CORROSION RESISTANCE OF STAINLESS STEEL CLAD REINFORCING BARS

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A Report on Research Sponsored by

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ABSTRACT

The corrosion resistance of No. 6 Type 316 stainless steel clad bars produced by Commercial Metals Company (CMC) was evaluated using the rapid macrocell and cracked beam tests (15 and 96 weeks, respectively), as described in the Annexes of ASTM A955. The bars were pickled in a 20% hydrochloric acid solution for five minutes, but exhibited some residue after the pickling process. Some bars were sandblasted and repickled at the University of Kansas to remove the residue; these repickled bars were also evaluated in the rapid macrocell test. Both the as-received and repickled bars met the requirements of ASTM A955 when evaluated using the rapid macrocell test. Two of the bars evaluated in the cracked beam test exceeded the 0.5 µm/yr, the upper limit for corrosion rate specified in ASTM A955. Upon autopsy of the specimens, it was determined that corrosion only occurred on the cut ends of the bars and not the cladding itself. The stainless steel clad reinforcing bars evaluated in this study met the requirements of ASTM A955. It is recommended that protection of the cut ends of stainless steel clad bars be employed where the use of corrosion resistant reinforcing bars is required.

Keywords: corrosion, concrete, reinforcing steel, stainless steel, stainless steel clad bars

ACKNOWLEDGEMENTS

The research described in this report was supported by Commercial Metals Company (CMC).

INTRODUCTION

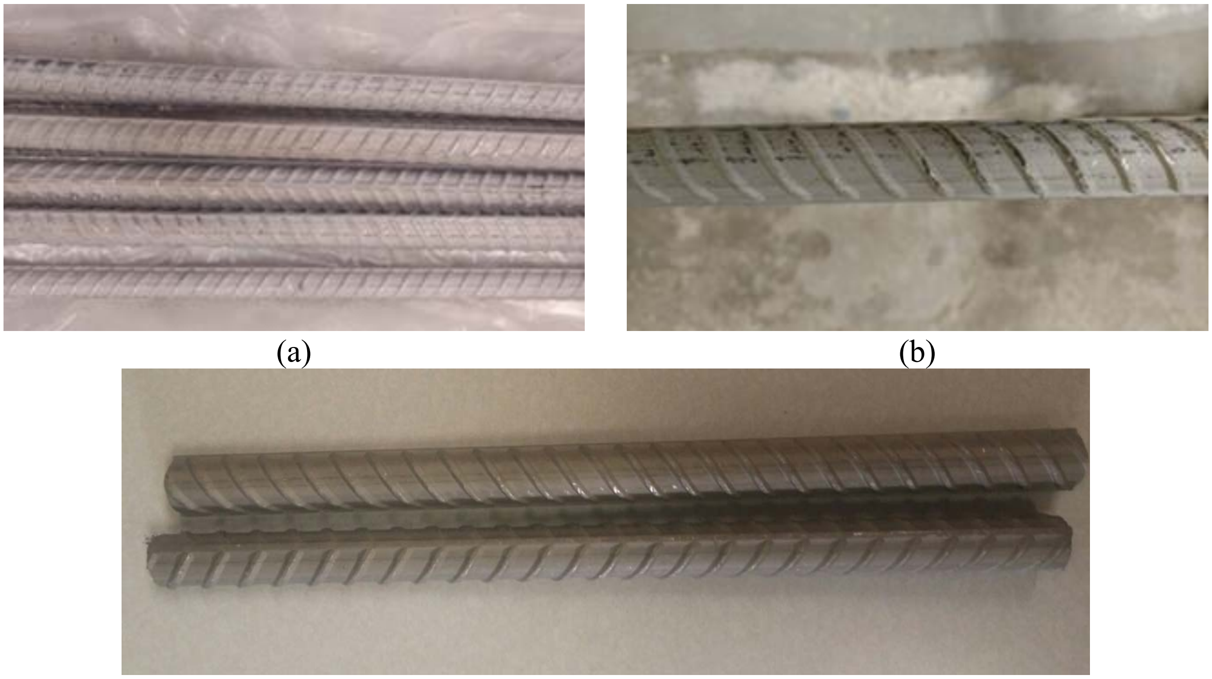
This report describes the evaluation of the corrosion performance of stainless steel clad reinforcing bars produced by Commercial Metals Company (CMC). The bars from one heat of No. 6 Type 316 stainless steel clad steel were tested using the two corrosion test methods specified in the Annexes A.1, A.2, and A.3 of ASTM A955–the rapid microcell and the cracked beam test, modified for No. 6 bars in place of the No. 5 bars specified in ASTM A995. Descriptions of the rapid macrocell and cracked beam tests, including fabrication, test procedure, and corrosion measurements, are presented in this report.

EXPERIMENTAL WORK

MATERIALS

Stainless Steel Clad Bars

The bars were hot-rolled carbon steel encased in a bonded Type 316 stainless steel shell. The stainless steel was pickled in a 20% hydrochloric acid solution for 5 minutes prior to shipment. Upon receiving the reinforcing bars, it was noted that a dark-colored residue was present on a portion of the bar surface (Figures 1a and 1b). The bars showed no surface rust (Figure 1a). To determine if the residue affected the corrosion performance of the steel, the bars were tested in the rapid macrocell test both in the as-received condition and after sandblasting and repickling the surface in a mixture of 25% nitric acid and 5% hydrofluoric acid at 73 °F for five minutes to remove the residue. Figures 1b and 1c show the surface of the bars before and after cleaning, respectively. The testing program is summarized in Table 1.


(a) (b)

(c)

Figure 1: Test bars a) As-received condition, b) Close up of residue on bars, c) Bars after cleaning and repickling

Table 1: Test Program

Bar Condition	**Number of Specimens**	
	Rapid Macrocell	**Cracked Beam**
As-received	6	6
Repickled	6	-

Concrete

The concrete mixture proportions used for the cracked beam specimens as shown in Table 2. Materials consisted of Type I Portland cement, Kansas River sand, and crushed limestone. The air entraining agent was Daravair 1400; the target air content was 6±1%. All specimens were cast from a single batch of concrete. The properties of the plastic and hardened concrete are summarized in Table 3.

Table 2: Mixture proportions for lab specimens based on SSD aggregate

Cement lb/yd^3 (kg/m^3)	**Water lb/yd^3 (kg/m^3)**	**Coarse Aggregate lb/yd^3 (kg/m^3)**	**Fine Aggregate lb/yd^3 (kg/m^3)**	**Air-entraining Agent oz/yd^3 (ml/m^3)**
598 (355)	269 (160)	1484 (880)	1435 (851)	5.37 (208)

Table 3: Properties of plastic and hardened concrete

Slump	2 in. (50.8 mm)
Temperature	82° F (28° C)
Air Content	5.5 %
Unit Weight	146.2 lb/ft^3 (2342 kg/m^3)
28-day Compressive Strength	5107 psi (35 MPa)

RAPID MACROCELL

Description

The rapid macrocell test exposes bars to simulated concrete pore solution with and without chloride contamination and is outlined in Annex A2 of ASTM A955/A955M-16a. A schematic of the test is shown in Figure 2. A single rapid macrocell specimen consists of an anode and a cathode. The cathode consists of two bars submerged to a depth of 3 in. in simulated concrete pore solution in a plastic container, as shown in Figure 2. One liter of pore solution consists of 974.8 g of distilled water, 18.81 g of potassium hydroxide (KOH), and 17.87 g of sodium hydroxide (NaOH). Air is bubbled into the cathode solution to remove carbon dioxide and provide oxygen required for the cathodic reaction. The anode consists of a single bar submerged in a solution consisting of the simulated pore solution and 15 percent sodium chloride (NaCl), prepared by adding 172.1 g of NaCl to one liter of pore solution. The solutions are changed every five weeks to limit the effects of carbonation. The anode and cathode are connected electrically across a 10-ohm resistor.

A potassium chloride (KCl) salt bridge provides an ionic connection between the anode and the cathode (Figure 2). Deionized water is added to maintain the desired solution depth.

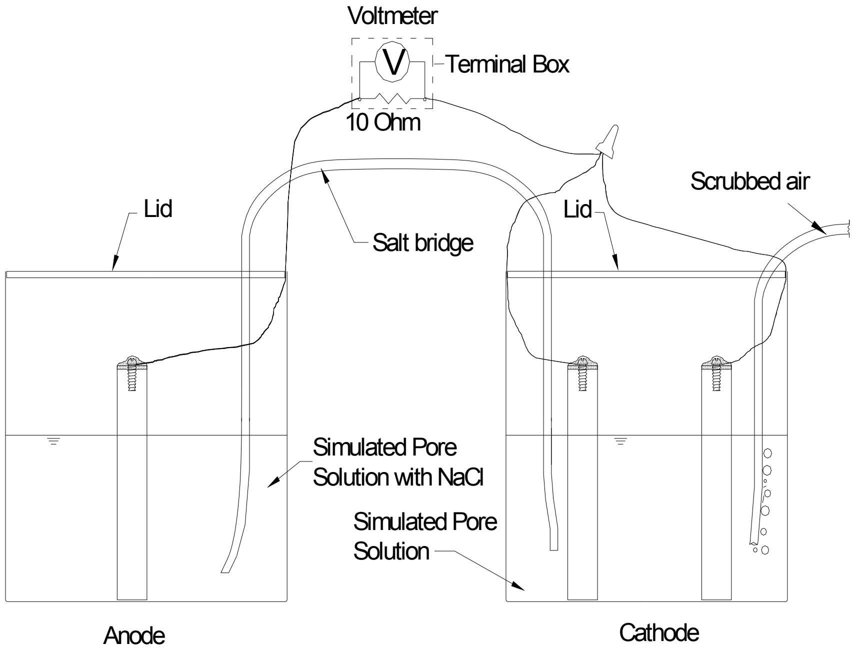


Figure 2: Schematic of rapid macrocell test

Fabrication

Fabrication of rapid macrocell specimens proceeds as follows:

1. Reinforcing bars are cut to a length of 5 in. with a band saw.
2. One end of each bar is drilled and tapped to a 0.75-in. depth with 10-24 threading.
3. Bare bars are soaked in acetone for a minimum of two hours and scrubbed to remove any oil.
4. Wire leads are connected to the test bars using a 10-24 × 0.5 in. stainless steel screw and a No. 10 stainless steel washer. Epoxy is applied to the electrical connection to protect it from corrosion.
5. Epoxy and caps are applied to the end of the specimens to protect their end from corrosion.

6. Bars are placed upright in the plastic containers and pore solution added to a depth of 3 in.
7. Bars are connected to a terminal box at the start of testing.

Test Procedure

The rapid macrocell test requires 15 weeks, with a solution change every 5 weeks to minimize the effects of carbonation. Corrosion rate and potential measurements are taken daily for the first week and weekly thereafter. Faraday's equation is used to calculate the corrosion rate according to the exposed area of anode measuring the voltage drop between anode and cathode bars across a 10-ohm resistor.

$$\text{Rate} = K \frac{V\ m}{n\ F\ D\ R\ A} \tag{1}$$

where the Rate is given in μm/yr,

K = conversion factor = $31.5 \cdot 10^4$ amp·μm ·sec/μA·cm·yr

V = measured voltage drop across resistor, millivolts

m = atomic weight of the metal (for iron, m = 55.8 g/mol; for zinc, m = 65.4 g/mol)

n = number of ion equivalents exchanged (for iron and zinc, n = 2 equivalents)

F = Faraday's constant = 96485 coulombs/equivalent

D = density of the metal, g/cm^3 (for iron, D = 7.87 g/cm^3, for zinc, D = 7.14 g/cm^3)

R = resistance of resistor, ohms = 10 ohms for the test

A = surface area of anode exposed to solution

The corrosion potential of rapid macrocell specimens was measured at the anode and cathode using a saturated calomel electrode (SCE) and was converted to an equivalent reading with respect to a copper sulfate electrode (CSE).

CRACKED BEAM TEST

Description

In the cracked beam (CB) test, specimens containing reinforcing steel are subjected to cyclic ponding and drying with a 15% sodium chloride (NaCl) solution. Cracked beam specimens (Figure 3) measure 12 × 6 × 7 in. These specimens contain two mats of steel. The top mat consists of a single No. 6 bar; the bottom mat consists of two No. 6 bars. This test simulates exposure conditions in cracked concrete. The specimens are cast in an inverted position. Prior to casting, a 12-mil thick × 6-in. long stainless steel shim is affixed in the mold in direct contact with the top reinforcing bar, producing a simulated crack that allows for direct infiltration of chlorides at the beginning of the test. The shim is removed about 12 hours after casting.

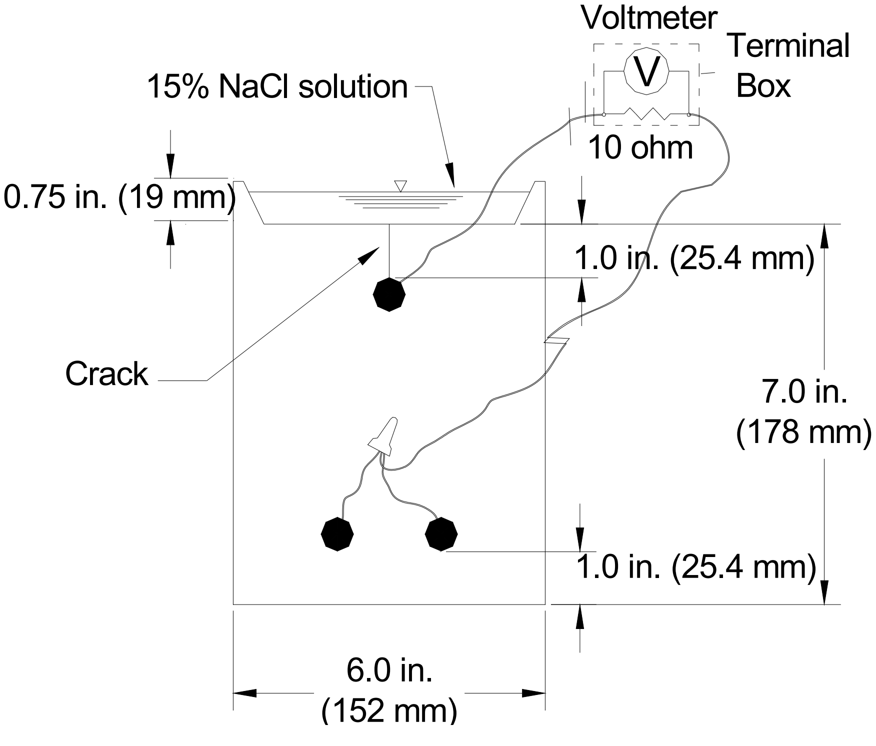


Figure 3: Schematic of cracked beam (CB) specimen

Fabrication

Fabrication of cracked beam specimens proceeds as follows:

1. Reinforcing bars are cut to a length of 12 in. with a band saw.
2. Both ends of each bar are drilled and tapped to a 0.75-in. depth with 10-24 threading.
3. Bare bars are soaked in acetone for a minimum of two hours and scrubbed to remove any oil.
4. The forms are assembled, and the reinforcement is attached. Forms and reinforcement are held in place using 1.25-in. long 10-24 threaded stainless steel machine screws.
5. Specimens are filled in two layers of concrete, with each layer consolidated using a 0.75-in. diameter vibrator. The free surface of the concrete (the bottom of the specimen) is finished with a trowel.
6. Specimens are cured for 24 hours at room temperature. A plastic cover is used to minimize evaporation. Stainless steel shims are removed from CB specimens after 12 hours, after the concrete has set.
7. Formwork is removed after 24 hours.
8. Specimens are cured for an additional two days in a plastic bag containing deionized water, then air-cured for 25 days.
9. Prior to test initiation, wire leads are connected to the test bars using 10-24 × 0.5 in. stainless steel screws and a No. 10 stainless steel washer. Epoxy is applied to the vertical sides of the specimens, while the top and bottom of the specimens are left uncoated.
10. The two mats of steel are connected to a terminal box. Specimens are left connected across the 10-ohm resistor, except when readings are taken. Specimens are placed

on 2 × 2 lumber to allow air flow under the specimens. Tests begin 28 days after casting.

Test Procedure

The test begins with 12 weeks of ponding and drying, followed by 12 weeks of ponding, for a total of 24 weeks. This exposure regime is repeated for the duration of the test. The test concludes after 96 weeks. Corrosion rate and potential measurements are taken weekly. Corrosion rates are calculated in the same manner as for macrocell specimens. The corrosion potential of cracked beam specimens is measured at the anode and cathode using a saturated AgCl electrode and converted to an equivalent potential with respect to a copper sulfate electrode (CSE).

Ponding and Drying Cycles:

The specimens are ponded with 300 mL of 15% NaCl solution at a room temperature of 68 to 76°F and covered with plastic sheeting to minimize evaporation. Readings are taken on Day 4. After all the readings are completed, the plastic sheeting is removed and the specimens are vacuumed to remove the salt solution, and a heat tent is placed over the specimens. The tent keeps the specimens at 100 ± 3° F (37 ±1° C) for three days. The tent is then removed, and the specimens are again ponded with the NaCl solution to start the second week of testing. Ponding and drying cycles continue for 12 weeks.

Ponding Cycle:

After 12 weeks of the ponding and drying, specimens are ponded for 12 weeks with the 15% NaCl solution and covered with plastic sheeting. The NaCl solution remains on the specimens throughout the 12 weeks at room temperature. Readings continue to be taken on a weekly basis. Deionized water is added to maintain the desired solution depth on the specimens during this time. After 12 weeks, the specimens are again subjected to the weekly ponding and drying cycles. The testing regimes will be repeated for a total of 96 weeks. Corrosion rate and corrosion potential measurements are taken weekly.

ASTM A955 Corrosion Rate Requirements

For rapid macrocell specimens, ASTM A955 states that the average corrosion rate for a minimum of five specimens should not exceed 0.25 μm/year at any time and no single specimen should exceed a corrosion rate of 0.50 μm/year.

For cracked beam specimens, ASTM A955 states that the average corrosion rate for a minimum of five specimens should not exceed 0.20 μm/year at any time and no single specimen should exceed a corrosion rate of 0.50 μm/year.

RESULTS AND DISCUSSION

Rapid Macrocell Test

Figures 4 and 5 show the individual corrosion rates for the as-received and repickled specimens, respectively. Figure 6 shows the average corrosion rate for the specimens. Through 15 weeks, the maximum individual corrosion rates for the as-received and repickled specimens were 0.174 and 0 μm/yr, respectively; the average corrosion rate was 0 for both series of tests (Negative corrosion rate values are artifacts of the test method and are not indicative of "negative" corrosion). Both series of specimens met the requirements of ASTM A955. The residue observed on the stainless steel clad bars did not have a significant impact on the corrosion resistance of the bars.

Figures 7 and 8 show the corrosion potentials of the as-received and repickled specimens, respectively. Figure 9 compares the average corrosion potentials for the two types of specimens. The potentials remained around –0.20 V for bars in both the as-received and repickled conditions, indicating little corrosion activity.

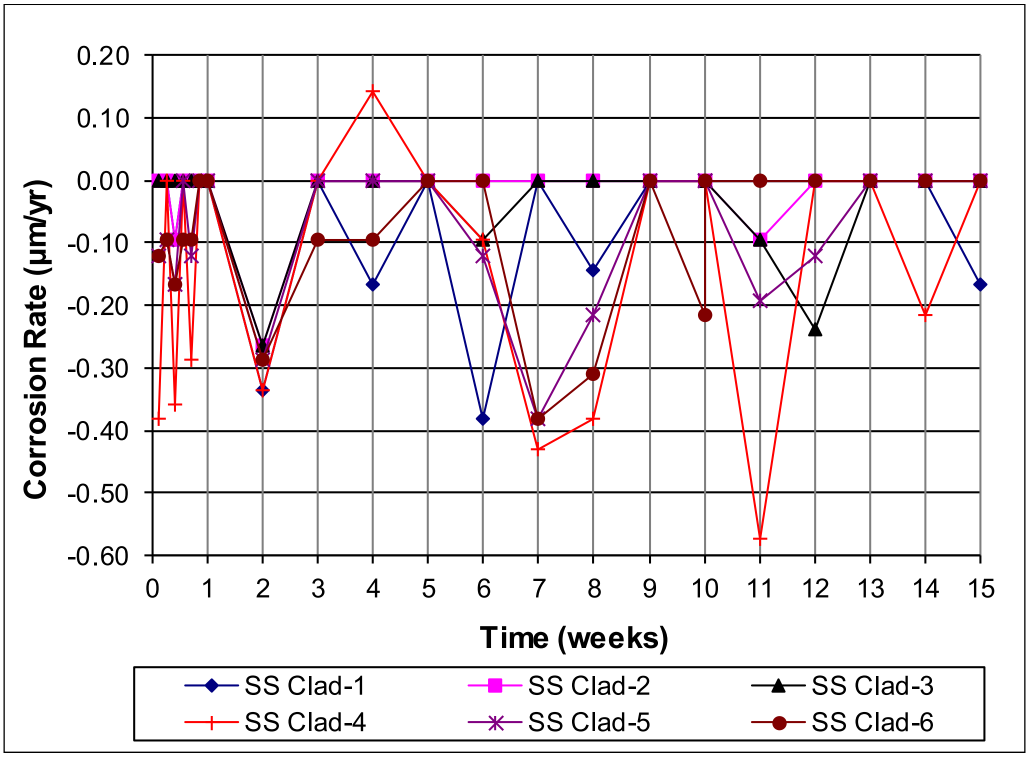


Figure 4: Corrosion rate for as-received specimens

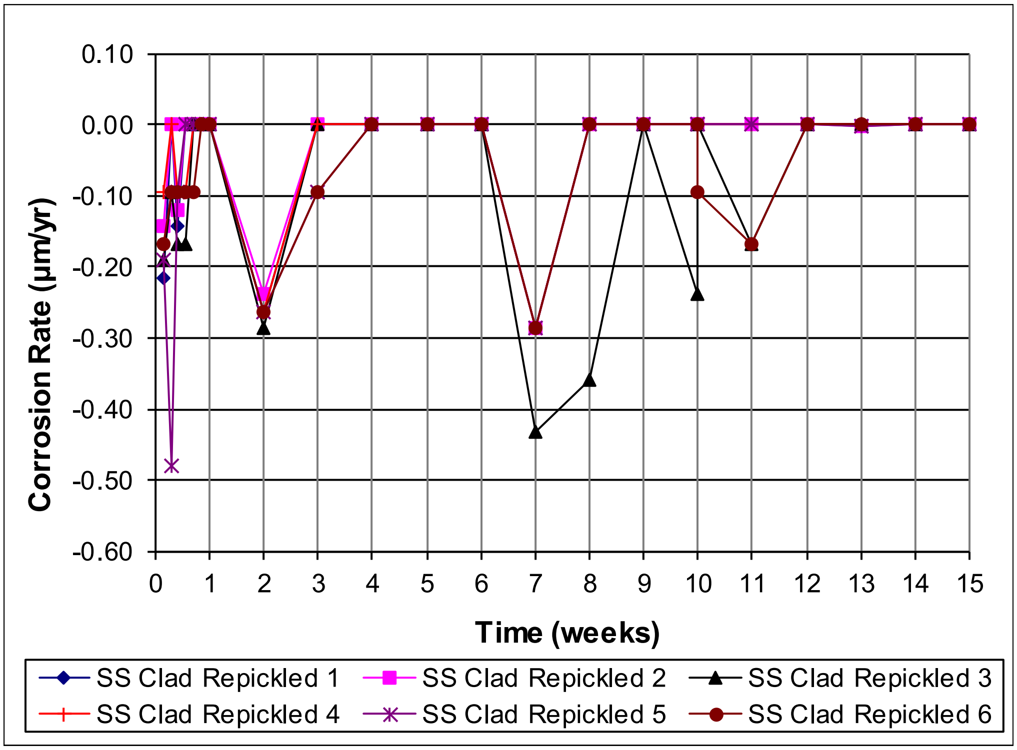


Figure 5: Corrosion rate for repickled specimens

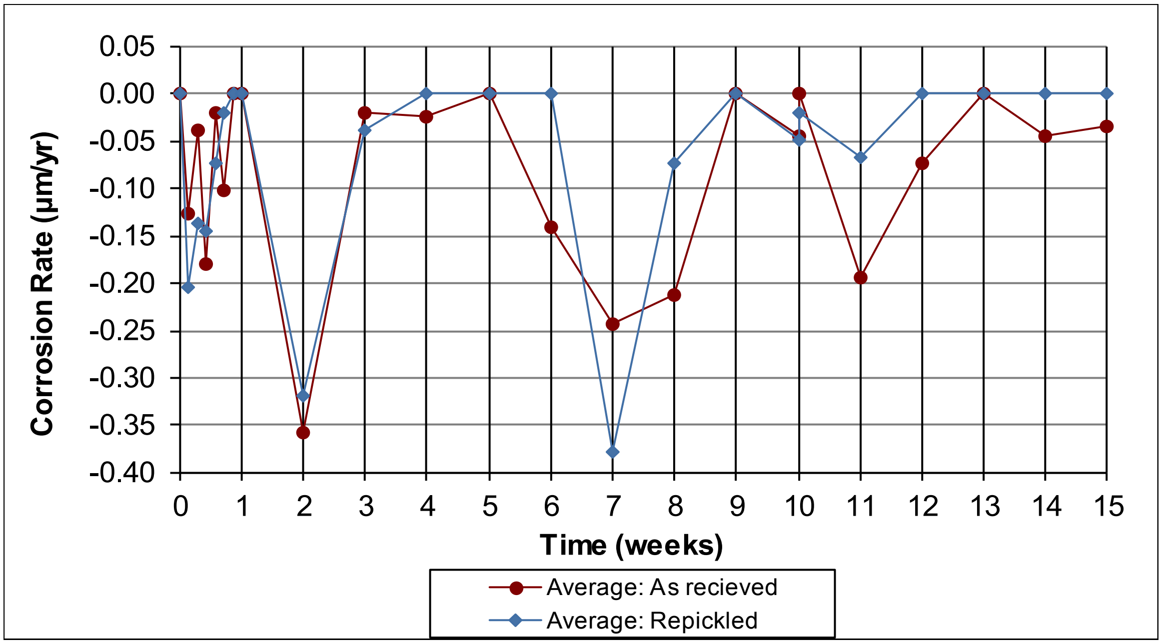


Figure 6: Average corrosion rate for as-received and repickled specimens

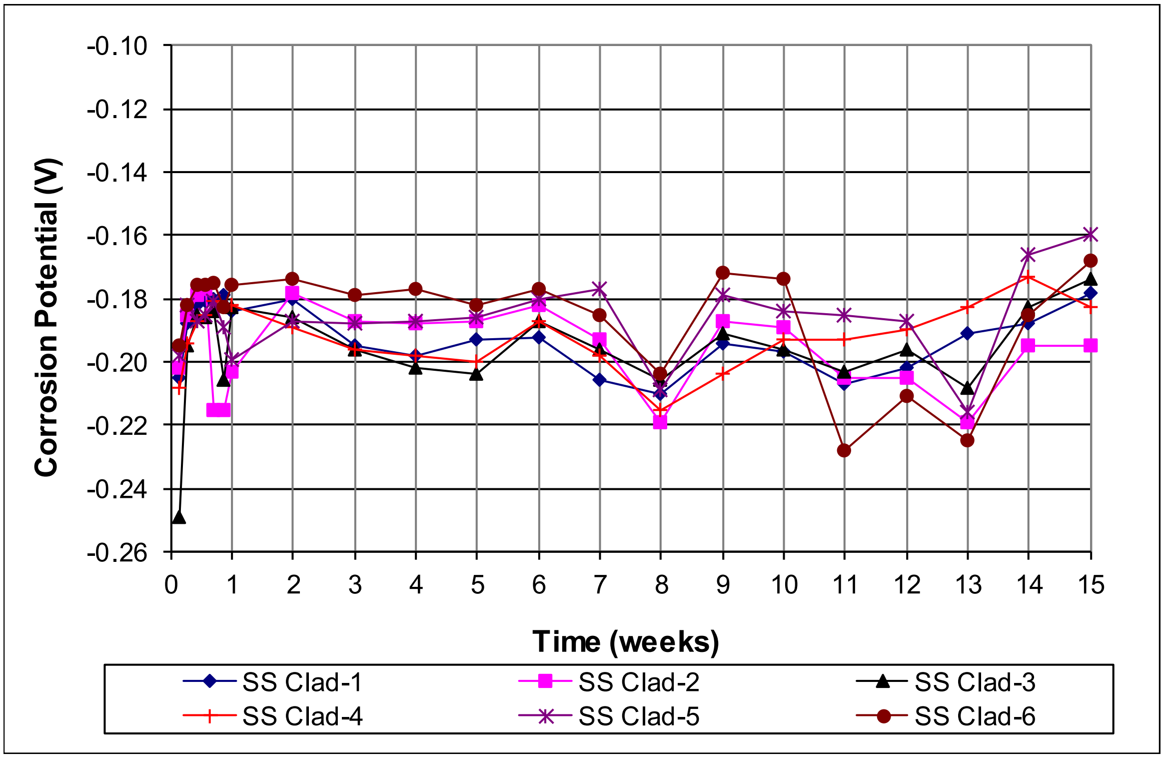


Figure 7: Corrosion potential for as-received specimens with respect to CSE.

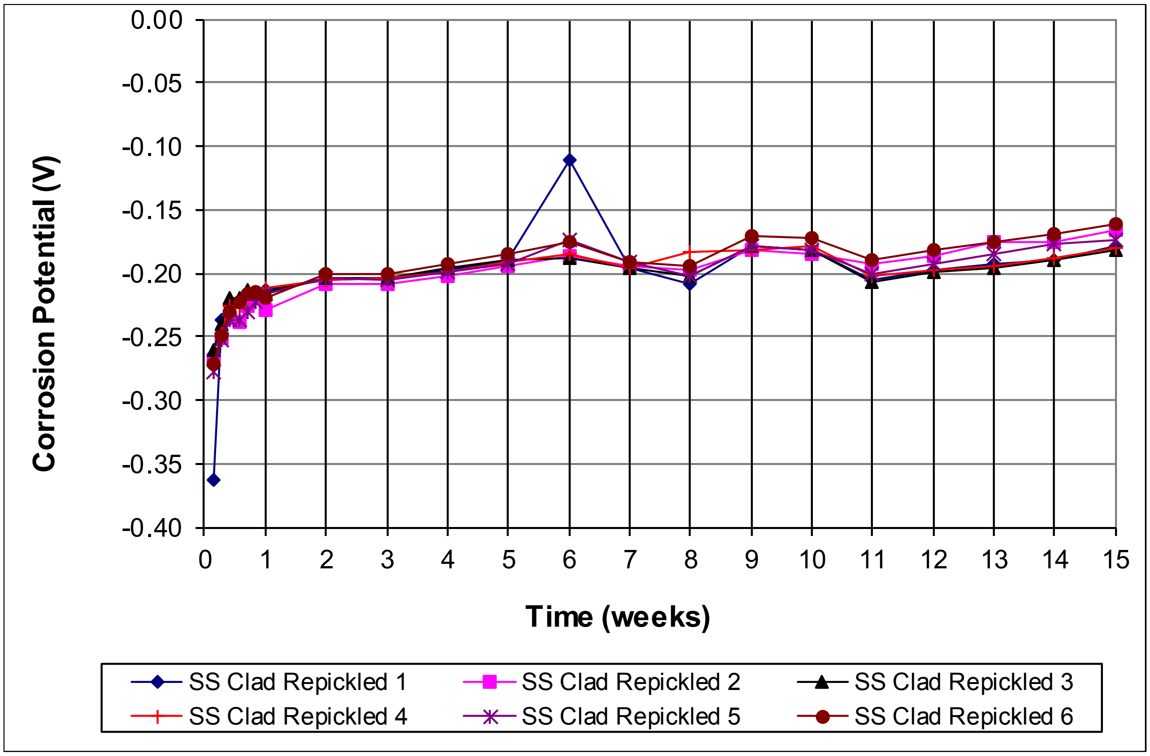


Figure 8: Corrosion potential for repickled specimens with respect to CSE

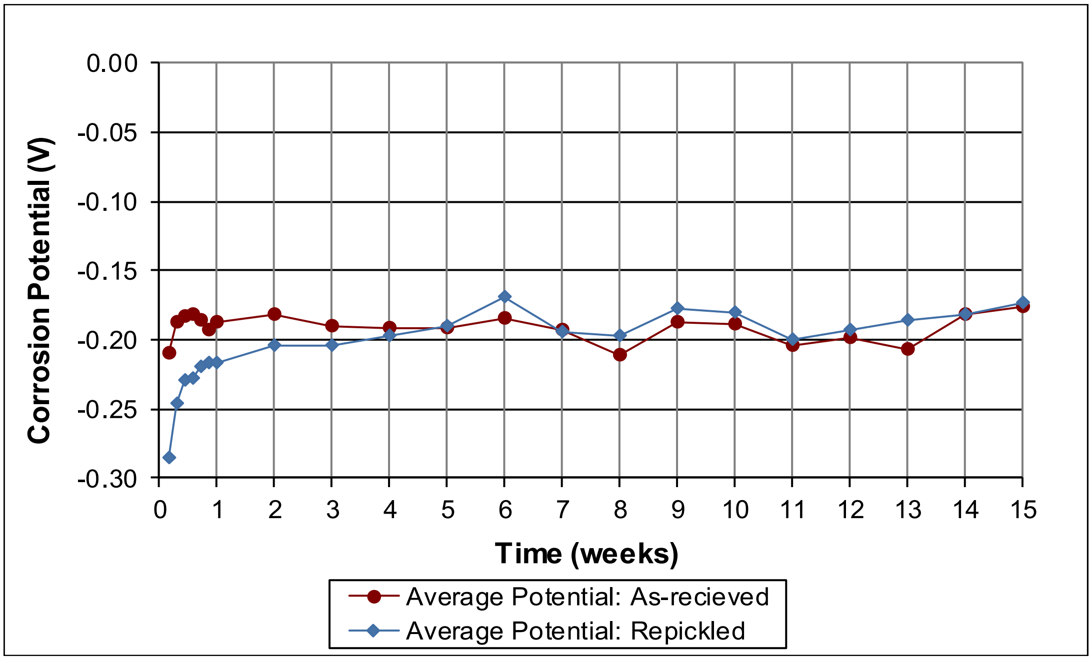
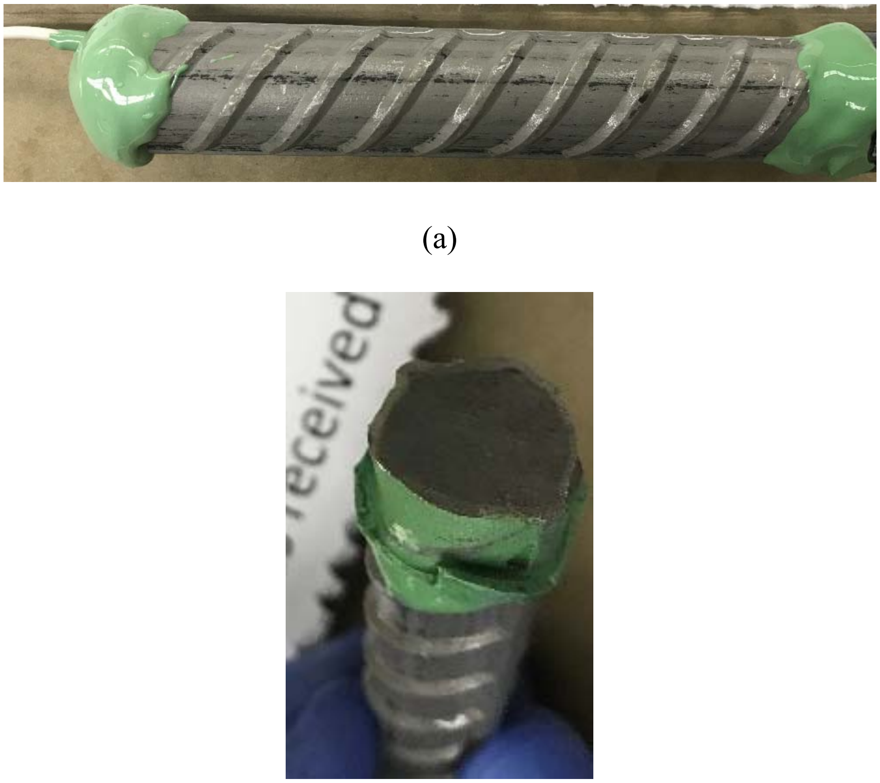


Figure 9: Average corrosion potential for as-received and repickled specimens wih respect to CSE

After testing, the surface of the bars were examined for corrosion, and the end caps removed to inspect for corrosion at the cut ends of the bar. Figure 10 shows specimen SSClad-1 after testing (Figure 10a) and with the end cap removed (Figure 10b). No signs of corrosion were observed on any of the bars.



(a)

(b)

Figure 10: Specimen SSClad-1 (as received), anode bar (a) after testing, (b) with end cap removed.

Cracked Beam Test

Figures 11 and 12 show the individual and average corrosion rates for the stainless steel clad bars in the cracked beam test. Figure 13 shows the individual top mat corrosion potentials with respect to a copper sulfate electrode (CSE). The corrosion rate of two specimens, SS Clad-2 and SS Clad-3, exceeded the maximum of value of 0.50 μm/yr permitted by ASTM A955. As explained below, however, these specimens are considered to have satisfied this test requirement.

The average corrosion rates of all six specimens remained below the maximum of 0.20 µm/yr permitted by ASTM A955. Through 96 weeks, the maximum individual corrosion rate for the specimens was 0.75 µm/yr (specimen SS Clad-2 at week 61). This specimen experienced a corrosion rate greater than 0.50 again at week 96 when it reached a corrosion rate of 0.541 µm/yr. Specimen SS Clad-3 exhibited a corrosion rate above 0.5 µm/yr at weeks 66, 67, 78, and 81. Specimen SS Clad-3 is the only specimen to have shown corrosion rates greater than 0.50 µm/year for two consecutive weeks. These spikes in corrosion rate correspond to drops in corrosion potential on the specimens (Figure 13). The maximum average corrosion rate was 0.162 µm/yr at week 60.

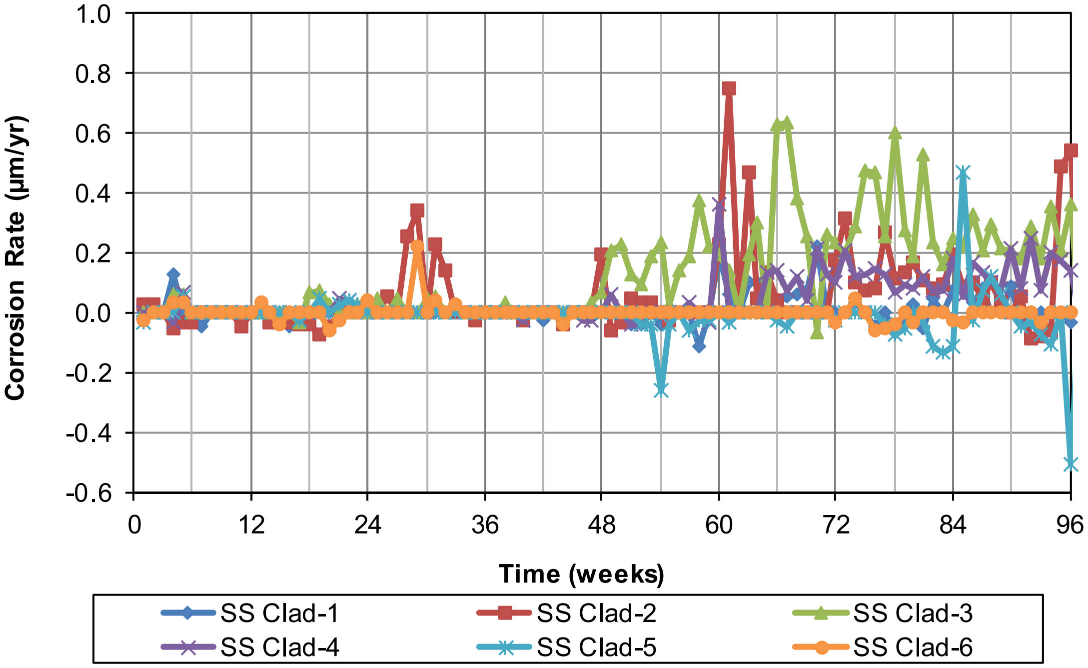


Figure 11: Corrosion rate for cracked beam specimens

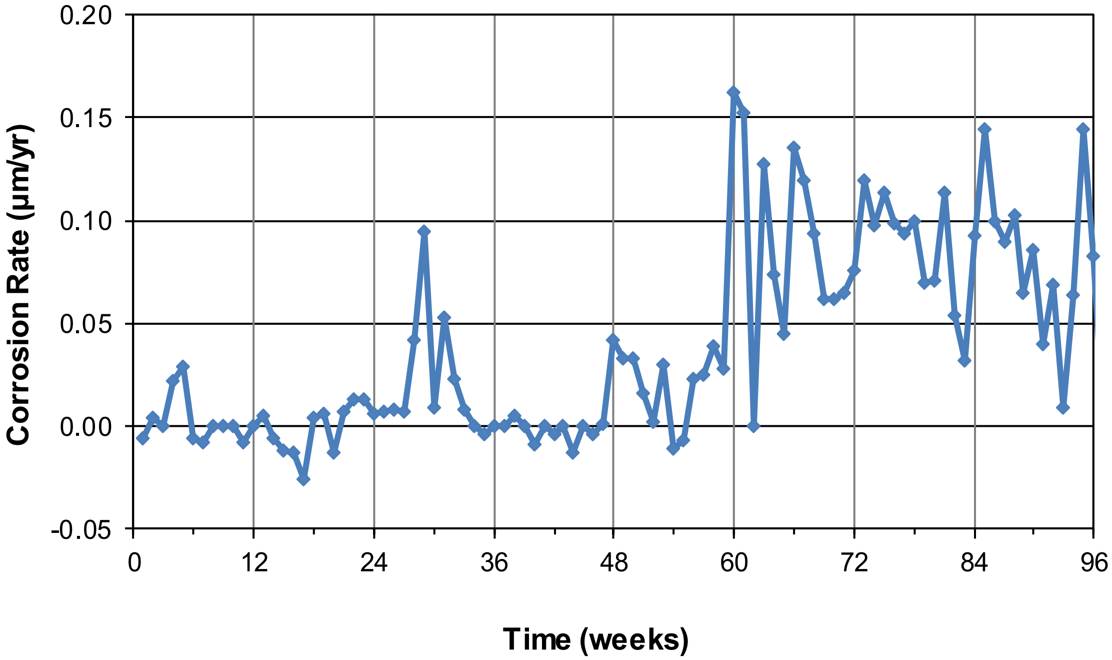


Figure 12: Average corrosion rate for cracked beam specimens

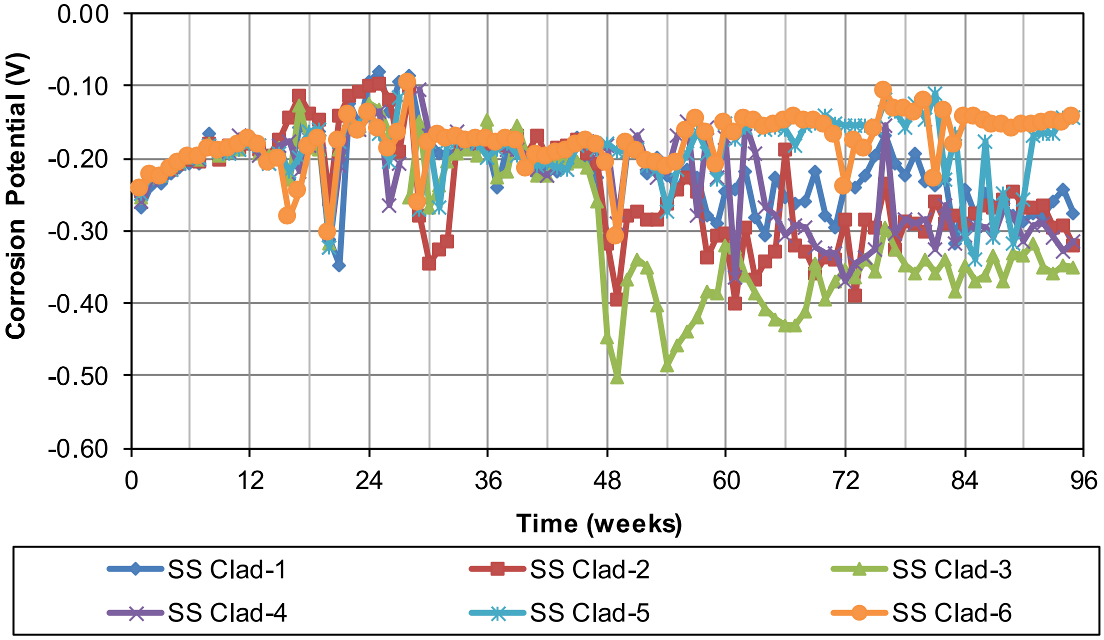
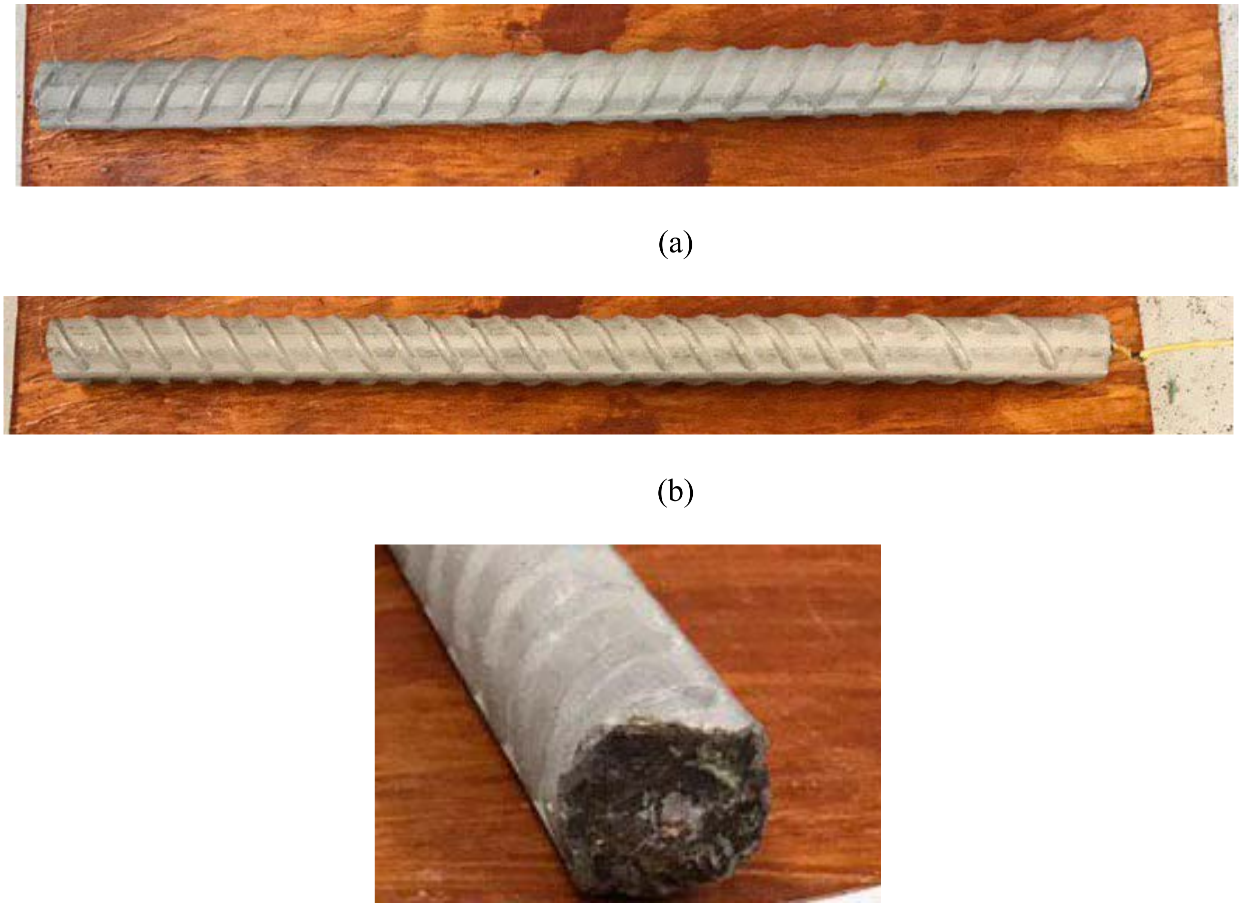


Figure 13: Top mat corrosion potential with respect to CSE for cracked beam specimens

After testing, the specimens were autopsied to determine if corrosion was occurring on the cladding or at the cut end of the bars. Figure 14 shows top bars after they were removed from the concrete blocks at week 96. Neither SS Clad-2 nor SS Clad-3, the two specimens that exhibited the high corrosion rates during the test, showed any signs of corrosion on the clad regions of the bars (Figures 14a and 14b). Corrosion, however, was visible on the cut end of the bars (Figure 14c). A number of the other bars also exhibited corrosion at this location, explaining the positive rates seen on several specimens in the cracked beam test (Figure 11).


(a)

(b)

(c)

Figure 14: Stainless steel clad bars after testing, (a) SSClad-2, top bar, (b) SSClad-3, top bar, (c) cut end of SSClad-2

Discussion:

The difference in behavior of the stainless steel clad bars between the rapid macrocell and cracked beam tests can be attributed to the end condition of the bars. In the rapid macrocell test, the cut ends of the bars are well-protected by a vinyl cap and two layers of epoxy. With the ends well protected, the bars exhibited low or no corrosion activity over the duration of the test. In the cracked beam test, the cut ends are not as well protected, and chlorides were able to reach the conventional steel core of the bars and initiate corrosion. The high corrosion rates observed in the cracked beam specimens should not be attributed to a failure of the cladding, but rather to the need to protect the cut ends of the bars with a durable cap when using them in the field. With protection, the bars are considered to have satisfied the requirements of Annex A of ASTM A955.

The residue on the surface of the bars posed some concern, as prior tests on multiple alloys of stainless steel have indicated stainless steel performs poorly when the surface finish is uneven (Darwin et al. 2013, O’Reilly et al. 2017). In this case, no such detrimental behavior was observed. Tthe source of the residue, however, should still be identified and eliminated if possible.

SUMMARY AND CONCLUSIONS

The corrosion resistance of Type 316 stainless steel clad bars produced by CMC was evaluated using the cracked beam and rapid macrocell tests in Annexes A.1, A.2, and A.3 of ASTM A955. The test procedures were modified to accommodate No. 6 bars in place of No. 5 bars prescribed in ASTM A955. The bars were pickled in a 20% hydrochloric acid solution for five minutes, but exhibited some residue after the pickling process. To remove the residue, some of the bars were sandblasted and then repickled in a mixture of 25% nitric acid and 5% hydrofluoric acid. Bars were evaluated in both the as-received and repickled condition in the rapid microcell test. The bars were evaluated in the as-received condition in the cracked beam test.

Both the as-received and repickled bars met the corrosion resistance requirements of ASTM A955 in the rapid macrocell test. Some of the bars evaluated in the cracked beam test exhibited corrosion rates greater than 0.5 μm/yr, which is the upper limit for the corrosion rate of individual specimens in ASTM A955. Upon inspection, it was found that this was due to corrosion on the conventional steel core at the cut end of the bars–no signs of corrosion were found on the cladding. Therefore, the stainless steel clad reinforcing bars evaluated in this study are considered to have satisfied the requirements of ASTM A955 in the cracked beam test.

Based on the results presented in this paper, the following conclusions can be drawn:

1. The stainless steel clad reinforcing bars evaluated in this study met the requirements of ASTM A955.
2. It is recommended that protective caps be provided for use with stainless steel clad bars in the field.

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