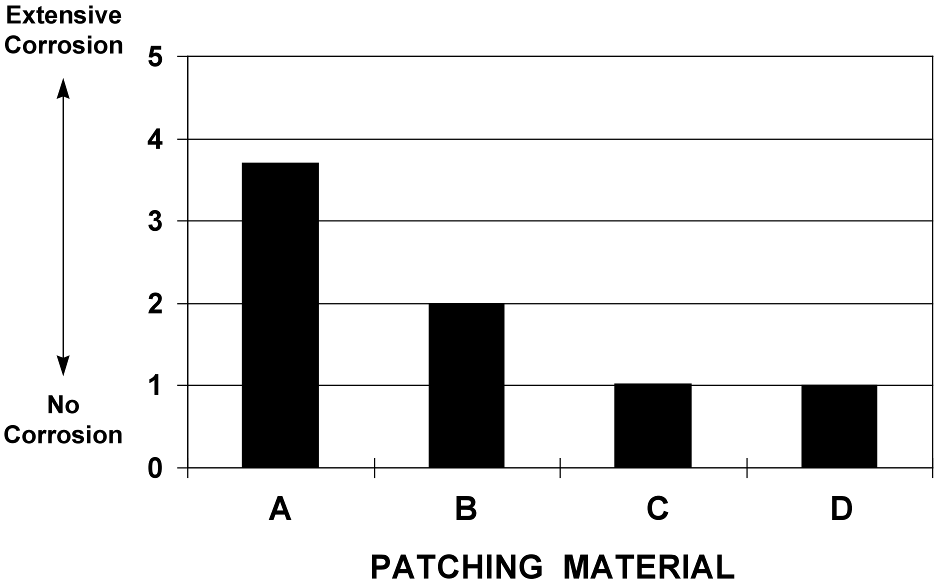


Figure 3.12 Corrosion performance of different patching materials.

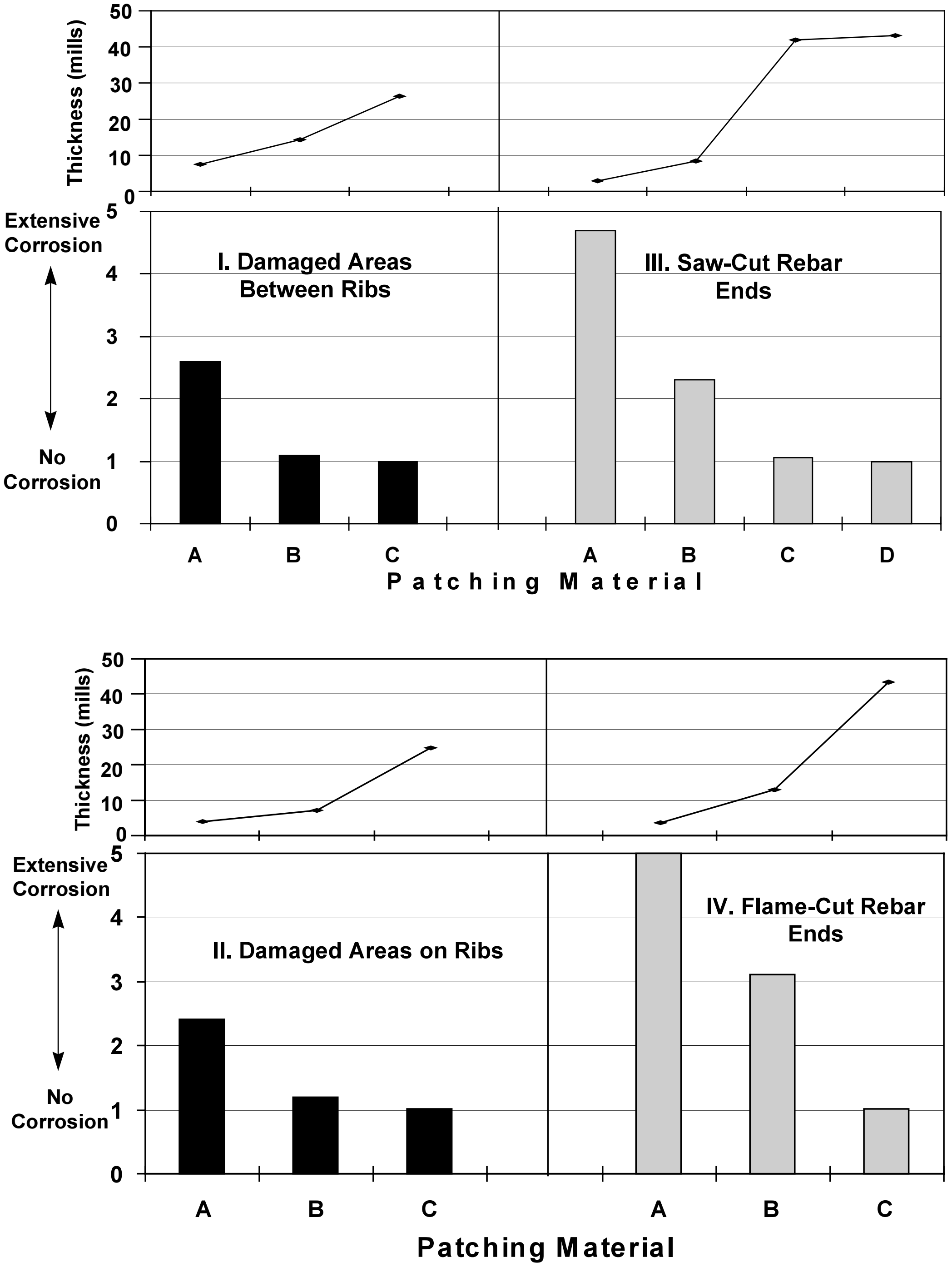


Figure 3.13 Comparative performance between different types of specimens repaired with different patching materials.

In Figure 3.14, thickness and corrosion performance are plotted for all patched areas. Although the data is scattered, trends can be observed. More specimens patched with material *A* lie in the high corrosion region and smaller patch thickness of the graph than specimens patched with other materials. For specimens patched with material *B*, more data points are in the low corrosion region and have greater thickness than specimens patched with material *A*. Finally, specimens patched with materials *C* and *D* are prevalent in the region of greatest patch thickness and little to negligible corrosion. Again, performance improved with increasing patch thickness. 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 3.15.

A statistical evaluation of the data in Figure 3.14 may help determine minimum patch thickness. If ratings of 1 and 2 are considered acceptable (little to no corrosion) and ratings above 2 are unacceptable (moderate to extensive corrosion), analysis of the latter group of points shows that a thickness of 14 mils roughly corresponds to the 95 percentile of points with ratings greater than 2. In other words, 95% of data points with ratings above 2 (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 3.14). If it is assumed that the data constitutes a representative sample and 14 mils is established as the minimum effective patch thickness, material A would not be acceptable, material B would not be acceptable in most instances (only about one third of samples patched with material B had a thickness equal or greater than 14 mils), and materials C and D would be acceptable. The region containing data points with thicknesses greater than 14 mils and acceptable performance (ratings lower than 2) is shaded in the graph (Figure 3.14).

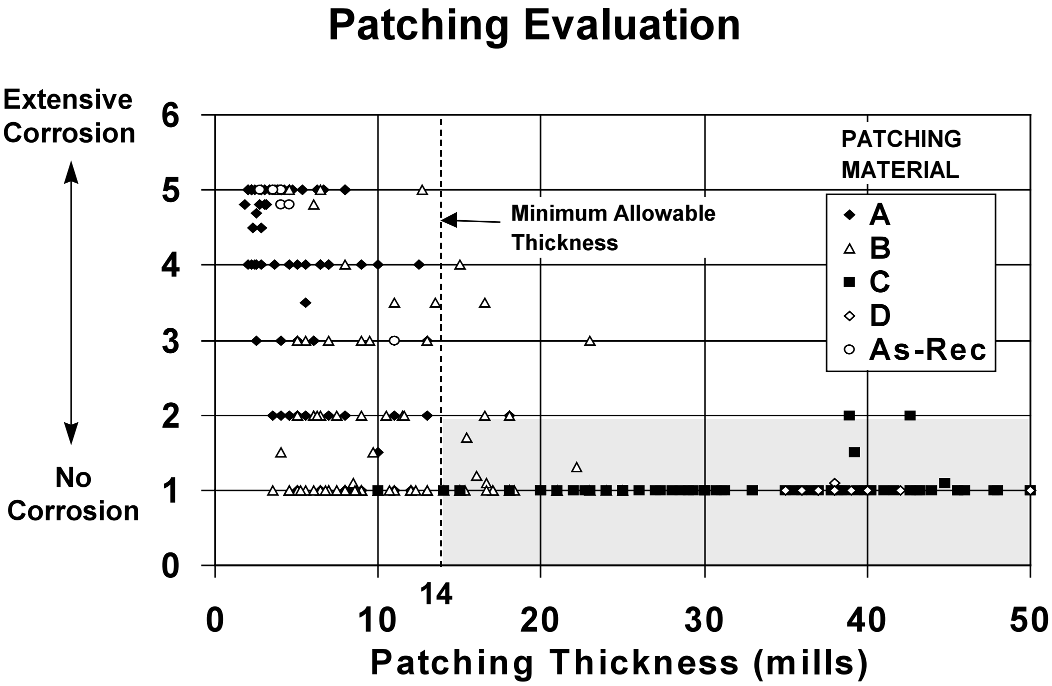


Figure 3.14 Corrosion rating vs. patch thickness of all specimens.

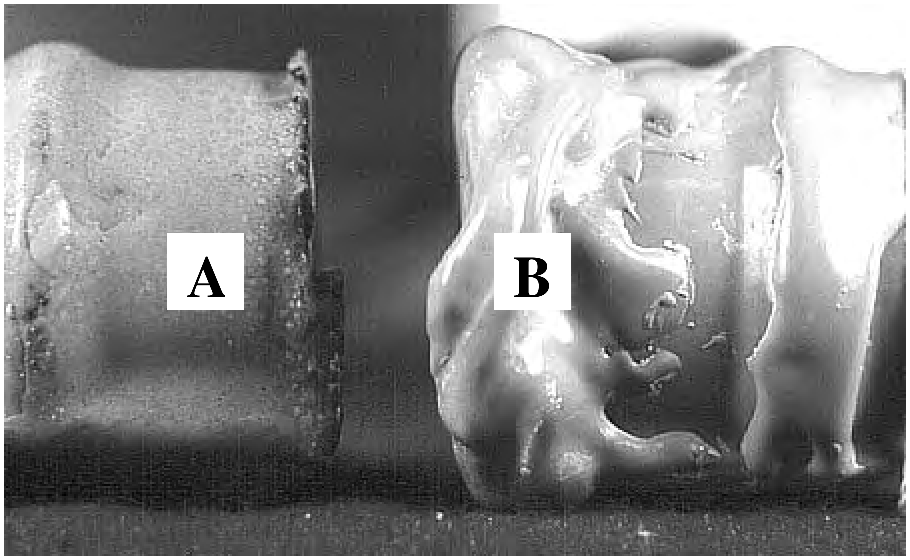
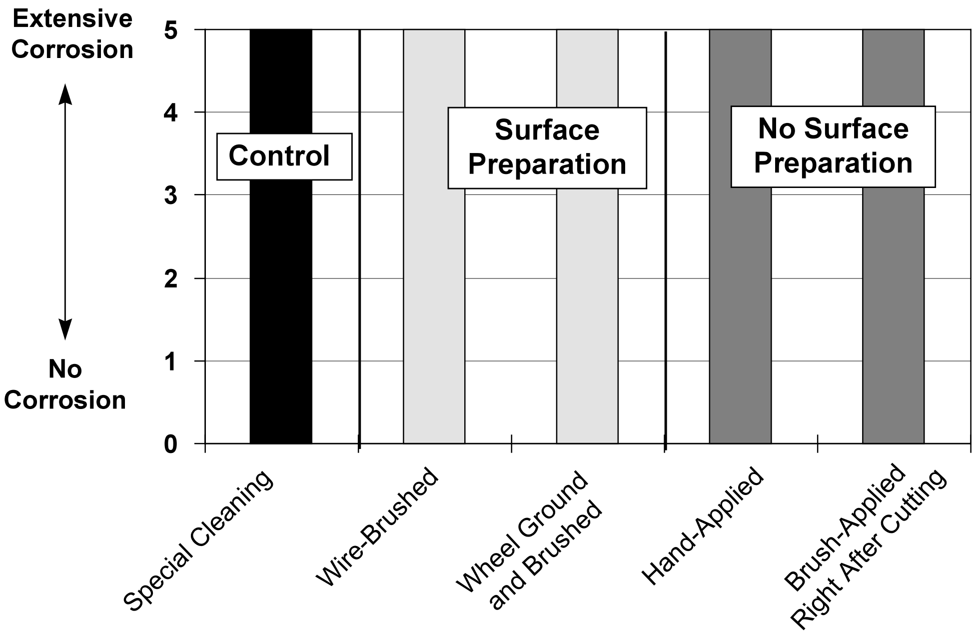


Figure 3.15 Performance of different patching materials.

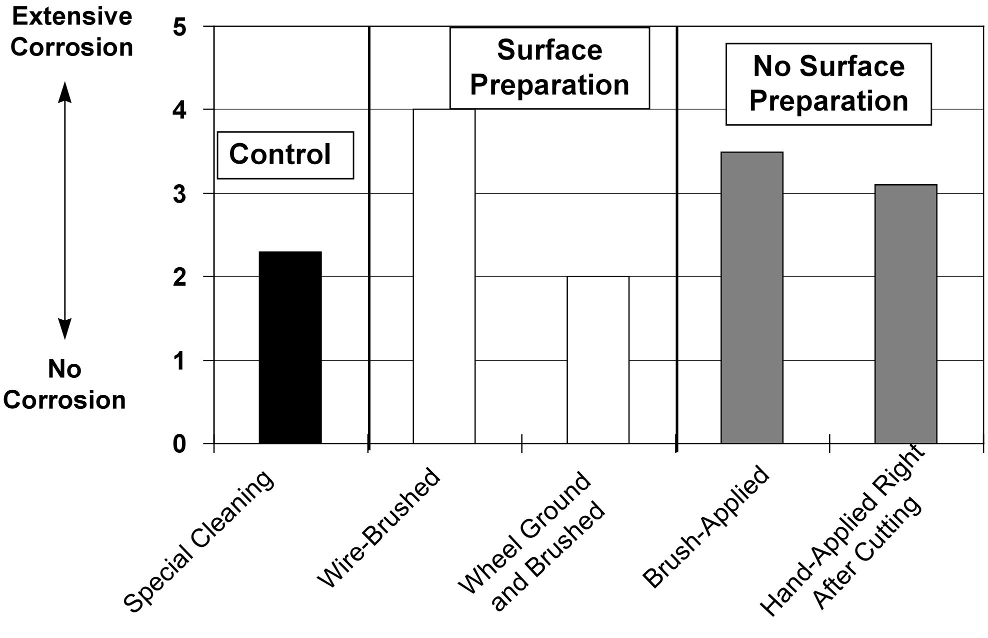
The thickness of a cured patch layer is largely dependent on the properties of the patching material. The greater the viscosity of uncured epoxy, the thicker the coating layer of the patched area. Also, with greater viscosity, fewer air voids (and possible discontinuities) formed in the patch and the cured surface was harder. In addition, as viscosity increased, drying and curing times became shorter. In terms of corrosion protection, materials *C* and *D* appear to be the best patching materials. However, some disadvantages are associated with their properties. Because of their thick consistency, the resins have poor workability and are difficult to prepare, mix, and apply. Unlike patching materials *A* and *B*, epoxy repair materials *C* and *D* cannot be applied by brush. A short, stiff rod, such as a spatula or tongue depressor is needed to thoroughly and vigorously mix the resin and to apply it to the damaged coating. In addition, these materials had a short pot life. Epoxy material suppliers need to continue developing new materials that provide acceptable corrosion protection and are easy to use. Of the materials considered here, material *B* provided good corrosion protection in many instances and was relatively easy to use.

Although thickness of the patch was identified as an important factor, it remains unclear what specific properties make a patching material perform well. One property seemed to be the viscosity, which had a direct effect on the thickness of the patch. There may be a series of properties, such as rheology, flow, percent of solids, modulus of elasticity, flexibility, hardness, and permeability, which may be interrelated and act together to give the material desirable characteristics. For instance, a viscous epoxy that has a greater content of solids may be less permeable to chloride diffusion. In addition to providing a thicker patch, materials *C* and *D* may be less permeable than materials *A* and *B*. It is important to keep the differences between thickness and permeability in mind because it could be wrong to assume that a very thick application of material *A* will provide adequate protection. In fact, it was not possible to obtain thicker patches by adding layers of material *A* because it remained fluid and simply flowed away. Successive applications might be possible after each layer has cured or is dry to the touch; however, time and cost rule out such successive applications. On the other hand, materials *C* and *D* provided thick patches in one application.

No clear trend was observed in terms of surface preparation. No improvement in performance was observed with surface cleaning before patching, as can be seen in Figures 3.16 and 3.17. Rounding and smoothing sharp edges at bar ends did not prove successful. Even some control specimens where the surface was specially cleaned showed poor performance (Figure 3.18). Manufacturers' application procedures indicate that proper surface preparation is important for satisfactory performance but this correlation is not supported by results obtained in this study. No correlation was found between size of patched areas and corrosion performance, as illustrated in Figure 3.19.



(a) Patching material *A*



(b) Patching material *B*

Figure 3.16 Corrosion rating for different surface preparations of flame-cut ends.

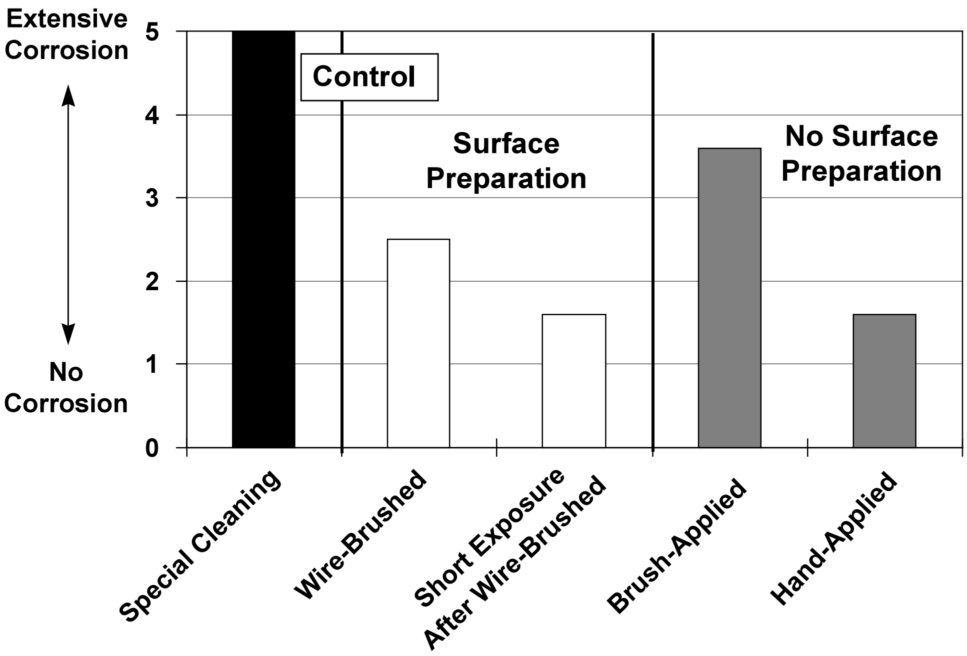


Figure 3.17 Corrosion rating for different surface preparations of damaged areas (patching material *A*).

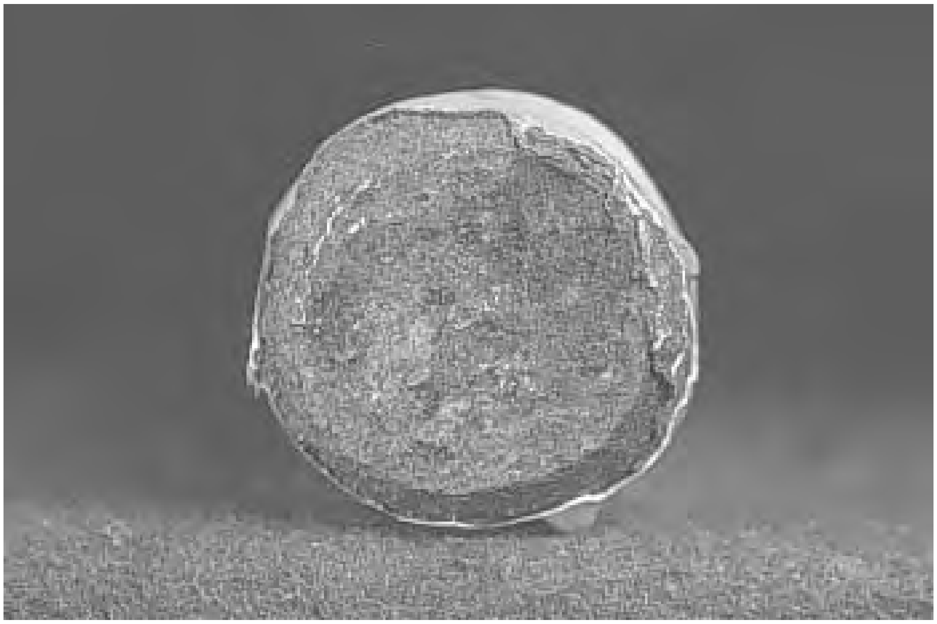


Figure 3.18 Corrosion of bar end surface that was specially cleaned before patch application.

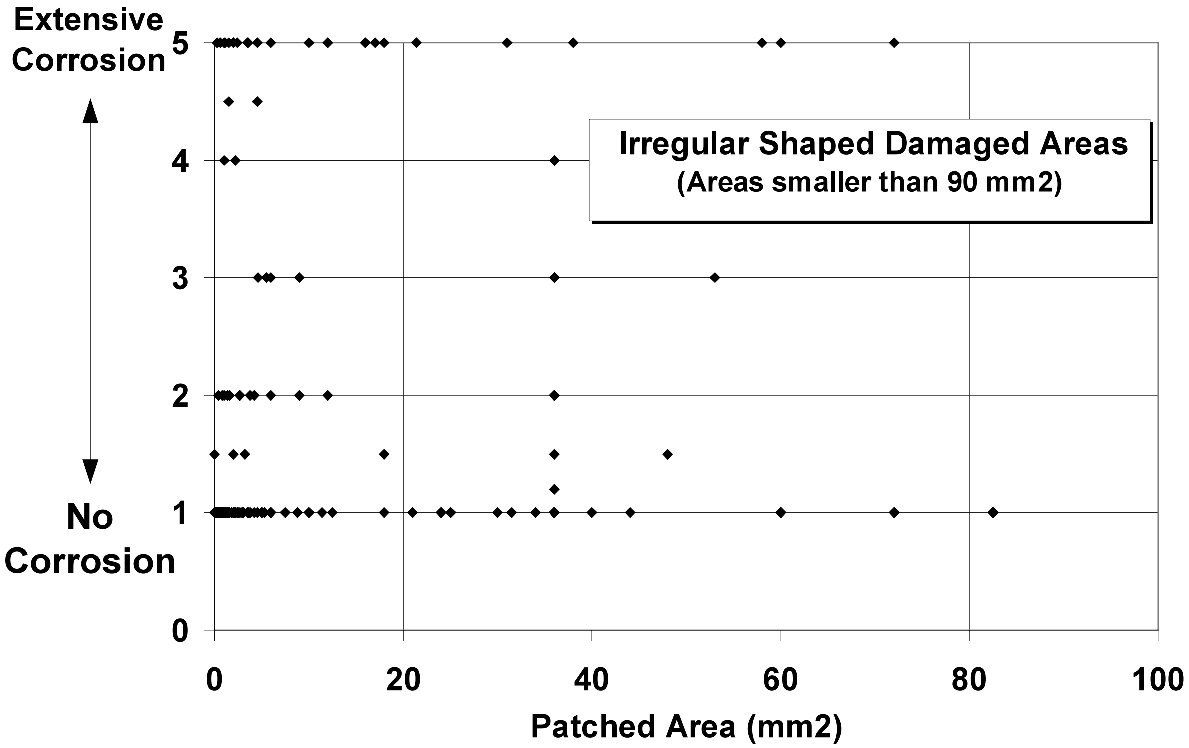


Figure 3.19 Corrosion rating vs. size of patched area.

CHAPTER 4

Electrochemical Impedance Spectroscopy and Polarization Resistance

Electrochemical impedance spectroscopy and polarization resistance tests were conducted on 9 bar samples immersed in 3.5% NaCl solution for 100 days. Sample preparation involved removing all the epoxy coating with a wheel brush, preparing the metallic surface, and coating the bar with patching material. Electrochemical measurements were intended to monitor the behavior of patching materials only. If patched ECR samples had been used, the effect of epoxy coating and the patch material would have been measured but the relative contribution of each could not have been attained. The decision to remove coating from epoxy-coated bars instead of using plain samples was based on the desire to apply patch materials to bars with the same surface preparation prior to plant coating by fusion bonding.

4.1 TEST PROCEDURE AND EVALUATION

At one end, a hole was drilled and tapped to insert a screw for electrical connection. The other bar end was sealed with a plastic cap filled with epoxy cold mount resin. Bar specimens were immersed individually in one-liter plastic containers filled with 3.5% NaCl solution up to a height of 8 cm. Two graphite counter electrodes and a calomel reference electrode with Luggin probe were placed around the specimens using a special apparatus (Figure 4.1). The bar samples and electrodes were connected to the measurement instruments (Potentiostat/Galvanostat, Lock-In Amplifier, and IBM PC-XT). Bar specimens were immersed for about 100 days and measurements were taken at 12 hours, 2, 4, 7, 10, 14 days and at subsequent week intervals until 98 days after immersion. More frequent measurements were conducted in the first week to attempt to monitor the coating pore resistance and the initiation of corrosion. The electrolyte levels of the immersion cells were checked every three days and when necessary, replenished with solution at the fixed level. The screws securing electrical connections were periodically inspected for signs of corrosion and replaced when necessary.

Corrosion potential (E_{corr}), polarization resistance, and impedance measurements were performed in order on each specimen at scheduled time intervals. There was a fifteen minute delay period between the polarization resistance and the impedance measurement to allow the specimen to return from the polarized condition back to its rest state. The polarization resistance measurement was run between $\pm$ 20 mV with respect to E_{corr} using a scan rate of 0.1 mV/sec. An impedance measurement consisted of three independent readings to cover a wide frequency range. One measurement, based on the Lock-in Amplifier (single-sine wave) technique, was set to cover the range from 10 hertz to 100 kilo-hertz, with 8 data points obtained per decade of frequency. The other two measurements were based on the Fast Fourier Transform (multi-sine wave) technique: One measurement was run using a base frequency of

0.1 hertz to cover the range from 0.1 hertz to 10 hertz. The other measurement was performed with a base frequency of 0.001 hertz to cover the range from 0.001 hertz to 0.1 hertz. Two data acquisition cycles were used for both measurements. All three measurements used sinusoidal voltage excitations with amplitudes of 15 mV and were run at the specimen's open circuit potential. Data obtained from the three measurements were merged in one curve for analysis. Frequencies lower than 0.001 hertz were not used because of the long times to complete the testing and of the potentially serious problems that might occur during data acquisition.

Figure 4.1 Test setup for EIS and polarization resistance tests.

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 coating was then removed with a utility knife or chiseled. The steel surface condition was examined visually and photographed.

4.2 STUDY VARIABLES

Three patching materials and three surface preparation conditions were evaluated. As in the immersion test, patching materials *A, B,* and *C* were used (Figure 4.2). Types of surface preparation were as follows:

1–No surface preparation: Specimens were subjected to two weeks of outdoor exposure until rust developed on steel surfaces. Water was poured on the specimens during dry days to simulate rain. The rusted steel surfaces were then coated with patching materials with no further surface preparation.

2–Wire-brushed surface: Specimens were subjected to two weeks of outdoor exposure until rust developed on steel surfaces. Water was poured on the specimens during dry days to simulate rain. Surfaces were then thoroughly cleaned with a wire brush before coating with patching materials.

3–Control: The surface was thoroughly cleaned with a wheel brush until a polished, near-white finish was achieved. Remaining grease and dirt was removed with acetone to produce a shiny, bright metallic surface. Immediately after cleaning, patching material was applied.

The three steel surface conditions can be seen in Figure 4.3. After samples were prepared, coated, and cured, coating thickness was measured with a Mikrotest thickness gage. Average coating thickness for each specimen is listed in Table 4.1. As before, no attempt was made to control coating thickness. Thickness was related to the viscosity of each epoxy material.

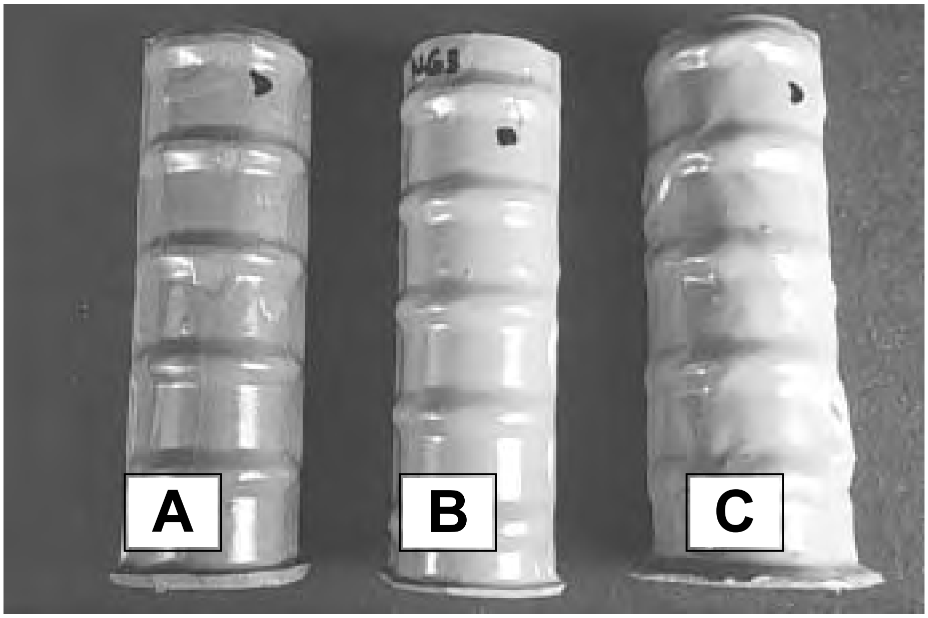


Figure 4.2 Specimens coated with patching materials *A, B,* and *C*.

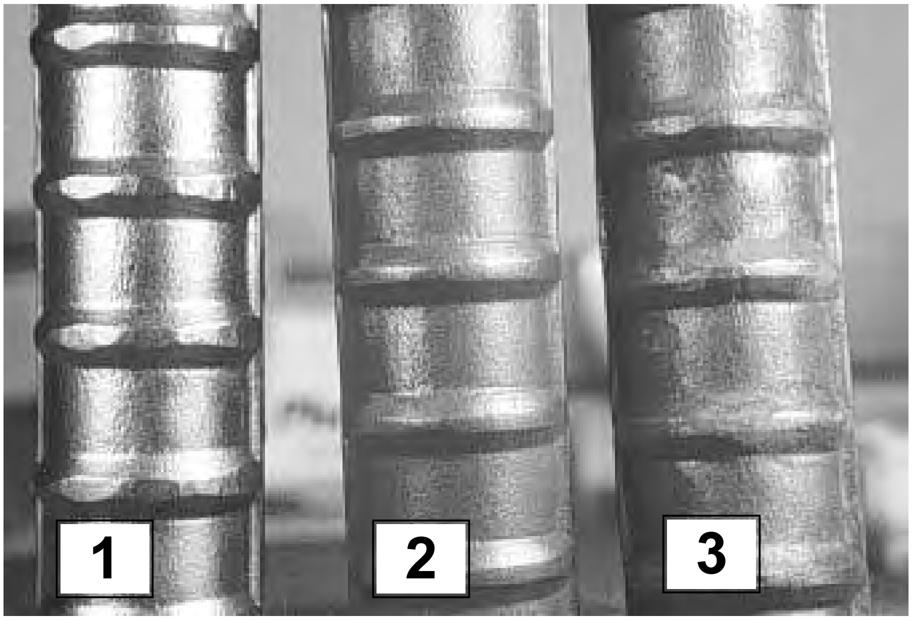


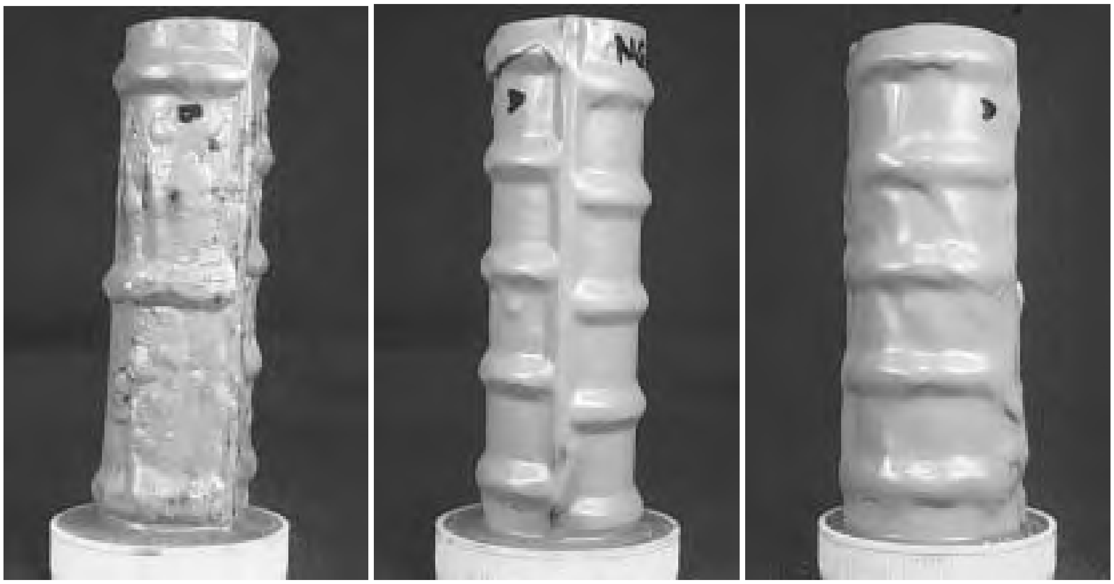
Figure 4.3 Steel surface conditions on specimens: (1) No surface preparation, (2) wire brushed, and (3) control.

Table 4.1 Average coating thickness (mills) of specimens for EIS and polarization resistance.

Patching Material	Surface Preparation		
	1	2	3
A	6.8	6.4	5.2
B	8.5	12.3	11
C	34	36.8	32.2

4.3 CORROSION OF SPECIMENS

Specimens patched with material *A* developed extensive blistering with formation of many small rust spots, mainly on ribs and mill marks [Figure 4.4(a)]. After several weeks of drying, coating cracked along longitudinal ribs. The steel surface underneath the coating had a uniformly dark rusted appearance with extensive accumulation of fine orange-brown rust, especially beneath blistered areas (Figure 4.5). The coating had poor adhesion and was easy to peel with a utility knife. Specimens patched with material *B* showed a few rust spots or stains. Coating material did not blister [Figure 4.4(b)]. Two specimens had some cracking in the coating along longitudinal corrugation. Outside localized rust spots, the coating remained in good condition. A few isolated, hardened dark and reddish-brown rust spots formed at sides of ribs on the bar surface beneath the coating. The degree of corrosion at such spots looked superficial, with no accumulation of loose, fine reddish or orange-brown rust. The rest of the steel surface appeared to be in very good, non-corroded condition (Figure 4.5). Patch adhesion was poor at corroded areas, and ranged from good to poor at non-corroded areas in all specimens. Finally, specimens coated with patching material *C* did not exhibit any rust spots or staining on the coating surface. The patch was clean and shiny [Figure 4.4(c)]. The steel surface underneath the coating was in extremely good condition (Figure 4.5). Coating removal required chiseling but practically no coating residues were left on the metallic surface. Observed corrosion agreed with EIS and polarization resistance measurements.



(a) Patch material *A*. (b) Patch material *B*. (c) Patch material *C*.

Figure 4.4 Surface condition of specimens coated with patching materials *A*, *B*, and *C* after 100 days in 3.5% NaCl solution.

Figure 4.5 Steel surface condition underneath patching materials *A*, *B*, and *C* after 100 days in 3.5% NaCl solution.

4.4 TEST RESULTS AND DISCUSSION

Electrochemical impedance results for all specimens are plotted in Bode format in Figure 4.6. There is a clear difference in behavior among the three patching materials. For the lower frequency region, the magnitude of impedance for patching material *C* is the greatest, followed by material *B*, and then by material *A*, regardless of surface preparation. The greater the impedance, the greater the corrosion resistance of the specimen. Therefore, patching material *C* showed the best corrosion performance, followed by *B* and *A*. Material *C* showed linear behavior with a slope of -1 throughout almost all frequencies. This represents purely capacitive behavior, which is indicative of a high quality coating with no defects. Curves for material *B* deviated from linearity and flattened at frequencies lower than 10^3 hertz. This is characteristic of a corrosion process largely controlled by diffusion of corrosive ions and oxygen to the steel surface. Curves for material *A* have small impedance magnitudes and are flat throughout the whole frequency range. The corrosion process is largely controlled by charge transfer reaction and is indicative of a coating with poor pore resistance (the coating does not retard the ingress of corrosive elements).

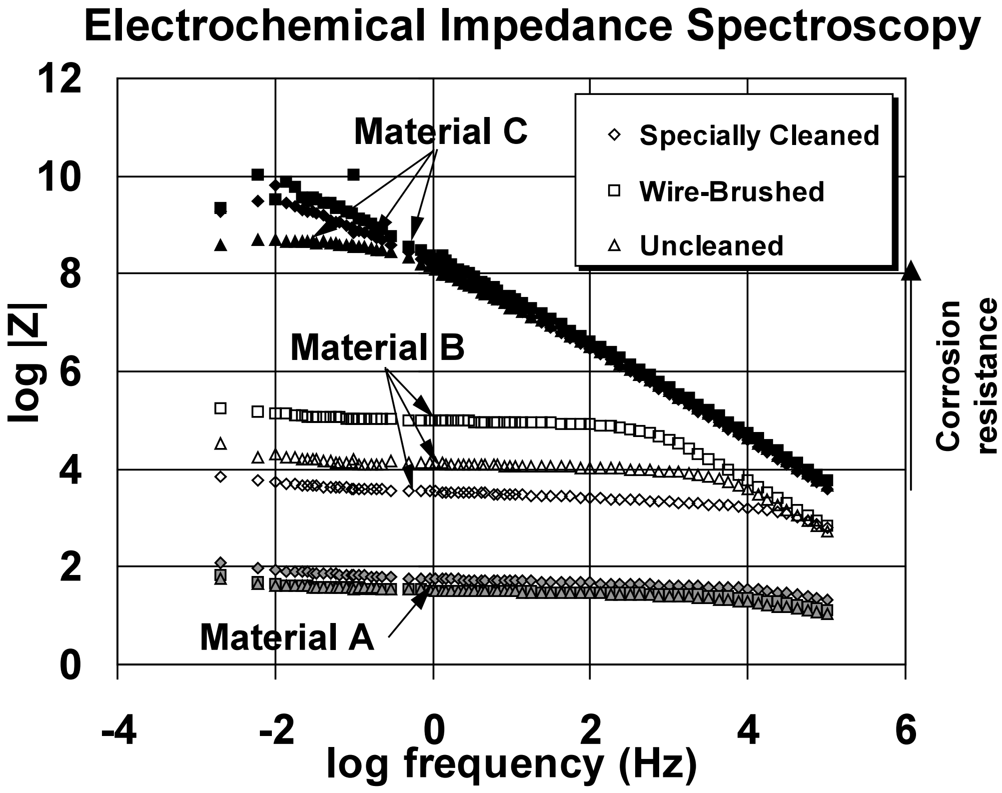


Figure 4.6 EIS results in Bode format (3 patching materials and 3 repair procedures) after 100 days in NaCl solution.

From Figure 4.6, it is clear that the effect of surface preparation on the corrosion performance of coated specimens is negligible when compared to the effect of patching material type. In addition, no surface preparation procedure was consistently better or worse. These results were in complete agreement with results from the cyclic immersion tests.

Corrosion currents after 100 days as measured by polarization resistance are summarized in Table 4.2. Again, specimens coated with material *A* experienced much greater corrosion currents than specimens patched with materials *B* and *C*. Specimens coated with material *B* showed small corrosion current. No stable values could be measured for specimens coated with material *C*, an indication of the absence of corrosion activity.

Table 4.2 Corrosion current (μA) as measured by polarization resistance after 100 days of immersion.

Patching Material	Surface Preparation		
	1	2	3
A	226.5	451.2	475.6
B	3.16	0.13	0.65
C	-	0.01	-

CHAPTER 5

Hot Water Immersion-Adhesion Test

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.

5.1 TEST PROCEDURE AND EVALUATION

Seventeen epoxy-coated bar samples containing 68 patched areas were tested. Samples 17 cm long were cut from epoxy coated #10 and #11 bars. Samples were prepared and patched using several repair materials and procedures as described in the next section. Once cured, patch thicknesses at repaired locations were measured with a Mikrotest thickness gage. Samples were subjected to 24 hours of hot water immersion at a temperature of 75°C. Specimens were allowed to dry for 24 hours at room temperature. Adhesion tests were then conducted at the patched areas following a procedure described in Appendix B.

5.1.2 Study Variables

The following variables were used for hot water immersion-adhesion tests:

Patching Materials

Four patching materials were used. In addition to materials *A* and *B* (previously described in chapter 2), materials *E* and *F* were tested. The characteristics of such repair material are as follows:

E	Material of very thin consistency in its liquid state. Can be applied by brush, roller, or spray. Dry to touch in about 6 hours in a small 2 oz. cup at a temperature of approximately 21°C. Bright green color.
F	Material of viscous consistency in its liquid state. Can be applied by brush or roller. Dry to touch in about 3 hours in a small 2 oz. cup at a temperature of approximately 21°C. Grayish green color.

Patching materials “*E*” and “*F*” are no longer manufactured. For this reason, they were not included in the immersion and EIS studies.

Damaged Areas

Coating damage was caused at areas between bar deformations. Rectangular incisions of 11 x 16 mm and 6 x 6 mm were made through the coating with a sharp utility knife. Coating inside the rectangular incision was removed with a chisel blade mounted on an X-acto knife.

Repair Procedures

b Patching Immediately Applied after Damage and Surface Cleaning (Wire Brush)

e Patching Applied on Surface Cleaned (Wire Brush) after Outdoor Exposure

f Patching Applied after Short Outdoor Exposure of Previously Cleaned Surface (Wire Brush)

i Brush-Applied Patching on Untreated Surface after Outdoor Exposure

k Hand-Applied Patching on Untreated Surface after Outdoor Exposure

A description of each of the above procedures is included in Appendix A.

5.2 TEST RESULTS AND DISCUSSION

Materials *A* and *E* showed poor adhesion to the steel surface. The patch was easily removed by cutting and prying with the knife blade. The integrity of the patch was generally preserved after the test, except when patch was very thin. Larger patched areas were easier to peel than smaller areas.

The behavior of areas patched with materials *B* and *F* was quite varied. Patches had a tendency to either break, disintegrate, chip off, or tear apart. In several cases, the blade cut a narrow strip of patch only, and the remaining patch area was intact. Adhesion ranged from relatively good to poor, but in most cases was difficult to assess. Larger patched areas were easier to peel than smaller areas. Patching materials *B* and *F* were more brittle and patching materials *A* and *E* were more flexible.

No attempt was made to rate patch adhesion of specimens because of the difficulty in adequately interpreting test results when the patch was broken, disintegrated, or chipped off during the test. Patching materials *B* and *F* seemed to have better adhesion to the steel surface than materials *A* and *E*. However, it was not possible to precisely assess their overall adhesion performance. In all cases, adhesion of the patch to steel surface was much lower than the adhesion of the original epoxy coating to the steel surface.

In conclusion, the hot water immersion-adhesion test was not found adequate to assess patching materials and procedures because of the difficulty in satisfactorily interpreting test results. Besides, there seemed to be little correlation between patch material adhesion and corrosion resistance.

CHAPTER 6

Summary, Conclusions, and Recommendations

6.1 SUMMARY

A pioneering experimental study of repair of coating damage was performed. No research in this area had been reported previously. 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 rebar, three major series of experiments were conducted: a) cyclic immersion in NaCl solution, b) electrochemical impedance and polarization resistance, and c) hot water immersion-knife 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.

6.2 CONCLUSIONS

Corrosion performance was mostly affected by the patching material consistency and texture. Materials of greater viscosity and shorter curing time produced patches of greater thickness. Thicker patches performed better than thinner patches. However, 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 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 also showed very poor performance. Damaged and patched areas on bar sides experienced less corrosion than patched bar ends.

There was no clear effect by cleaning and application procedure and size of damaged area. No improvement in performance was observed with surface cleaning before patching. Rounding and smoothing sharp edges at bar ends did not prove successful. Manufacturers' application procedures indicate that proper surface preparation is important for satisfactory performance but this correlation is not supported by results obtained in this study. There was excellent agreement of test results between cyclic immersion testing and electrochemical experiments. Hot water immersion-adhesion test proved unsuccessful to assess coating repair quality.

Corrosion of patched areas was in the form of coating blisters, patch softening and debonding, rust spotting and staining, fine rust exudation, and breakage and delamination of patch at perimeter of bar end section. Corrosion on the steel surface beneath patches was in the form of uniform black or dark rusted surfaces combined with areas of reddish-brown (or other tones of brown) rust.

6.3 RECOMMENDATIONS

6.3.1 Recommended Practice

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 on bottom surfaces. The minimum thickness of a patch should be 14 mils. Discontinuities on the patch surface should be avoided. Slag and burrs should be removed from bar cut ends. Preferably, epoxy coated rebar should not be flame-cut and patched. Patching materials of high viscosity and thick texture provide excellent protection but are difficult to use. Additional research is needed to develop repair materials with good workability and acceptable corrosion performance. Of the materials considered here, material "B" was one of the easiest to apply. It also provided generally satisfactory corrosion performance if properly applied. The combination of ease of use and performance made it a desirable material. Based on research findings from this study, 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. The development of a small wire brush with closely spaced bristles would greatly facilitate cleaning of small damaged areas without abrading the adjacent epoxy coating.

6.3.2 Future Research

Future research efforts should be directed at a) defining the specific engineering properties that make a patching material perform well, and b) developing an improved patch formulation that will be easy to apply and still provide adequate corrosion protection. The relevant properties must be identified in order to develop a satisfactory and practical patch formulation.