RAPID MACROCELL TESTS OF
2304 AND XM-28 REINFORCING BARS

By

Matthew O'Reilly

David Darwin

A Report on Research Sponsored by the

NEW YORK STATE
DEPARTMENT OF TRANSPORTAION

Structural Engineering and Engineering Materials
SL Report 12-3a

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
LAWRENCE, KANSAS
November 2012

ABSTRACT

The corrosion resistance of 2304 and XM-28 stainless steel bars, produced by a single mill and supplied by a single supplier, was evaluated using the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955-12. Bars were tested both before and after undergoing mechanical straightening. Based on the test results, the stainless steel bars satisfy the requirements of ASTM A955-12. The straightening process allowed corrosion to initiate on the bars, but had limited to no effect on the macrocell corrosion rate.

Keywords: chlorides, concrete, corrosion, macrocell, reinforcing steel, stainless steel

INTRODUCTION

This report describes the test procedures and results of rapid macrocell tests to evaluate the corrosion performance of 2304 and XM-28 stainless steel reinforcing bars before and after straightening. Six specimens are tested for each sample of steel in accordance with Annexes A1 and A2 of ASTM A955-12.

EXPERIMENTAL WORK

Materials

Tests were performed on pickled No. 5 (No. 16) stainless steel bars in both the coiled and straightened condition. The bars were inspected upon receipt and found to be in good condition; however, the straightened bars did show damage to the bar deformations resulting from the straightening process, as shown in Figure 1. The chemical composition of the stainless steels is given in Table 1.

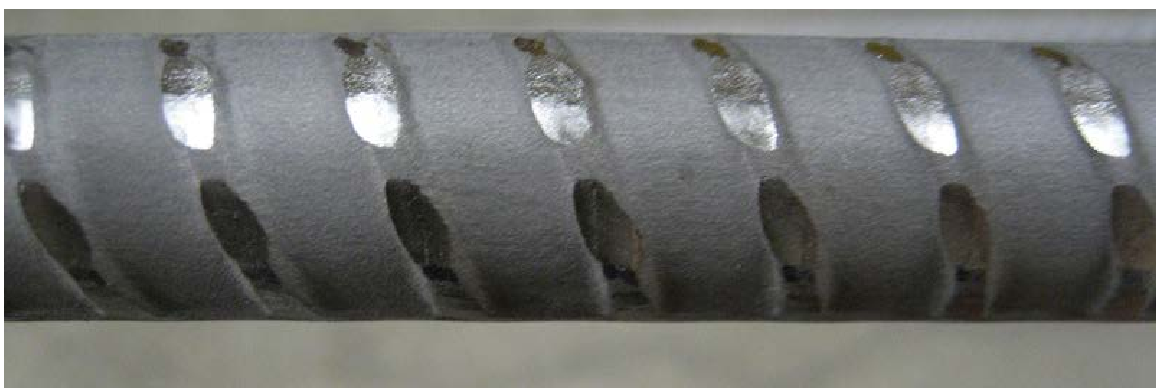

Figure 1: Damage to deformations from straightening process.

Table 1: Chemical Composition of Stainless Steels (Provided by Manufacturer)

	Material Composition Report (%)										
Material	**C**	**Co**	**Cr**	**Cu**	**Mn**	**Mo**	**N**	**Ni**	**P**	**S**	**Si**
2304	0.021	0.08	22.46	0.37	1.53	0.21	0.133	4.19	0.032	0.001	0.83
XM-28	0.074	-	18.12	-	12.54	-	0.264	1.10	0.030	0.0015	0.71

Experimental Procedures

Six specimens were tested for each sample in accordance with the rapid macrocell test outlined in Annexes A1 and A2 of ASTM A955/A955M-12 and illustrated in Figure 2. Bars were tested in both the coiled and straightened condition. Each bar used in the rapid macrocell is 5 in. long and is drilled and tapped at one end to accept a 0.5-in., 10-24, stainless steel machine screw. Bars are wiped down with acetone prior to testing to remove oil and surface contaminants introduced by machining. A length of 16-gauge insulated copper wire is attached to each bar via the machine screw. The electrical connection is coated with epoxy to protect the wire from corrosion.

A single rapid macrocell specimen consists of an anode and a cathode. The cathode consists of two bars submerged in simulated 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). The solution has a pH of about 13.9. Air, scrubbed to remove carbon dioxide, is bubbled into the cathode solution. The anode consists of a single bar submerged in a solution consisting of simulated pore solution and 15 percent sodium chloride (NaCl). The "salt" solution is prepared by adding 176.5 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).

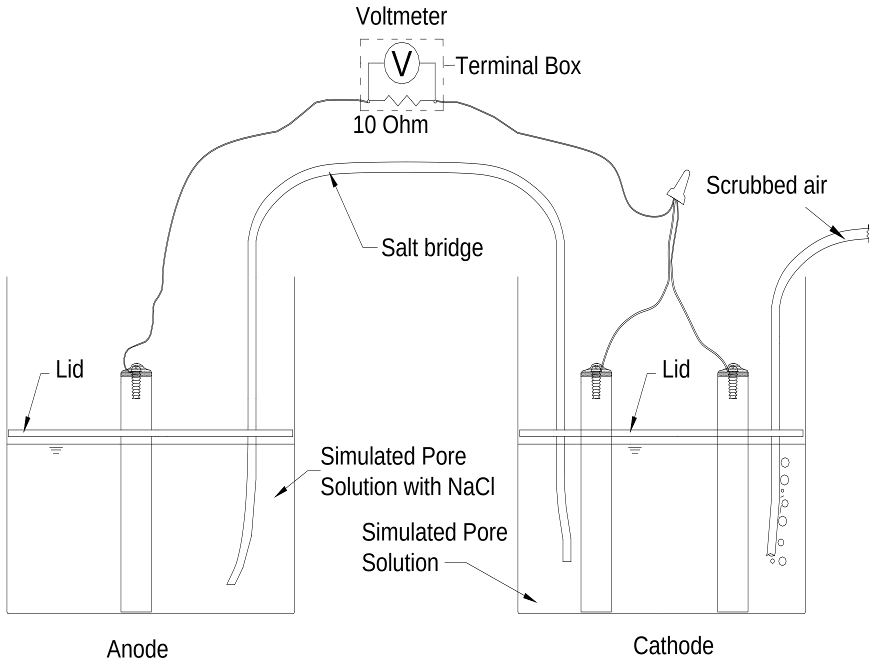

Figure 2: Rapid Macrocell Test Setup

The corrosion rate is calculated based on the voltage drop across the 10-ohm resistor using Faraday's equation.

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

where the Rate is given in μm/yr, and

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/g-atom)

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

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

A = surface area of anode exposed to solution, 39.9 cm^2

Using the values listed above, the corrosion rate simplifies to:

$$\text{Rate} = 29.0V \tag{2}$$

To satisfy ASTM A955, no individual reading may exceed 0.50 μm/yr and the average rate of all specimens may not exceed 0.25 μm/yr. In both cases, the corrosion current must be such as to indicate net corrosion at the anode. Current indicating a "negative" value of corrosion, independent of value, does not indicate corrosion of the anode and is caused by minor differences in oxidation rate between the single anode bar and the two cathode bars.

In addition to the corrosion rate, the corrosion potential is measured at the anode and cathode using a saturated calomel electrode (SCE). Readings are taken daily for the first week and weekly thereafter.

RESULTS

The individual corrosion rates for the coiled (2304c) and straightened (2304s) 2304 stainless steel are shown in Figures 3a and 3b, respectively. For coiled 2304 steel (Figure 3a), the peak corrosion rate, 0.12 μm/yr, was observed on specimen 2304c-3 at day 3 and specimens 2304c-2 and 2304c-5 at week 3. No specimen exhibited a positive corrosion rate after week 3. For straightened 2304 (Figure 3b), the peak corrosion rate, 0.34 μm/yr, was observed on specimen 2304s-6 at week 3. No specimen exhibited a positive corrosion rate for two or more consecutive readings. No coiled or straightened 2304 specimen exceeded the 0.5 μm/yr limit specified by ASTM A955.

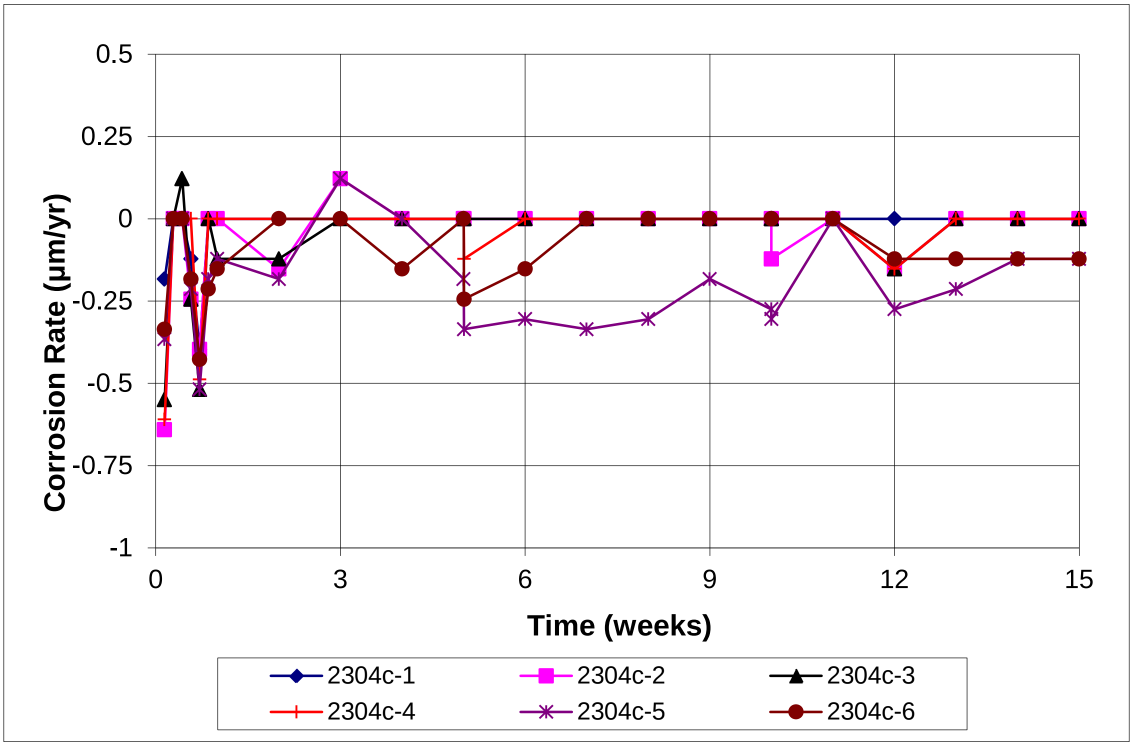

Figure 3a: Individual corrosion rates (µm/yr) for coiled 2304 stainless steel.

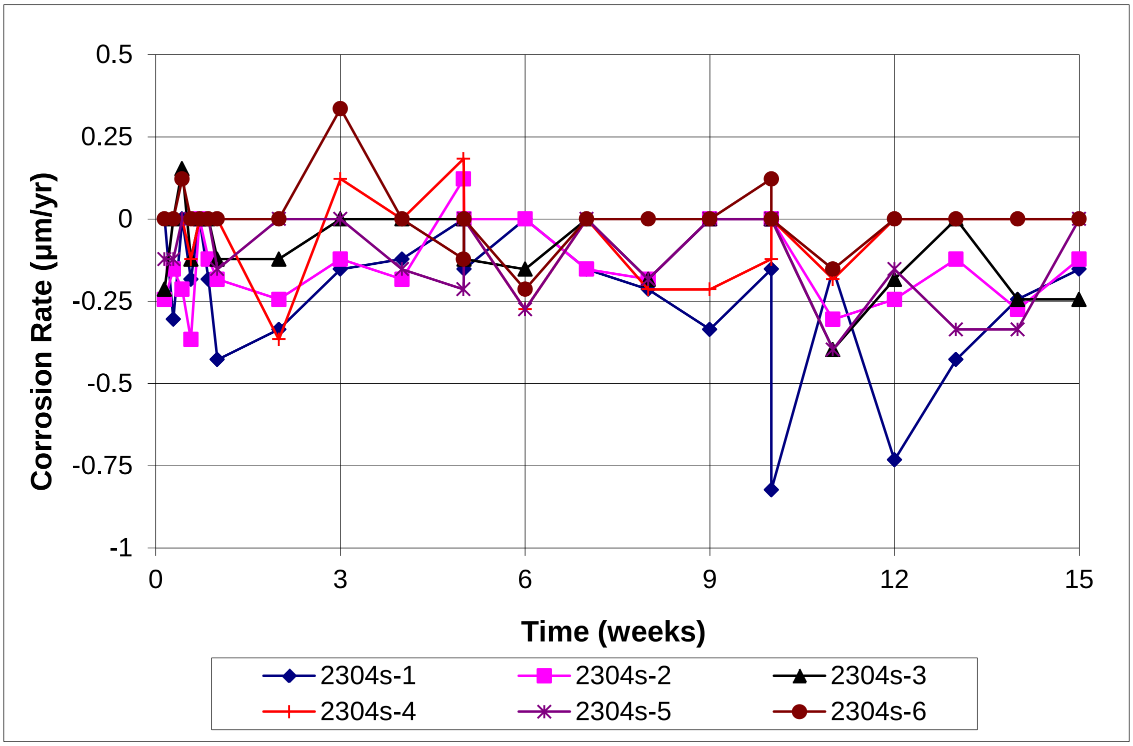

Figure 3b: Individual corrosion rates (µm/yr) for straightened 2304 stainless steel.

The individual corrosion rates for the coiled (XM-28c) and straightened (XM-28s) XM-28 stainless steel are shown in Figures 4a and 4b, respectively. For coiled XM-28 (Figure 4a), the peak corrosion rate, 0.40 µm/yr, was observed on specimen XM-28c-6 at week 2. No specimen exhibited a positive corrosion rate after week 6. For straightened XM-28 (Figure 4b), the peak corrosion rate, 0.49 µm/yr, was observed on specimen XM-28s-2 at day 2. No coiled or straightened XM-28 specimen exceeded the 0.5 µm/yr limit specified by ASTM A955.

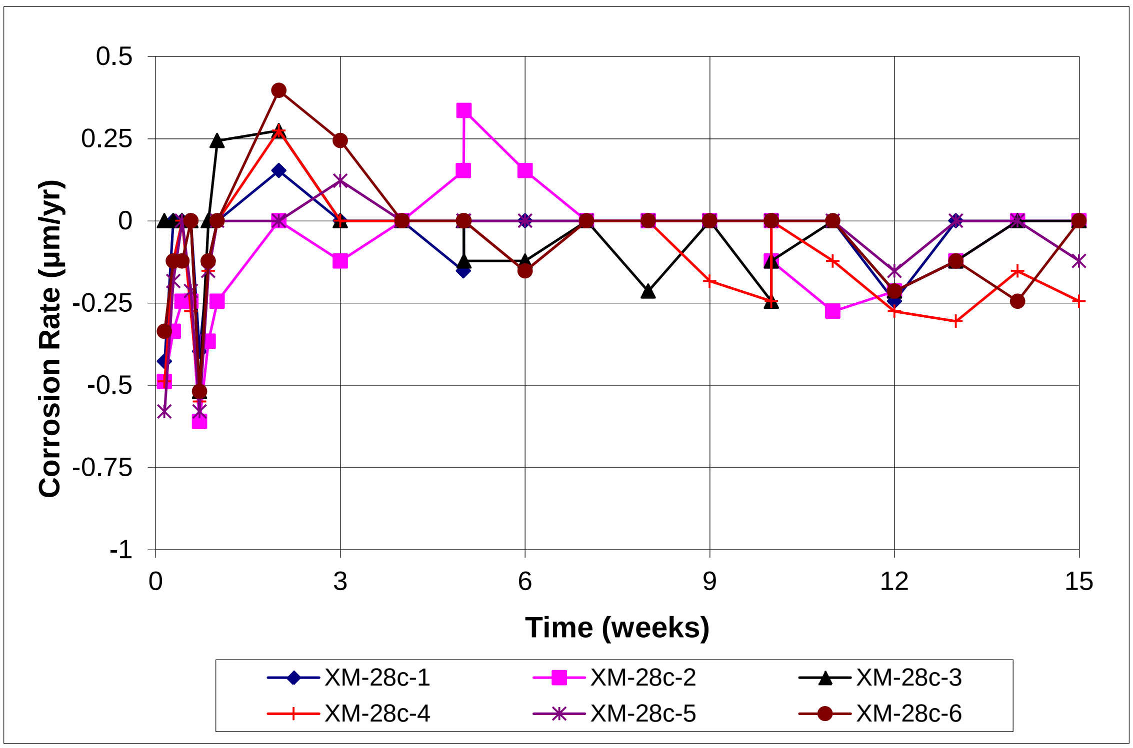

Figure 4a: Individual corrosion rates (µm/yr) for coiled XM-28 stainless steel.

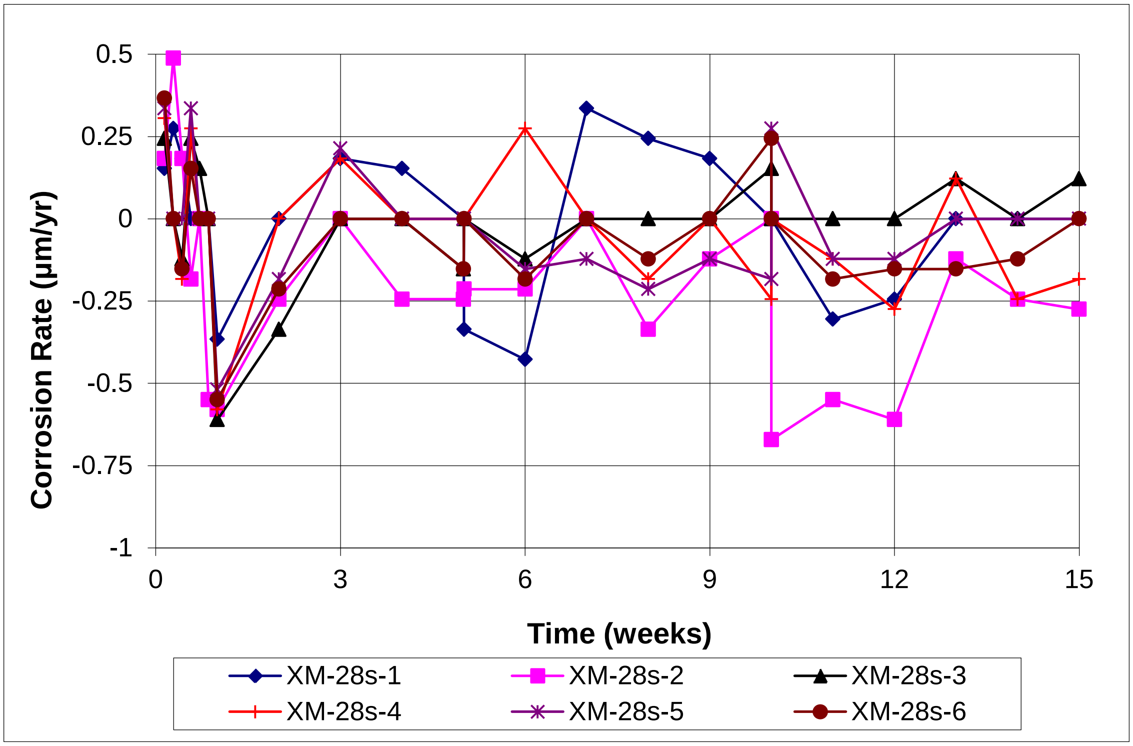

Figure 4b: Individual corrosion rates (µm/yr) for straightened XM-28 stainless steel.

The average corrosion rates for coiled and straightened 2304 and XM-28 are shown in Figure 5. Coiled 2304 bar exhibited a peak average corrosion rate of 0.04 µm/yr at week 3, with a zero or negative corrosion rate after week 3. Straightened 2304 bar exhibited a peak corrosion rate of 0.03 µm/yr at week 3 and also maintained a zero or negative corrosion rate after week 3. The behavior of coiled and straightened 2304 was comparable throughout the test. For coiled XM-28, the peak average corrosion rate of 0.18 µm/yr was observed at week 2, while straightened XM-28 exhibited a peak corrosion rate of 0.26 µm/yr on day 1. After week 1, coiled and straightened XM-28 exhibited similar corrosion rates, with most values near or below 0. Although straightened XM-28 exceeded the 0.25 µm/yr limit established in ASTM A955, this is not grounds to disqualify the steel as the limits of ASTM A955 do not apply to steel that has been fabricated after rolling.

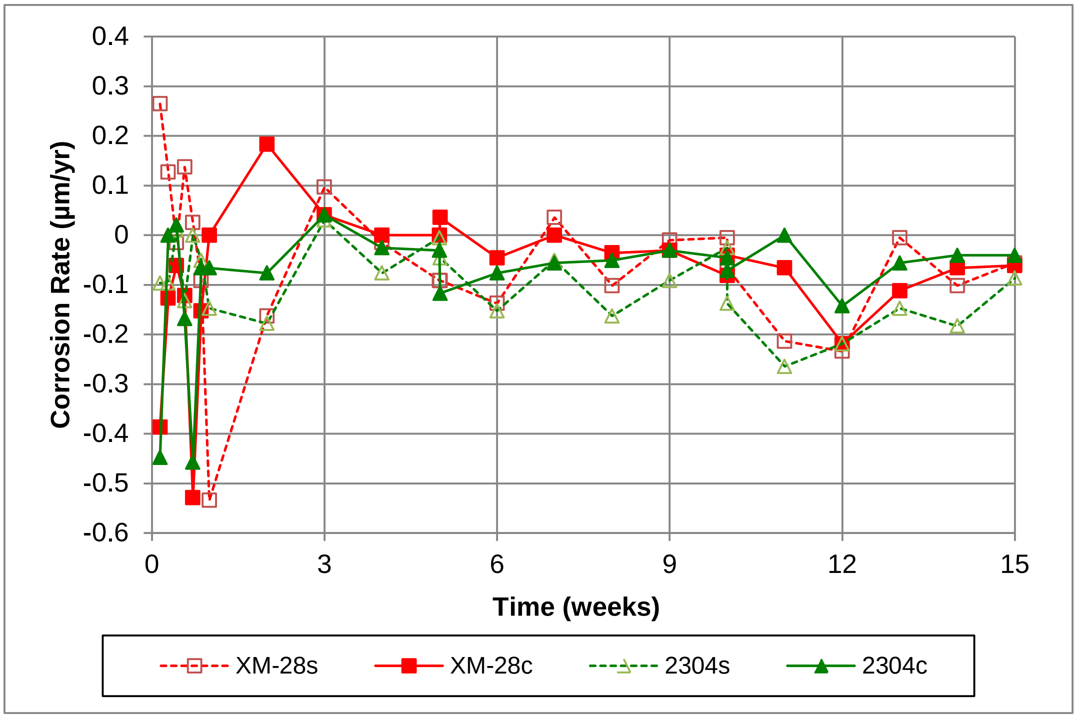

Figure 5: Average corrosion rates (µm/yr) for 2304 and XM-28 stainless steel.

The average anode corrosion potentials with respect to a saturated calomel electrode (SCE) for 2304 and XM-28 steel are shown in Figure 6. All steels exhibited a corrosion potential around –0.25 V at the start of testing. Coiled XM-28 rose to a potential of –0.15 V at week 1 and remained around –0.15 V for the remainder of testing. Straightened XM-28 exhibited a more negative potential than coiled XM-28 for the first two weeks of testing but exhibited a comparable potential to coiled XM-28 thereafter. Both forms of 2304 stainless steel exhibited a more negative corrosion potential than XM-28 for the first 10 weeks of testing, reaching –0.20 V at week 1 and slowly increasing to –0.15 V at week 11. Coiled and straightened 2304 exhibited similar corrosion potentials throughout the test.

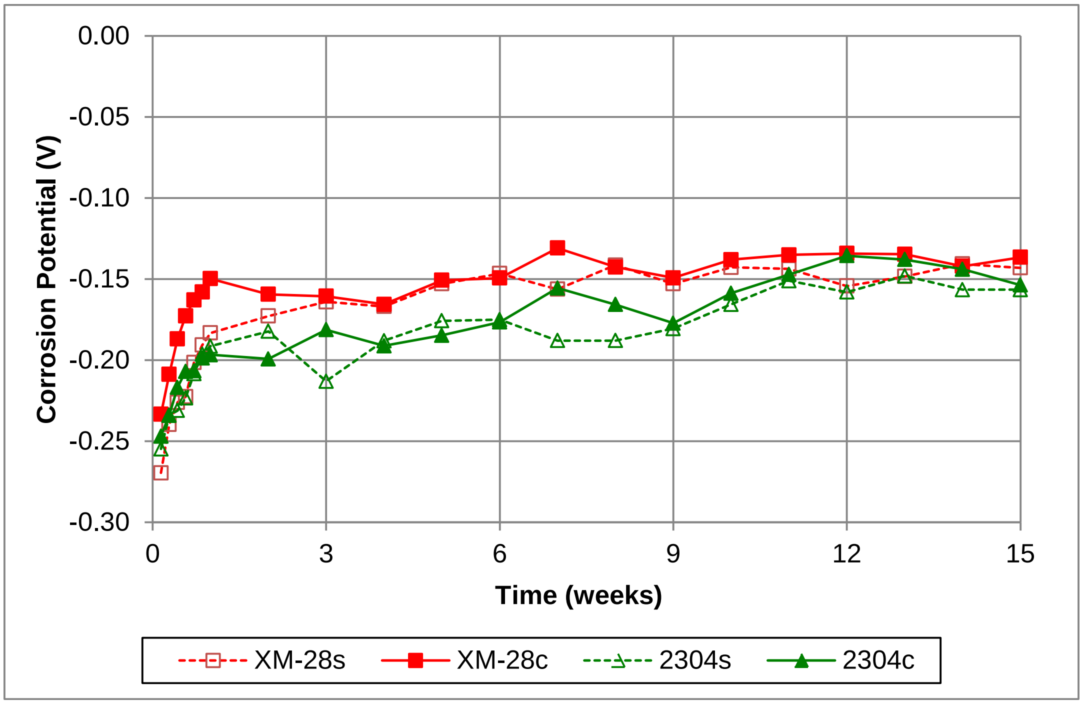

Figure 6: Average corrosion potential (vs. SCE) for 2304 and XM-28 stainless steel.

After testing, the bars were inspected for signs of corrosion. No corrosion products were observed on the coiled 2304 (Figure 7) or coiled XM-28 (Figure 8) stainless steel. Two of the six straightened 2304 specimens had light corrosion products on the anode bar (Figure 9), as did three of the six XM-28 specimens (Figure 10). The corrosion products were all located at damaged areas of the transverse deformations (Figure 9b, Figure 10b) and may have resulted from local damage of from the deposition of material from the fabricating equipment during straightening.

Figure 7: Coiled 2304 stainless steel after testing. Anode (top bar) and cathode (bottom bars).

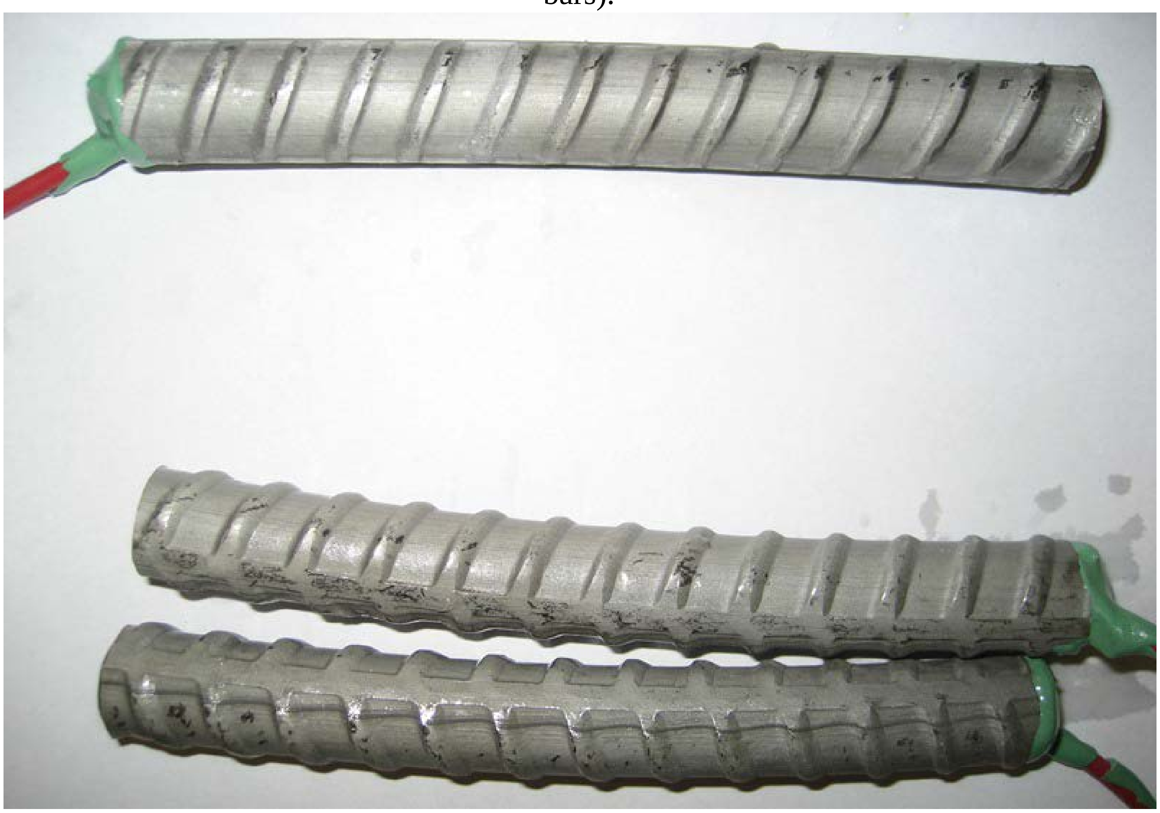

Figure 8: Coiled XM-28 stainless steel after testing. Anode (top bar) and cathode (bottom bars).

Figure 9a: Straightened 2304 stainless steel after testing. Anode (top bar) and cathode (bottom bars). Corrosion products indicated with arrow.

Figure 9b: Close-up of straightened 2304 stainless steel after testing showing corrosion products on anode bar.

Figure 10a: Straightened XM-28 stainless steel after testing. Anode (top bar) and cathode (bottom bars). Corrosion products indicated with arrow.

Figure 10b: Close-up of straightened XM-28 stainless steel after testing showing corrosion products on anode bar.

SUMMARY AND CONCLUSIONS

The corrosion resistance of 2304 and XM-28 stainless steel bars was tested using the rapid macrocell test in accordance with Annexes A1 and A2 of ASTM A955-12. The following conclusions are based on the test results presented in this report:

1) The XM-28 and 2304 stainless steel reinforcement tested in this study satisfy the requirements specified in Annexes A1 and A2 of ASTM A955-12.

2) The process of straightening coiled stainless steel reinforcement causes damage to the bar or the deposition of material from the fabricating equipment that can serve as an initiation site for corrosion. However, the 2304 bars exhibited no significant difference in macrocell corrosion rate, and the XM-28 bars only exhibited a significantly different rate during the first week of testing.

REFERENCES

ASTM A955, 2010, “Standard Specification for Plain and Deformed Stainless-Steel Bars for Concrete Reinforcement (ASTM A955/A955M-10),” ASTM International, West Conshohocken, PA, 11 pp.