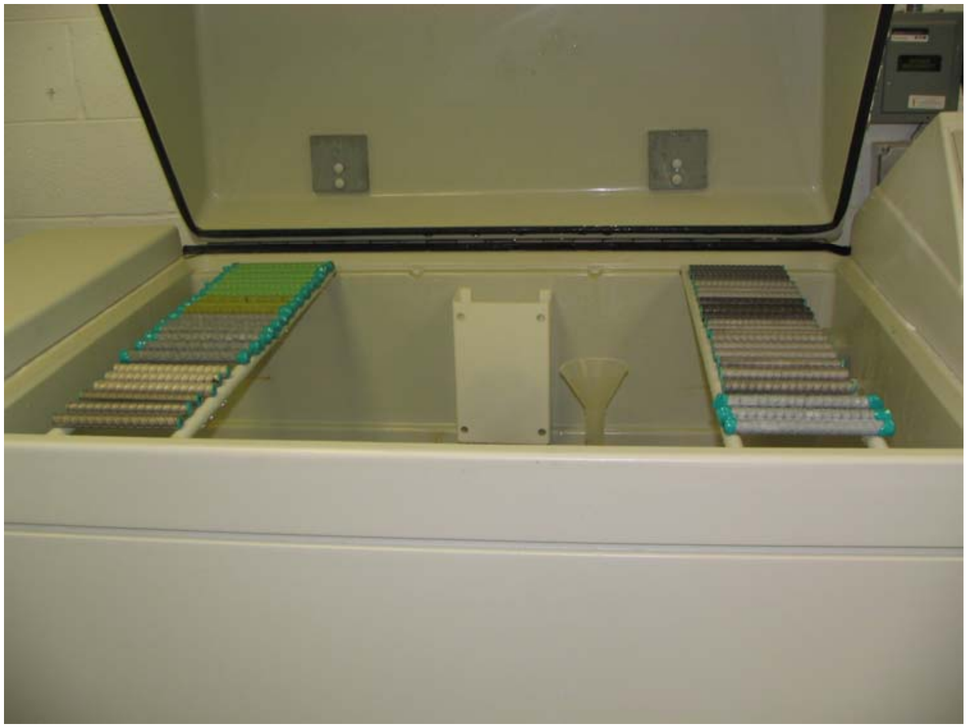
Corrosion Resistance of Alternative Reinforcing Bars: An Accelerated Test



Final Report
24 July 2006
WJE No. 2006.0773

Prepared for:
CRSI

Prepared by:
Wiss, Janney, Elstner Associates, Inc.

CORROSION RESISTANCE OF ALTERNATIVE REINFORCING BARS: AN ACCELERATED TEST

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INTRODUCTION

An accelerated test program was performed to contrast the corrosion resistance of various alternative reinforcing bars. The main goal was to produce a simple comparison among bars of different types to assist engineers to better comprehend the relative corrosion resistance of those bars.

Epoxy coated reinforcing bar (ECR), an iron chromium alloy (8-10 wt% Cr), galvanized bars, stainless steel 3Cr 2201, 2205 and 316LN were studied, using regular carbon steel bars as a control. The bars follow the following ASTM standards:

Bar Types	ASTM
Epoxy coated reinforcing bars	A 775
Iron Chromium Alloy	A 1035
Galvanized bars	A 767
Stainless steel 3Cr12	A 995
Stainless steel 2201	A 995
Stainless steel 2205	A 995
Stainless steel 316LN	A 995
Carbon steel	A 615

The bars were exposed in a Q-fog chamber to 5 percent NaCl salt spray at 35^{o}C for up to 672 hours (4 weeks). The bars were visually examined periodically and at 174, 440 and 672 hours one bar per type was removed from the chamber, cleaned, and weight loss was determined.

EXPERIMENTAL

Bar Materials

As shown below, eight types of reinforcing bars, with various surface conditions, were tested. A total of 14 specimen types were tested in triplicate. All bars, except the sandblasted A1035 bars, were No. 5 deformed bars (16mm). Due to the available supply of A1035 bars, No. 4 (13 mm) deformed A1035 bars were used for the sandblasted test condition.

Material	Test Condition	Nomenclature	Source
Epoxy coated bars-type A	0% damage	ECR-Type A-no hole	Toltec
Epoxy coated bars-type A	0.064% damage	ECR-Type A-hole	Toltec
Epoxy coated bars-type B*	0.064% damage	ECR-Type B-hole	N/A
Iron Chromium Alloy	As received	A1035-as received	Florida Atlantic University
Iron Chromium Alloy **	Sandblasted	A1035-sandblasted	CRSI
Galvanized bars-type A	As received	Galvanized-Type A-no hole	Stock
Galvanized bars-type A	0.064% damage	Galvanized-Type A-hole	Stock
Galvanized bars-type B	0.064% damage	Galvanized-Type B-hole	J.W. Peters, Inc
Stainless steel 3Cr12	Sandblasted	3Cr12-sandblasted	Florida Atlantic University
Stainless steel 2201	Sandblasted	2201-sandblasted	Florida Atlantic University

Material	Test Condition	Nomenclature	Source
Stainless steel 2205***	As received	2205-as received	Salit Specialty Rebar, Inc
Stainless steel 316LN***	As received	316LN-as received	Salit Specialty Rebar, Inc
Carbon Steel	As received	A615-as received	Stock
Carbon Steel	Sandblasted	A615-sandblasted	Stock

* Bars extracted from a 15-year-old bridge deck; **#4 bar; ***manufacturer pickled

All bar cut-ends were sealed with epoxy, exposing approximately 6 inches of bar length. For epoxy-coated and galvanized bars, as-received specimens and specimens with intentional small damaged areas were tested. The damage was introduced with a single 1/16 inch drill hole, resulting in a damaged area of ~0.064 percent.

Recently produced ECR (holiday free, ECR-Type A) and ECR retrieved from a 15 year old bridge deck in the Chicago area (ECR-Type B) were tested. Two of the extracted bar segments had a single smashed area (holiday indicated) and the third sample was holiday free.

For solid bars, as-received specimens were tested when possible. Among them, as-received A615 and A1035 bars had as-rolled mill scales while stainless steel 316LN and 2205 were pickled by the manufacturer. Picking is a process which removes mill scales by chemical reactions. Because the surface condition of as-received stainless steel 3Cr12 and 2201 varied from bar to bar with different amount of rust, these bars were sandblasted to achieve comparable surface between replicates. A615 and A1035 bars were also tested in sandblasted condition for compassion. Figure 1 shows appearance of selected bars before the exposure commenced.

Testing Program

All the bars were degreased with solvent, rinsed with Deionized water and air-dried. The bars were then exposed in a Q-fog chamber to 5 percent NaCl salt spray at 35^{o}C for up to 672 hours (4 weeks). The exposure condition followed the ASTM B117 test protocol with the following exceptions: 1) salt spray flow collection rate was between 2 and 3 ml/hour instead of specified 1-2 ml/hour; and 2) no pH adjustment or monitoring was performed.

Visual inspection of the samples was performed after 12, 30, 60, 108, 174, 440 and 672 hours of exposure. At 174, 440 and 672 hours, one bar per test condition was removed from the chamber and cleaned following ASTM G1-03 *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens* methods. The bars were then weighed to obtain weight loss data which was used to calculate average corrosion rates.

RESULTS

Photographs taken at selected inspection times (12, 30, 60, 108, 174, 440 and 672 hours) is provided in the Appendix. The photos were organized according to exposure time for visual comparison of different reinforcing bars. Selected photos of the bars are presented below.

A615 Bars

Both as-received and sandblasted bars corroded extensively and corrosion progressed quickly with time. Corrosion of as-received bars appeared to be more localized, probably due to the presence of the millscale oxide layer. The averaged corrosion rate of the three bars exposed for up to 28 days was 914.7 μm/year. As shown in Figure 2, the sandblasted bars experienced rather uniform corrosion. Corrosion rates, however, were consistently higher than the as-received bars. The estimated average corrosion rate of metal loss was about 70% higher than the as-received bars. Figure 2 shows the appearance of the bars after 174 hours of exposure.

A1035 Bars

Both as-received and sandblasted bars corroded significantly and corrosion progressed quickly with time. In both conditions, as illustrated in Figure 3, corrosion often took the form of deep pitting. Some pits had depths as high as 1 mm (measured with micrometer, one was 1mm and many were in the order of 0.5mm) after 440 hours of exposure. The average corrosion rate of metal loss were 625 and 523.6 μm/year for as received and sandblasted bars, respectively, which are about 60 percent of that of as received A615 bars.

Galvanized Bars

Galvanized bars with two different types of deformations were tested. All galvanized bars experienced extensive corrosion of a similar pattern: the zinc (Zn) coating corroded first producing a white color corrosion product and then the underlying carbon steel started to corrode producing a rusty color. Rust color was prominent after 2 weeks of exposure. The exposed carbon steel at drilled holes was protected until the adjacent zinc coating was consumed.

Weight loss analysis showed that these galvanized bars experienced extensive corrosion with very high corrosion rates. Average corrosion weight loss of the undamaged (Type A) galvanized bars, for example, was 1330 μm/year which is about 30 percent higher than that of the as-received A615 bars. Figure 4 shows the appearance of the Type A galvanized bars after 174 hours of exposure. Photos of pre-damaged (Type B) bars are documented in the appendix.

Stainless Steel 3Cr12

Soon after exposure started, as shown in Figure 5, surfaces of the sandblasted bars assumed a largely uniformly rusty color. After cleaning, it was observed that the bars experienced general corrosion attack at most areas and also some deep pitting corrosion near ribs. While corrosion of 3Cr12 appeared to be extensive, its average corrosion was just ~300 μm/year, half of the A1035 and about 1/3 the rate of the as-received A615 steel bars.

Stainless steel 2201

After 12 hours of exposure, as shown in Figure 5, corrosion products were visible on most of the bar surfaces and corrosion progressed with time. However, the cleaned bar showed that corrosion was rather superficial and no obvious pits were observed. Weight loss analysis yielded a very low average corrosion of 29.7 μm/year, which is about 3% of as-received A615 bars.

Stainless Steel 316 LN and 2205

Both types of stainless steels experienced some very localized corrosion and such corrosion evidently progressed with time. However, the total amount of corrosion was trivial and such corrosion was speculated to have been induced by local contamination or crevices generated by the coating used to seal cut ends. The estimated corrosion rates were lower than 2 μm/year for both materials. Surface condition of these bars after 174 hours of exposure is shown in Figure 6.

ECR-Type A

These epoxy-coated bars were recently produced and initially had no holidays. Specimens tested in the as-received condition experienced no corrosion throughout the 28-day testing program. The specimens with a drilled hole only corroded at the holes.

ECR-Type B

ECR bars (type B) were extracted from a 15-year-old bridge deck in Chicago area, and these bars also performed very well in this testing program. For the first 174 hours of exposure, corrosion only took placed at the drilled holes where underlying carbon steel was exposed. At time 440 hours, corrosion at addition sites (one location on each of the two remaining bars) was observed which apparently took place at pre-existing coating defects (one at a smashed area and one at a holiday).

For all the ECR specimens, corrosion only took place at coating defects such as drilled holes. Likely due to moisture absorption by the epoxy coating, weight loss measurement often yielded negative values. Accurate corrosion rates of these specimens consequently were not obtained. Corrosion of these specimens was nevertheless very localized and mass loss appeared to be trivial when comparing to that of uncoated A615 bars.

Surface conditions of both types of ECR with drilled holes are shown in Figure 7, and photos of ECR-Type A without holes can be found in the appendix.

DISCUSSION

Table A1 summarizes the weight loss and estimated corrosion rate data, which are illustrated in Figure 8. The corrosion rate ratios compared to the least corroded bars (316LN) are also included in this table. The bars can be divided into 4 groups based on their average corrosion rates:

1) A615 and galvanized bars- high corrosion rates (915 to 1558 μm/year)
2) A1035 and 3Cr12-intermediate corrosion rates (297 to 625 μm/year)
3) 2201-moderate corrosion rates (30 μm/year)
4) All ECR, 316 and 2205-minor corrosion rates. (less than 2 μm/year)

As stated earlier, corrosion rates of ECR specimens could not be accurately determined from weight loss data. However, they can be roughly estimated by assuming that exposed carbon steel at drilled hole will have the same corrosion rate as sandblasted A615 bars:

Corrosion rate of sandblasted A615:	1557.6 μm/year
Total percentage of damaged area in ECR:	0.064%
Estimated corrosion of ECR:	1.0 μm/year

This crude estimation is qualitative in nature, nevertheless, it suggests that ECR had very low corrosion rate. Therefore, ECR bars were assigned to group 4 which has minor corrosion rates.

The testing condition employed in this program is very aggressive and the corrosion rates are not typical of bars in a concrete environment. For example, the average corrosion rate of A615 black bars was about 900 μm/year in this test and about two orders of magnitude higher than typical corrosion rates of black bars in concrete. Nevertheless, this test program was able to provide a quick comparison of various reinforcing bars both qualitatively (visually) and quantitatively (weight loss).

While a number of studies have reported that A1035, 3Cr12 and galvanized bars provide improved corrosion resistance than conventional ASTM A615 bars, this test program demonstrated that these bars can corrode rapidly when subjected to salt spray. Further for galvanized bars, its corrosion resistance comes from the zinc coating of limited thickness (typically approximately 100 μm). This test program demonstrated that the zinc coated corrodes at rapid rate and is consumed, thereby loosing its protection to the underlying carbon steel.

Stainless steel 2201, with an average corrosion rate of approximately 30μm/year, performed substantially better than A1035 and 3Cr12 and its corrosion rate was just 3 percent of the as-received A615 bars. Stainless steel 316LN and 2205 bars were largely free of corrosion except some minor corrosion product near to cut ends. The coating applied to the cut ends may have generated crevices which are at least partially responsible for the observed corrosion. These two types of stainless bars exhibited phenomenal low corrosion rates, approximately 0.1 percent of conventional steel.

All the epoxy coated bars performed very well in this test program, and corrosion only took place at drilled holes and at other existing defects. The ECR-Type B bars were extracted from a 15-year old bridge deck in Chicago. Chloride analysis of the concrete showed that the chloride concentration at the bar depth was approximately 600 ppm, twice the typical chloride threshold for conventional black steel. All the extracted bars, however, had no signs of corrosion and the deck had no delaminations.

Table A2 summarizes the adhesion of the epoxy coating before and after being tested in the salt-spray chamber for up to 4 weeks. The recently coated bars (ECR-Type A) only lost some adhesion (1 to 1.5 points) at the drilled holes while the coating remained well bonded to the steel away from the drill holes. Likewise, the bars (ECR-Type B) extracted from the Chicago deck showed some adhesion loss at drilled holes (about 1.5 points) while adhesion at areas away from the holes remained largely unchanged. Figure 9 shows the knife adhesion results of three epoxy-coated bars after up to 4 weeks of exposure. All the three bars removed from the deck, including the two that had low adhesion before exposure, were largely corrosion-free except for localized corrosion at existing defects.

While chloride concentrations at the bar depth in the 15-year old Chicago bridge deck were higher than the threshold for black steel, no corrosion was observed on any of extracted bars and no distress was detected in the deck. As shown in Figure 10, the extracted bars had coating adhesion from very good (1) to poor (5). In addition, the bars with poor adhesion (5) remained passive in this highly accelerated testing program. These observations attest that adhesion loss does not necessarily indicate loss of protection.

CONCLUSIONS

1. A615 bars, both as-received and sandblasted condition, corroded at high corrosion rates. The sandblasted bars had corrosion rates even higher than the as-received bars. Pitting corrosion was noted.

2. A1035 and stainless steel 3Cr12 offered some improvement in corrosion protection and yet still corroded rapidly in this testing environment.

3. While the zinc offered protection to the underlying steel, the galvanized bars corroded extensively. Within 2 weeks, the zinc layer was essentially consumed and underlying steel corrosion was observed.

4. Stainless steel 2201 bars had a higher corrosion resistance and experienced only moderate corrosion in this test despite its rusty surface appearance.

5. Stainless steel 316LN and 2205 stainless bars had very high corrosion resistance and only experienced minor corrosion likely due to presence of crevices or steel contamination.

6. Type A epoxy-coated bars (recently produced) performed very well, corrosion was only observed at drilled holes.

7. Epoxy-coated bars removed from a 15-year old deck performed well during the test. Corrosion was minor and only took place at drilled holes and later at existing defects in the coating. The epoxy coating adhesion did not affect the corrosion performance. Bars with poor coating adhesion performed well in the test.

8. The salt spray tests were very aggressive to some steels. The corrosion rates measured were much higher than expected on bars embedded in concrete. Nevertheless, the observed corrosion performance provides a simple and useful comparison of the corrosion resistance of the various bar types.

Figure 1. Condition of selected bars before exposure. From left to right: A615-as received; Galvanized-Type B-hole; A1035-as received; ECR-Type B-hole; and 2205-as received.

A **B** **C** **D**

Figure 2. Appearance of A615 bars after 174 hours of exposure. A) as-received; B) as-received after cleaning; C) sandblasted; D) sandblasted after cleaning

A **B** **C** **D**

Figure 3. Appearance of A1035 bars after 174 hours of exposure. A) as-received; B) as-received after cleaning; C) sandblasted; D) sandblasted after cleaning

A **B** **C** **D**

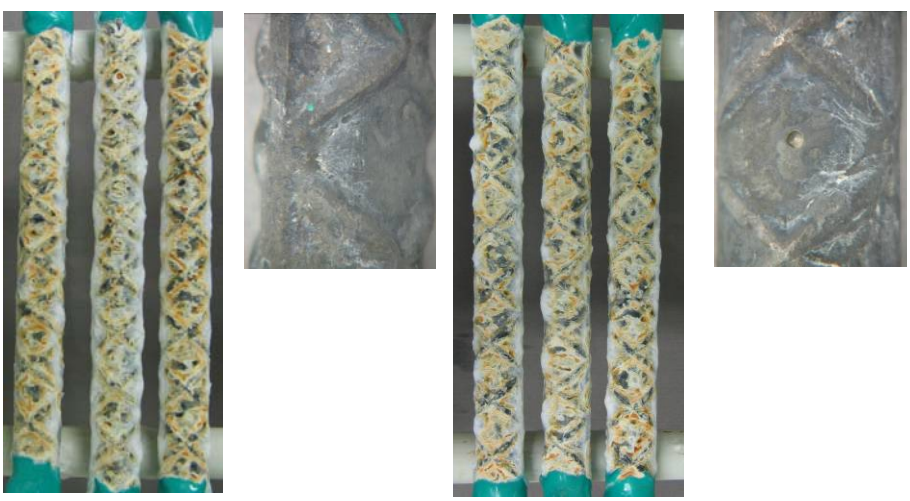


Figure 4. Appearance of Type A galvanized bars after 174 hours of exposure. A) no hole; B) no hole after cleaning; C) with a hole; D) with a hole after cleaning

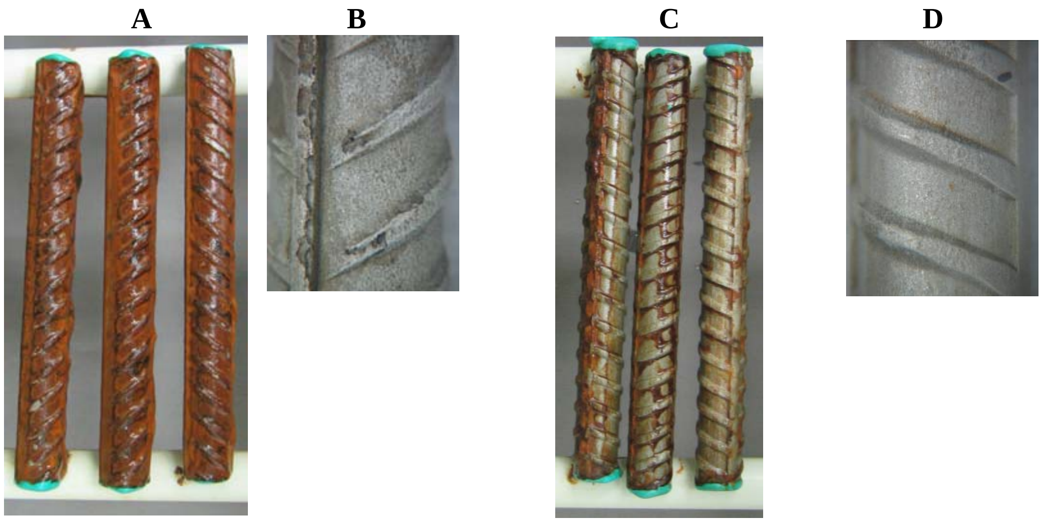


Figure 5. Appearance of stainless steel 3Cr12 and 2201 after 174 hours of exposure. a) 3Cr12; b) 3Cr12-after cleaning; c) 2201; d) 2201 after cleaning

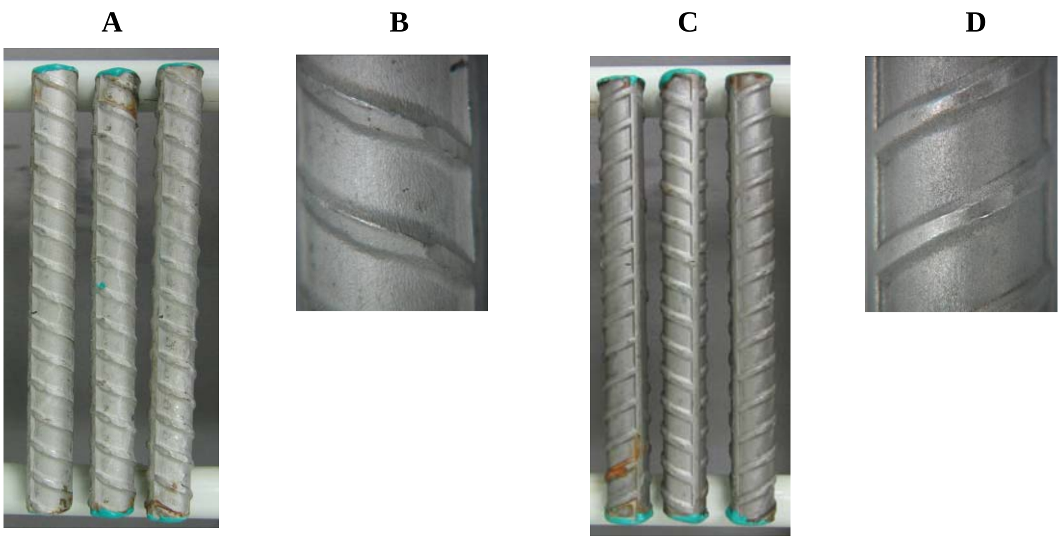


Figure 6. Appearance of stainless steel 316LN and 2205 after 174 hours of exposure. A) 316LN; B) 316LN after cleaning; C) 2205; D) 2205 after cleaning

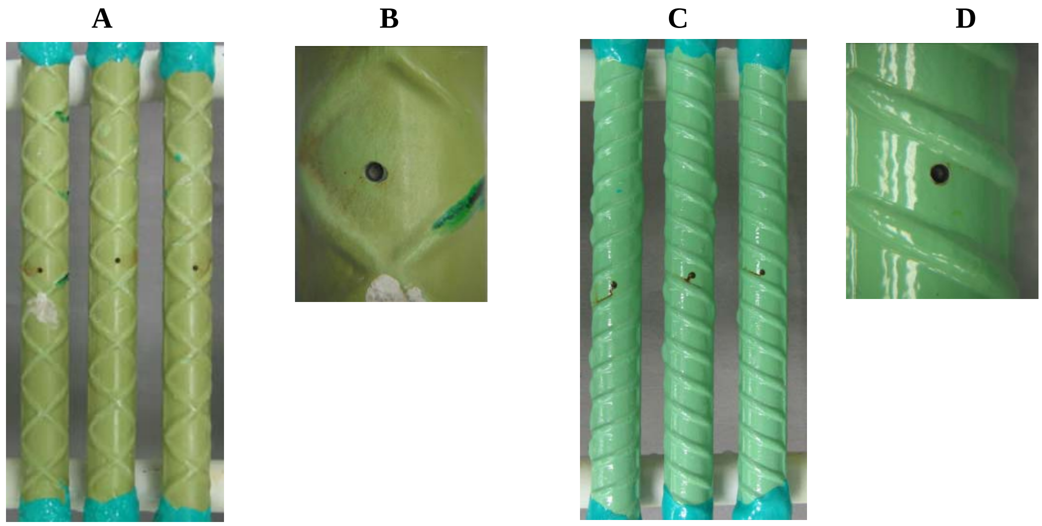


Figure 7. Appearance of ECR after 174 hours of exposure. A) ECR-Type B-hole (15 years old extracted from a Chicago bridge deck); B) ECR-Type B-hole, after cleaning; C) ECR- Type A-hole; D) ECR- Type A-hole, after cleaning

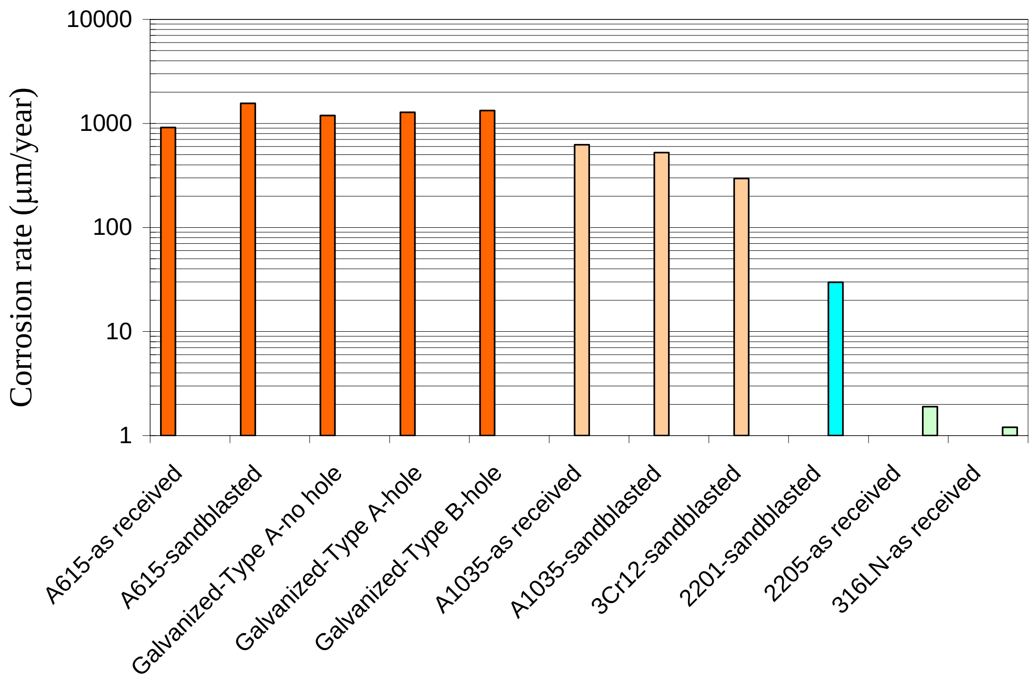


Figure 8. Average corrosion rates of various reinforcing bars. The method using weight loss data to determine corrosion rate was not applicable to epoxy-coated rebar (ECR). Corrosion rate of ECR, however, was minor and estimated to be in the same order as stainless steel 316LN and 2205.

Figure 9. Knife adhesion test of Epoxy-coated bars after 4 weeks of exposure. From top to bottom: ECR-Type A-no hole; ECR- Type A-hole; ECR- Type B-hole

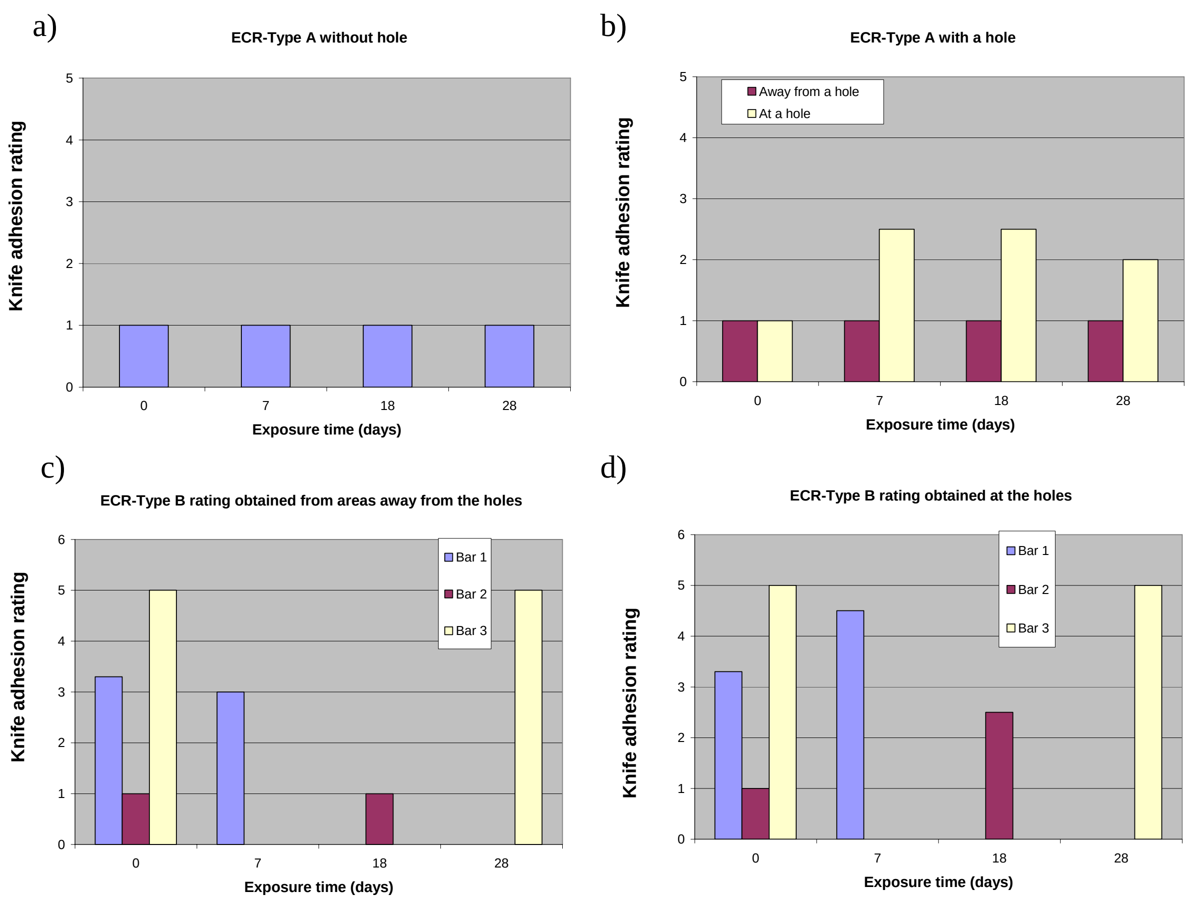


Figure 10. Knife adhesion rating of epoxy-coated bars

APPENDIX 1- TABLES

Table A1. Weight Loss and Calculated Corrosion Rates

	weight loss (grams)			corrosion rate (μm/year)			Average corrosion rate (μm/year)	Ratio vs 316LN
	174h/7days	440h/18days	672h/28days	174h/7days	440h/18days	672h/28days		
A615-as received	0.753	3.535	4.170	639.8	1187.3	917.1	914.7	779.9
A615-sandblasted	1.615	4.582	8.015	1371.6	1538.7	1762.5	1557.6	1327.9
Galvanized-Type A-no hole	1.702	3.644	4.101	1445.3	1223.7	901.7	1190.2	1014.7
Galvanized-Type A-hole	1.868	3.845	4.391	1586.1	1291.3	965.5	1281.0	1092.1
Galvanized-Type B-hole	1.738	4.278	4.899	1475.9	1436.8	1077.4	1330.0	1133.9
A1035-as received	0.758	1.831	2.803	643.7	615.0	616.4	625.0	532.9
A1035-sandblasted[1]	0.605	1.318	1.727	639.7	551.3	379.7	523.6	446.4
3Cr12-sandblasted	0.437	0.835	1.086	371.2	280.4	238.7	296.8	253.0
2201-sandblasted	0.054	0.076	0.082	45.7	25.5	17.9	29.7	25.3
2205-as received	0.001	0.004	0.016	0.8	1.3	3.4	1.9	1.6
316LN-as received	0.002	0.002	0.005	1.6	0.7	1.2	1.2	1.0
ECR-Type B-hole[2]	-0.018	-0.042	-0.064	N/A	N/A	N/A	N/A	N/A
ECR-Type A-no hole[2]	-0.011	-0.024	-2.015	N/A	N/A	N/A	N/A	N/A
ECR-Type A-hole[2]	0.001	--	-1.748	N/A	N/A	N/A	N/A	N/A

[1] #4 bars (surface area ~61cm^2); all others are #5 bars (surface area ~76cm^2).

[2] Corrosion rates of epoxy coated rebar couldn't be accurately determined based on weight loss data. Weight loss induced by steel corrosion at drilled hole was very small.

Table A2. Adhesion of Epoxy Coated Rebar Before and After Exposure

	Adhesion Before Exposure			**Adhesion After Exposure**		
				7 days	2 weeks	4 weeks
ECR-Type A-no hole-1	1	1	1	1,1,1		
ECR-Type A-no hole-2	1	1	1		1,1,1	
ECR-Type A-no hole-3	1	1	1			1,1,1
ECR-Type A-hole-1	1	1	1	At hole: 2.5 Elsewhere: 1,1,1		
ECR-Type A-hole-2	1	1	1		At hole: 2.5 Elsewhere: 1,1,1	
ECR-Type A-hole-3	1	1	1			At hole: 2 Elsewhere: 1,1,1
ECR-Type B-hole-1	2	3	5	At hole: 4.5 Elsewhere: 3,3,3		
ECR-Type B-hole-2	1	1	1		At hole: 2.5 Elsewhere: 1,1,1	
ECR-Type B-hole-3	5	5	5			At hole: 5 Elsewhere: 5,5,5

APPENDIX 2 - SURFACE CONDITION OF REINFORCING BARS

Figure A1. Surface condition of bars before exposure

A615-as received

Galvanized-Type B-hole

ECR-Type B-hole

A1035-as received

3Cr12-sandblasted

2201-sandblasted

316-as-received

2205-as received

A615-sand blasted

Galvanized-Type A-no hole

Galvanized-Type A-hole

ECR-Type A-no hole

ECR-Type A-hole

A1035-sand blasted

Figure A2. Surface condition of bars after 12 hours of exposure

A615-as received

Galvanized-Type B-hole

ECR-Type B-hole

A1035-as received

3Cr12-sandblasted

2201-sandblasted

316-as-received

2205-as received


A615-sand blasted


Galvanized-Type A-no hole


Galvanized-Type A-hole

ECR-Type A-no hole


ECR-Type A-hole


A1035-sand blasted


Figure A3. Surface condition of bars after 30 hours of exposure



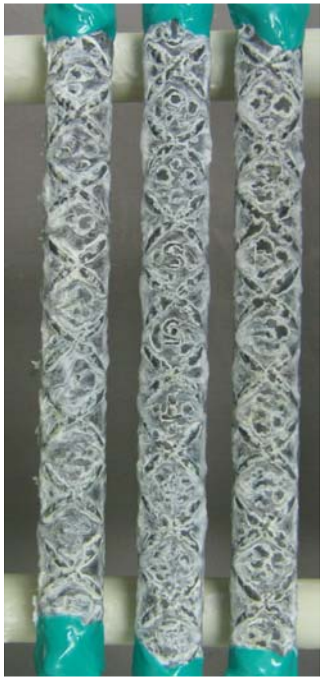

A615-as received Galvanized-Type B-hole ECR-Type B-hole A1035-as received

3Cr12-sandblasted 2201-sandblasted 316-as-received 2205-as received




A615-sand blasted

Galvanized-Type A-no hole



Galvanized-Type A-hole

ECR-Type A-no hole

ECR-Type A-hole

A1035-sand blasted

Figure A4. Surface condition of bars after 60 hours of exposure

A615-as received

Galvanized-Type B-hole

ECR-Type B-hole

A1035-as received

3Cr12-sandblasted

2201-sandblasted

316-as-received

2205-as received

A615-sand blasted

Galvanized-Type A-no hole

Galvanized-Type A-hole

ECR-Type A-no hole

ECR-Type A-hole

A1035-sand blasted

Figure A5. Surface condition of bars after 108 hours of exposure




A615-as received Galvanized-Type B-hole ECR-Type B-hole A1035-as received

3Cr12-sandblasted 2201-sandblasted 316-as-received 2205-as received




A615-sand blasted

Galvanized-Type A-no hole

Galvanized-Type A-hole

ECR-Type A-no hole

ECR-Type A-hole

A1035-sand blasted

Figure A6. Surface condition of bars after 174 hours of exposure

A615-as received

Galvanized-Type B-hole

ECR-Type B-hole

A1035-as received

3Cr12-sandblasted

2201-sandblasted

316-as-received

2205-as received


A615-sand blasted


Galvanized-Type A-no hole


Galvanized-Type A-hole

ECR-Type A-no hole


ECR-Type A-hole


A1035-sand blasted


Figure A7. Surface condition of bars after 440 hours of exposure

A615-as received Galvanized-Type B-hole ECR-Type B-hole A1035-as received

3Cr12-sandblasted 2201-sandblasted 316-as-received 2205-as received

A615-sand blasted

Galvanized-Type A-no hole

Galvanized-Type A-hole

ECR-Type A-no hole

ECR-Type A-hole

A1035-sand blasted

Figure A8. Surface condition of bars after 672 hours of exposure



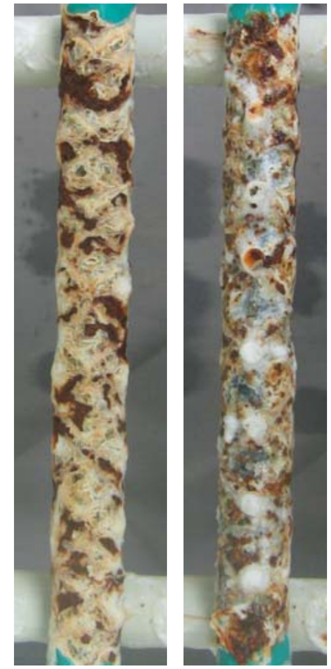

A615-as received Galvanized-Type B-hole ECR-Type B-hole A1035-as received

3Cr12-sandblasted 2201-sandblasted 316-as-received 2205-as received




A615-sand blasted

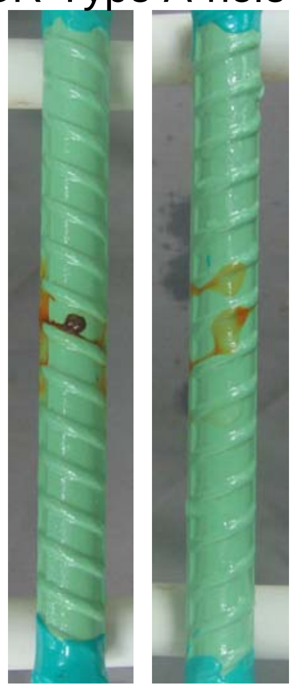
Galvanized-Type A-no hole



Galvanized-Type A-hole

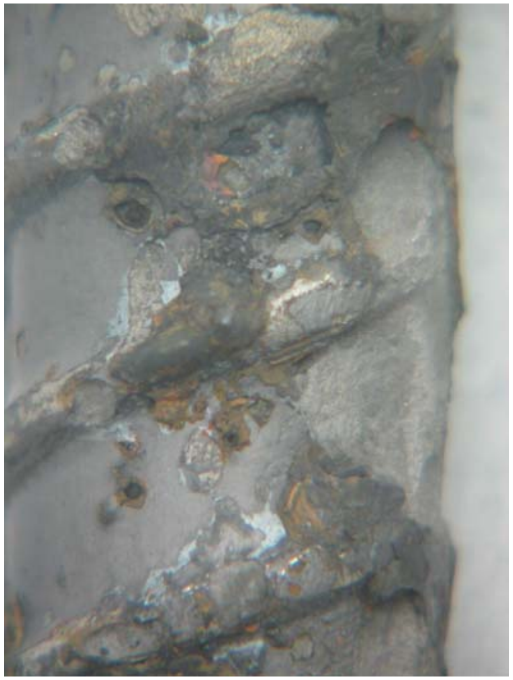
ECR-Type A-no hole

ECR-Type A-hole



A1035-sand blasted

Figure A9. Cleaned Surface Condition of Representative Bars After Four Weeks of Exposure



As received A615 bar: extensive corrosion, many broad pits

Sandblasted A615 bar: extensive corrosion, more uniform

As received A1035: deep pits

Sandblasted A1035: broader pitting attack

Galvanized-type A: extensive corrosion, many parts lost Zn coating. Steel in hole was largely protected

Sandblasted 3Cr12: extensive corrosion, pits and general

Sandblasted 2201: widespread superficial corrosion

As received 316LN: pristine condition except minor corrosion at bar ends

ECR-Type A: only steel exposed at the drilled hole corroded

ECR-Type A-adhesion: dark area lost adhesion, rate-2.5

ECR-Type B:

Only steel exposed at the drilled hole and a pre-existing defect corroded

ECR-Type B-adhesion: coating easy to peel: rate-5