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# Surface Condition Effects on Critical Chloride Threshold of Steel Reinforcement

by Radhakrishna G. Pillai and David Trejo

*To evaluate the influence of the steel reinforcement surface condition on the corrosion performance, the critical chloride threshold values of five uncoated steel reinforcement types (ASTM A 706, ASTM A 615, microcomposite, stainless steel 304, and stainless steel [SS] 316LN) with as-received and polished surface conditions were quantitatively determined using the accelerated chloride threshold (ACT) test procedure. Micrographs of the surfaces for all steel reinforcement types were obtained using both optical and scanning electron microscopy (SEM). This qualitative assessment was correlated with critical chloride threshold values. This study indicated that the mean critical chloride threshold values increased with the complete removal of the as-received surface and with surface polishing for the ASTM A 706, microcomposite, and stainless steel 304 reinforcements and decreased with the complete removal of the as-received surface and with surface polishing of the ASTM A 615 and SS316LN steels.*

**Keywords:** corrosion; mill scale; steel reinforcement.

## INTRODUCTION

Premature deterioration of reinforced concrete (RC) structures resulting from exposure to aggressive chloride environments is a serious challenge facing engineers, designers, contractors, and owners. Corrosion of steel reinforcement in existing RC structures has been recognized as the largest cause for the overall maintenance cost in U.S. infrastructure. Deicing and anti-icing salts and seawater are main sources of chloride ions that cause the corrosion of steel reinforcement embedded in RC bridge and marine structures. The chloride-induced corrosion of steel reinforcement initiates only after the chloride concentration near the steel reinforcement reaches a minimum concentration. Glass and Buenfeld (1997) defined this chloride concentration level as the level at the depth of the steel that results in a significant corrosion rate that leads to corrosion-induced deterioration. Mohammed and Hamada (2001) defined the chloride threshold level as the "chloride ion concentration that caused the initiation of active corrosion of steel bars in concrete, provided that there are no voids/damages at the steel-concrete interface." Critical chloride threshold values for different steel reinforcement types have been reported in the literature (Glass and Buenfeld 1997; Alonso et al. 2000; and Trejo and Pillai 2003 and 2004). There exists, however, a large variability among the critical chloride threshold values reported in the literature by the various researchers. One reason for this variability is that the critical chloride threshold value depends on various factors. These factors include the microstructure and other metallurgical parameters of the steel reinforcement, the complex microstructure of the surrounding concrete and transition zone, the pH of the concrete pore solution, the chemistry of the concrete pore solution, the local

environmental characteristics, and the test procedures used to evaluate this parameter (Alonso et al. 2000). It has been well established that the steel surface characteristics are also important factors influencing the critical chloride threshold level of the reinforcement.

The surface condition of the steel can have a significant influence on the critical chloride threshold value (Mammoliti et al. 1996). Cooling procedures during the steel manufacturing process lead to the formation of a thin oxide scale (that is, mill scale) around the steel surface, and these oxide scales can influence the corrosion characteristics of the steel reinforcement (Maslehuddin et al. 2002). Steels with corrosion-resistant microstructures can still be susceptible to localized corrosion due to heterogeneities in the mill scale layer or on the steel surface itself. In fact, most corrosion-resistant steel reinforcement currently available in the market has the mill scale removed to prevent corrosion initiation. Pan et al. (1998) found that laser surface remelting can improve the corrosion resistance of structural steel as a result of the removal of surface irregularities. Pantelis et al. (2002) confirmed that resistance against localized corrosion could be increased with laser surface hardening of structural steel. Li and Sagues (2001) reported that the removal of the mill scale and other rust products from the reinforcing bar surface resulted in an increase in the critical chloride threshold of the steel reinforcement immersed in solutions simulating concrete environments. Limited work has been performed on steel reinforcement embedded in cementitious materials.

This paper presents quantitative information on the critical chloride threshold values of five different steel reinforcement types with as-received and polished surfaces embedded in cementitious materials. Micrographs characterizing the mill scale and surface topography of the five different steel reinforcement types and discussions on the effect of the mill scale and surface finish on the critical chloride threshold values are presented.

## RESEARCH SIGNIFICANCE

Corrosion of steel reinforcement can lead to RC structures that are unusable, unsafe, and costly to maintain. Improving the corrosion performance of the steel reinforcement, either by increasing the critical chloride threshold or by decreasing the corrosion rate, can make structures containing these reinforcement types more cost effective. Altering the surface conditions of the steel reinforcement to better resist

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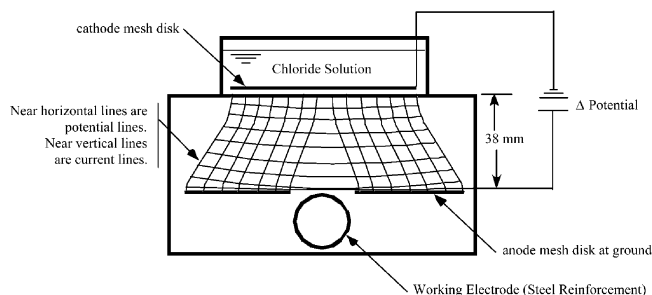


Fig. 1—Potential and current lines in accelerated chloride threshold sample (Trejo and Pillai 2003).

**Table 1—Sample population for accelerated chloride threshold test program**

Steel type (surface condition)	Preliminary statistics of critical chloride threshold values		Sample population	
	$\bar{X}_3$ , kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	$SD_3$ , kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	Minimum required	Actually tested
ASTM A 706 (P)	0.23 (0.38)	0.07 (0.12)	9	9
ASTM A 706 (R)	0.27 (0.46)	0.02 (0.03)	9	9
ASTM A 615 (P)	0.49 (0.83)	0.38 (0.64)	8	17
ASTM A 615 (R)	0.74 (1.24)	0.54 (0.91)	18	18
Microcomposite (P)	8.71 (14.67)	4.32 (7.28)	17	17
Microcomposite (R)	4.41 (7.44)	0.96 (1.17)	9	9
SS304 (P)	5.48 (9.23)	1.37 (2.31)	8	8
SS304 (R)	4.36 (7.34)	0.67 (1.13)	9	9
SS316LN (P)	7.83 (13.18)	1.12 (1.89)	9	9
SS316LN (R)	10.33 (17.40)	1.52 (2.55)	10	10

Note: P and R indicate “polished” and “as-received” samples, respectively.

corrosion initiation may be one alternative to improving the corrosion resistance of steel reinforcing bars. This research investigated the effect of surface condition on the critical chloride threshold of five reinforcement types.

## EXPERIMENTAL DESIGN

To determine the influence of the steel reinforcement surface condition on the corrosion performance of the steel reinforcement embedded in cementitious material, a statistically valid test program was developed. Initially, three test specimens with each steel type were cast and tested for critical chloride threshold values. From these preliminary test results, the mean and standard deviation values for the critical chloride threshold values were obtained for each steel type. These values were then used to provide an initial estimate of the number of samples required for the test program. A half 95% confidence interval length of 40% of the mean value was used to determine the total sample

population required for obtaining statistically valid test results (Trejo and Pillai 2003). Table 1 shows the mean and standard deviation values obtained from the preliminary tests, the sample population required for the overall test program, and the actual number of samples tested in the critical chloride threshold test program.

The microscopy study included obtaining micrographs from representative samples. Representative samples were prepared and their surfaces were qualitatively assessed. Representative micrographs of the surfaces of each as-received reinforcement type are presented in a following section.

## TEST PROCEDURES

The accelerated chloride threshold (ACT) test procedure was used to quantitatively determine the critical chloride threshold value of the steel reinforcement samples embedded in cementitious materials. Trejo and Pillai (2003) provided a detailed description of the test procedure. In simplified terms, the ACT test procedure consists of four distinct systems as follows:

1. An accelerated chloride transport system that uses the intermittent application of a potential gradient across a cathode-anode system, separate from the embedded steel reinforcement, to gradually increase the chloride concentration near the embedded steel reinforcement over a relatively short time period;

2. A corrosion initiation detection system that includes embedded electrochemical components to determine polarization resistance  $R_p$  values as a function of applied potential time (the inverse  $R_p$  value is directly proportional to the corrosion rate);

3. A statistical analysis procedure to identify when the steel reinforcement transfers from a passive to active corrosion state; and

4. A chemical analysis system used to determine the chloride concentration in the mortar adjacent to the steel reinforcement surface.

This testing procedure consists of sequentially applying a potential gradient in relatively short durations followed by 42-h rest periods to increase, in a relatively short time period, the chloride concentration near the steel reinforcement surface. Electrochemical testing of the steel reinforcement is performed at the end of the rest periods to determine the corrosion activity using  $R_p$  test procedures. A statistical analysis is then performed to determine if the embedded steel reinforcement is actively corroding. Once the statistical analysis indicates that the steel reinforcement is actively corroding, the samples are sheared at the steel-mortar interface, and the mortar directly adjacent to the steel reinforcement is evaluated for total chloride concentration. This chloride concentration is reported as the critical chloride threshold level.

Figure 1 shows the anode-cathode system. Note that the anode is separate from the steel reinforcement (the working electrode). This prevents the steel reinforcement from being directly polarized from the applied potential gradient. Excessive polarization of the reinforcement can change the surface characteristics and result in inaccurate corrosion rate measurements (Tait 1994). A potential gradient was applied between the anode and cathode for 6 h followed by a 42-h rest period. Near the end of the rest period, the  $R_p$  of the steel reinforcement was evaluated. The scan rate was 0.0667 mV/s, and the scan typically started  $-20$  mV from the open circuit potential. The  $R_p$  is inversely proportional to the corrosion rate  $i_{corr}$  as follows

**Table 2—Chemical composition of Type I cement used in accelerated chloride threshold test program**

SO <sub>3</sub>	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	NaO	C <sub>3</sub> S	C <sub>3</sub> A	LOI	IR
2.99	20.78	1.96	1.27	5.24	0.49	64.45	57.95	10.58	1.68	0.18

Note: LOI = loss on ignition; and IR = insoluble residue.

$$i_{corr} = \frac{B}{R_p} \quad (1)$$

where  $B$  is the proportionality constant that is dependent on the anodic and cathodic Tafel slopes. Because the Tafel slopes are difficult to accurately obtain, are time consuming, and because only the change in corrosion activity is necessary for determining corrosion activation, this analysis only focused on the relationship

$$i_{corr} \propto \frac{1}{R_p} \quad (2)$$

Once determined, the inverse  $R_p$  was plotted as a function of applied time of potential gradient  $T_p$ . After a minimum of four  $R_p$  values were obtained from the ACT samples, a statistical analysis procedure was implemented to determine if the change in the inverse  $R_p$  value was significantly different from a predicted inverse  $R_p$  value estimated from the previous inverse  $R_p$  values as follows

$$t\text{-score} = \frac{\left( \text{New} \frac{1}{R_p} - \text{Predicted} \frac{1}{R_p} \right)}{\text{Standard error of prediction}} \quad (3)$$

The predicted inverse  $R_p$  value was based on linear regression of the previous  $R_p$  values. The standard error of prediction was determined as follows

$$\text{Standard error of prediction} = \sigma \cdot \sqrt{1 + \frac{1}{n} + \frac{(New T_p - \bar{T}_p)^2}{\sum T_p^2 - \frac{(\sum T_p)^2}{n}}} \quad (4)$$

where  $\sigma$  is the standard error of all previous inverse  $R_p$  values,  $n$  is the sample size, and  $\bar{T}_p$  is the mean value of all previous  $T_p$  values. A typical inverse  $R_p$  versus  $T_p$  plot showing corrosion initiation after 132 h of applied voltage is shown in Fig. 2. For this work, the change in the inverse  $R_p$  value was significantly different if the  $t$ -score was greater than 3.

When a  $t$ -score of 3 or greater was observed from the statistical analysis, the sample was removed from the testing program, sheared at the steel-mortar interface, and the mortar directly adjacent to the steel surface was evaluated for total chloride concentration using the *Standard Test Method for Total Chloride Content in Concrete Using the Specific Ion Probe* (Cady and Gannon 1992). An area of approximately 25 mm (1 in.) in diameter was ground to a depth of 2 mm (0.08 in.), resulting in approximately 3 g (0.07 lb) of mortar dust to perform the total chloride analysis. The value obtained from this testing was reported as the critical chloride threshold because this was the chloride concentration that caused the steel reinforcement to transfer from a passive to active corrosion state, as defined in the statistical analysis.

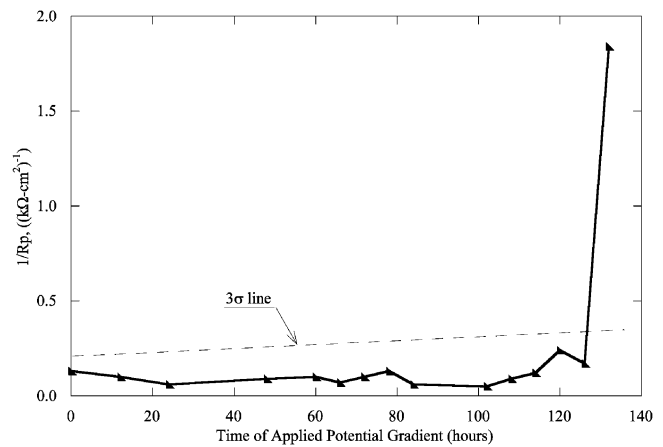


Fig. 2—Typical plot of inverse polarization resistance versus time of applied voltage for accelerated chloride threshold testing.

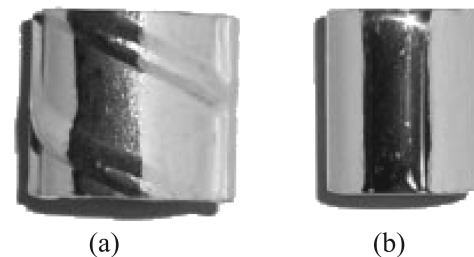


Fig. 3—Typical surface conditions of tested reinforcing bars: (a) “as-received” condition; and (b) “polished” condition.

## MATERIALS

The mortar mixtures for this testing program were prepared using Type I ordinary portland cement meeting ASTM C 150 specifications and Ottawa sand meeting ASTM C 778 specifications. The water:cement:sand ratio was 1:2:4.5. Table 2 shows the chemical composition of the Type I cement used for the ACT testing. The ACT test samples were cured in an environmental chamber for 7 days at 32 °C ± 3 °C (90 °F ± 5 °F). The compressive strength of mortar was 11.3 MPa (1640 psi) at 1 day, 33.2 MPa (4800 psi) at 7 days, 37.7 MPa (5475 psi) at 14 days, and 38.6 MPa (5600 psi) at 28 days. The average 28-day permeability of three test samples following ASTM C 1202-97 (1997) was determined to be very high, as testing was terminated for all samples due to high temperatures.

The five reinforcement types evaluated in this testing program included ASTM A 706, ASTM A 615, microcomposite, 304 stainless steel (SS304), and 316LN stainless steel (SS316LN). The chemical compositions of these reinforcement types are shown in Table 3. ASTM A 706 and A 615 steels consist of a typical pearlitic-ferritic microstructure. The microcomposite steel microstructure consists mostly of lath martensite. The SS304 and SS316LN consist of austenitic microstructures. Each reinforcing steel type used in this study was obtained from the same production lot. Two types of surface conditions (as-received and polished) were tested. Both as-received and polished samples, as shown in Fig. 3, were prepared by cutting the 19 mm (3/4 in.) diameter steel reinforcing samples into 19 mm (3/4 in.) long pieces using a lathe. The additional processes for the preparation of polished samples

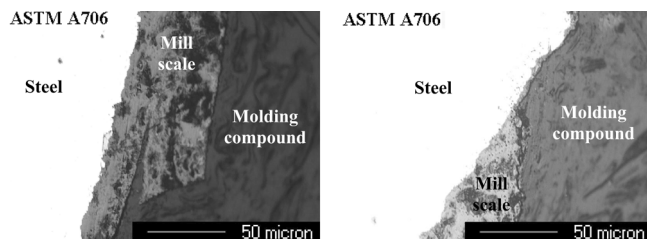


Fig. 4—Typical micrographs of ASTM A 706 steel reinforcement surface.

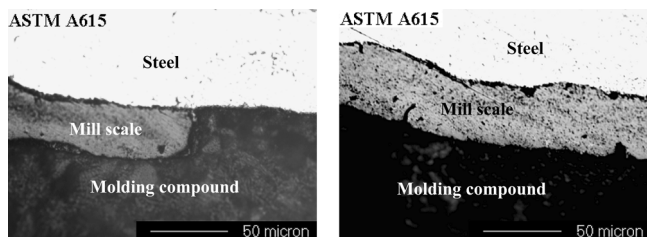


Fig. 5—Typical micrographs of ASTM A 615 steel reinforcement surface.

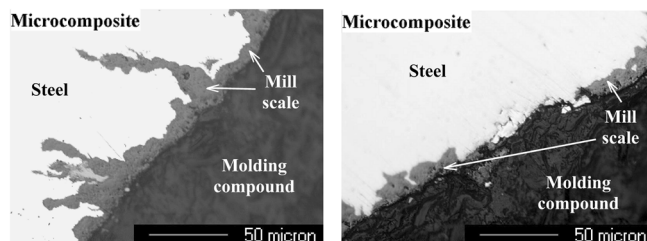


Fig. 6—Typical micrographs of microcomposite steel reinforcement surface.

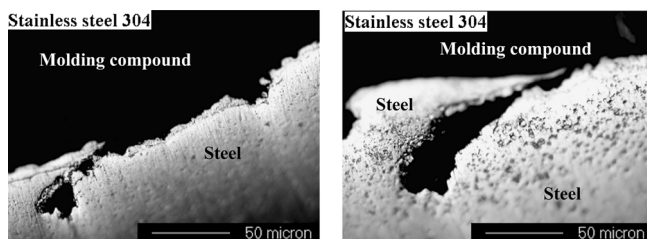


Fig. 7—Typical micrographs of SS304 steel reinforcement surface.

included the removal of surface layers using the lathe until the diameter of the remaining steel was 15 mm (0.6 in.), followed by polishing of the surface. Polishing consisted of using a 600 grit paper to remove any surface imperfections followed by further polishing on a cotton buffing wheel. The polished samples were then ultrasonically cleaned in acetone, followed by ultrasonic cleaning in ethyl alcohol. The polished samples had all macro surface irregularities removed. After polishing and cleaning, the samples were coated with a low-viscosity epoxy. An area of 150 mm<sup>2</sup> (0.23 in.<sup>2</sup>) was left uncoated to evaluate the corrosion activity of the sample.

### STEEL SURFACE CHARACTERIZATION

To characterize the steel reinforcement surfaces, metallographic specimens for all five as-received steel reinforcement types were prepared following ASTM E 01-01 (2001). Micrographs of surfaces of the five different steel reinforcement types were obtained using optical and

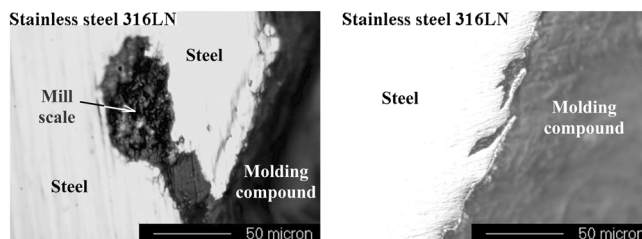


Fig. 8—Typical micrographs of SS316LN steel reinforcement surface.

**Table 3—Chemical composition (as weight %) of steel reinforcement used in accelerated chloride threshold tests**

Chemical constituent	ASTM A 615	ASTM A 706	Microcomposite	SS304	SS316LN
C	0.32	0.23	0.08	0.025	0.018
Mn	0.91	0.89	0.45	1.19	1.32
Si	0.23	0.24	0.24	0.53	0.58
S	0.039	0.040	0.011	0.009	0.026
P	0.034	0.012	0.014	0.030	0.027
Cu	0.51	0.41	0.13	0.56	0.54
Cr	0.55	0.18	10.4	18.43	17.57
Ni	0.30	0.18	0.11	8.64	10.80
Mo	0.09	0.07	0.03	0.35	2.01
V	0.014	0.032	—	—	—
Fe	Balance	Balance	Balance	Balance	Balance

scanning electron microscopy (SEM) techniques. It should be noted that the SS304 and SS316LN reinforcements were received with the mill scale removed. This is typical for stainless steel reinforcements marketed in the U.S. Typical micrographs of the surfaces for all five steel reinforcement types are shown in Fig. 4 through 8. In these micrographs, the light areas are the steel base material, the dark areas are the molded plastic used to mount the specimens, and the intermediate gray areas, where present, are the mill scale.

Figure 4 indicates that the ASTM A 706 exhibits crevices in the mill scale and has a generally discontinuous mill scale. The discontinuous mill scale can lead to the formation of microgalvanic cells that can decrease the critical chloride threshold of the steel. The crevices can also result in a decreased critical chloride threshold level. Figure 5 shows the surface of the ASTM A 615 reinforcement. Although some discontinuities were observed in this mill scale, in general, this reinforcement type exhibited a fairly uniform, continuous mill scale. Although some discontinuities were observed in the mill scale, these discontinuities were in general less frequent than that observed on the ASTM A 706 reinforcement.

Figure 6 shows the surface of the microcomposite steel reinforcement. The microcomposite reinforcement exhibited a fairly nonuniform surface, with discontinuous mill scale and a significant amount of mill scale (iron-oxide) rolled into the base steel. Some crevices were identified on the mill scale and steel surface. The nonuniform surface with the presence of crevices could lead to lower critical chloride threshold values when compared with more uniform surfaces.

The surface conditions of the SS304 are shown in Fig. 7. This reinforcement type is distributed from the manufacturer with the mill scale removed. No mill scale was observed in the micrographs for this reinforcement type. The SS304 reinforcement did exhibit crevices in the surface. The micrographs

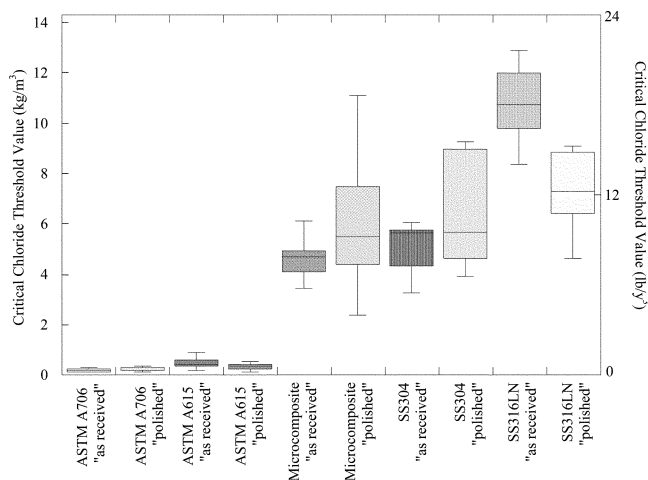


Fig. 9—Critical chloride threshold values for different reinforcement types evaluated in test program

seem to indicate that the mill scale was initially rolled into the base steel and then later removed during the mill scale removal process. Only a limited number of sites on the surface showed remaining mill scale (iron oxides) in these crevices. Because no mill scale was observed, no detrimental effects due to the formation of microgalvanic cells between the areas covered with mill scale and the areas free of mill scale would be expected, although the crevices could be detrimental to the corrosion resistance.

Figure 8 shows the surface condition of SS316LN steel reinforcement. As shown, the crevices on the surface of this reinforcement type seemed to be smaller than the crevices on the SS304. In addition, it was observed during the microscopy work that many of these crevices tended to contain iron oxides. Although these oxides could result in the formation of microgalvanic cells, these oxides tended to completely fill the crevices, possibly reducing the chance of crevice corrosion.

All polished samples had similar surface conditions, with all mill scale, crevices, and discontinuities removed.

## RESULTS AND DISCUSSIONS

The critical chloride threshold values obtained from the ACT testing for the five reinforcement types with the different surface conditions embedded in mortar are shown in Table 4 through 8. They are also shown graphically in Fig. 9.

The mean critical chloride threshold of the ASTM A 706 increased from 0.2 to 0.3 kg/m<sup>3</sup> (0.3 to 0.4 lb/yd<sup>3</sup>) as a result of polishing the surface. The standard deviation for these sample sets remained the same for both surface conditions. Although relatively minor, the increase in the mean critical chloride threshold level is likely a result of the elimination of the discontinuous mill scale and crevices, both of which can lead to active corrosion at lower chloride concentrations.

The ASTM A 615 exhibited a decrease in the mean critical chloride threshold values from 0.5 to 0.3 kg/m<sup>3</sup> (0.9 to 0.5 lb/yd<sup>3</sup>) when the samples were polished. The standard deviations were 0.2 and 0.1 kg/m<sup>3</sup> (0.3 and 0.2 lb/yd<sup>3</sup>) for the as-received and polished conditions, respectively. The decrease in the standard deviation as a result of the polishing is likely a result of eliminating the surface imperfections. The decrease in the critical chloride threshold of the polished ASTM A 615 samples could be a result of fewer numbers of discontinuities and more uniform mill

Table 4—Critical chloride threshold values of ASTM A 706 steel reinforcement with different surface conditions

Sample number	Critical chloride threshold value, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	
	ASTM A 706 "as-received"	ASTM A 706 "polished"
1	0.3 (0.5)	0.2 (0.3)
2	0.3 (0.6)*	0.2 (0.3)
3	0.2 (0.3)	0.3 (0.5)
4	0.1 (0.2)	0.3 (0.5)
5	0.2 (0.3)	0.3 (0.4)
6	0.2 (0.4)	0.3 (0.5)
7	0.2 (0.4)	0.3 (0.5)
8	0.1 (0.3)	0.3 (0.6)
9	0.1 (0.2)	0.1 (0.2)
Mean	0.2 (0.3)	0.3 (0.4)
Standard deviation	0.1 (0.1)	0.1 (0.1)

\*Outlier; not included in mean and standard deviation calculations.

Table 5—Critical chloride threshold values of ASTM A 615 steel reinforcement with different surface conditions

Sample number	Critical chloride threshold value, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	
	ASTM A 615 "as-received"	ASTM A 615 "polished"
1	0.5 (0.8)	0.2 (0.3)
2	0.4 (0.6)	0.9 (1.5)*
3	1.4 (2.3)*	0.4 (0.6)
4	0.6 (0.9)	0.2 (0.4)
5	0.3 (0.4)	0.1 (0.2)
6	0.9 (1.5)	0.4 (0.8)
7	0.6 (1.0)	0.1 (0.2)
8	0.5 (0.9)	0.4 (0.6)
9	0.6 (1.1)	0.4 (0.7)
10	0.3 (0.6)	0.2 (0.4)
11	0.4 (0.7)	0.9 (1.6)*
12	0.6 (1.0)	0.4 (0.7)
13	0.4 (0.7)	0.4 (0.7)
14	0.2 (0.4)	0.4 (0.6)
15	0.2 (0.3)	0.2 (0.4)
16	0.4 (0.6)	0.3 (0.5)
17	0.7 (1.1)	0.5 (0.9)
18	0.4 (0.6)	—
Mean	0.5 (0.8)	0.3 (0.5)
Standard deviation	0.2 (0.3)	0.1 (0.2)

\*Outlier; not included in mean and standard deviation calculations.

scale on the as-received ASTM A 615 samples. The lower number of discontinuities in the mill scale, in conjunction with a more continuous mill scale, likely resulted in the formation a quasi-protective barrier against the transport of chloride ions to the base steel. Because the chemical composition and microstructure make this steel more susceptible to chloride-induced corrosion, it is likely that when the quasi-protective mill scale barrier was removed, the product became more susceptible to corrosion initiation and exhibited a lower critical chloride threshold.

The microcomposite as-received and polished reinforcement samples exhibited a mean critical chloride threshold value of 4.6 and 6.1 kg/m<sup>3</sup> (7.7 and 10.2 lb/yd<sup>3</sup>),

**Table 6—Critical chloride threshold values of microcomposite steel reinforcement with different surface conditions**

Sample number	Critical chloride threshold value, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	
	Microcomposite as-received	Microcomposite polished
1	4.7 (7.9)	4.8 (8.1)
2	3.6 (6.1)	13.3 (22.5)*
3	4.9 (8.3)	8.0 (13.5)
4	3.4 (5.8)	9.0 (15.2)
5	6.1 (10.3)	5.4 (9.1)
6	4.1 (6.9)	11.1 (18.7)
7	5.0 (8.5)	7.4 (12.5)
8	4.8 (8.2)	7.5 (12.6)
9	4.5 (7.5)	2.4 (4.0)
10	—	4.9 (8.2)
11	—	4.3 (7.3)
12	—	4.2 (7.0)
13	—	5.6 (9.4)
14	—	4.8 (8.1)
15	—	6.0 (10.1)
16	—	4.4 (7.4)
17	—	7.2 (12.1)
Mean	4.6 (7.7)	6.1 (10.2)
Standard deviation	0.81 (1.36)	2.2 (3.7)

\*Outlier; not included in mean and standard deviation calculations.

**Table 7—Critical chloride threshold values of stainless steel 304 reinforcement with different surface conditions**

Sample number	Critical chloride threshold value, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	
	Stainless steel 304 as-received	Stainless steel 304 polished
1	4.3 (7.3)	6.0 (10.0)
2	5.0 (8.5)	3.9 (6.6)
3	3.7 (6.2)	6.5 (11.0)
4	5.8 (9.7)	4.7 (8.0)
5	5.8 (9.7)	5.4 (9.1)
6	5.7 (9.6)	9.0 (15.1)
7	3.3 (5.5)	9.3 (15.6)
8	6.1 (10.2)	4.6 (7.8)
9	5.7 (9.5)	—
Mean	5.0 (8.5)	6.2 (10.4)
Standard deviation	1.0 (1.7)	2.0 (3.4)

respectively. The standard deviations were 0.8 and 2.2 kg/m<sup>3</sup> (1.4 and 3.7 lb/yd<sup>3</sup>) for the as-received and polished conditions, respectively. This significant increase (260%) in the standard deviation after polishing is contradictory to what would be expected. Further investigations indicated that some of the steel samples exhibited a large number of sulfide inclusions that were exposed on the polished samples. These inclusions could result in localized corrosion activity. The number of inclusions varied greatly among the batch of reinforcing steel. As a result, when the mill scale was removed, the inclusion sites could have acted as corrosion initiation sites. For samples that exhibited sufficient sites, the threshold would be expected to be lower. For samples that had a limited number of inclusions, the critical chloride threshold would be expected to be higher.

**Table 8—Critical chloride threshold values of stainless steel 316 LN steel reinforcement with different surface conditions**

Sample number	Critical chloride threshold value, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	
	Stainless steel 316LN as-received	Stainless steel 316LN polished
1	10.0 (16.9)	7.0 (11.7)
2	9.0 (15.1)	7.4 (12.5)
3	12.0 (20.2)	9.1 (15.3)
4	12.9 (21.7)	3.8 (6.3)*
5	11.8 (20.5)	8.0 (13.4)
6	9.8 (16.5)	4.6 (7.8)
7	10.3 (17.3)	6.4 (10.8)
8	8.4 (14.1)	7.2 (12.1)
9	12.2 (19.8)	8.8 (14.9)
10	11.2 (18.9)	—
Mean	10.8 (18.1)	6.9 (11.6)
Standard deviation	1.5 (2.5)	1.8 (3.0)

\*Outlier; not included in mean and standard deviation calculations.

Under these conditions, the standard deviation for this type of reinforcement would increase, as determined from the tests. Because the surface of the microcomposite reinforcing bars exhibited a large percentage of discontinuities, a mill scale of varying thickness, and a large relative volume of mill scale was rolled into the base steel, the removal of these heterogeneities should result in higher critical chloride threshold values. This was the case. Results indicate that an increase in the mean critical chloride threshold value is possible if the mill scale is removed. This investigation only evaluated the change in the critical chloride threshold of as-received and polished reinforcing bars. It is not practical to “polish” reinforcing bars for field use. Although an increase in the critical chloride threshold would be expected from the removal of the mill scale, further work is needed to justify this.

The SS304 as-received and polished samples exhibited a mean critical chloride threshold value of 5.0 and 6.2 kg/m<sup>3</sup> (8.5 and 10.4 lb/yd<sup>3</sup>), respectively. The standard deviation changed from 1.0 kg/m<sup>3</sup> (1.7 lb/yd<sup>3</sup>) for the as-received samples to 2.0 kg/m<sup>3</sup> (3.4 lb/yd<sup>3</sup>) for the polished samples. This increase in the standard deviation from the as-received to polished condition is also contradictory to what was expected. Although this increase is significantly lower than the increase in the standard deviation for the microcomposite reinforcement (2.0 kg/m<sup>3</sup> [3.4 lb/yd<sup>3</sup>]), the polishing of the surface was expected to decrease the standard deviation. It is possible that the microstructure characteristics or heterogeneities caused the larger scatter. The increase in the critical chloride threshold level is likely due to the removal of the crevices formed during the rolling process.

The as-received and polished SS316LN steels exhibited the highest critical chloride threshold values for all reinforcement types tested in this program: 10.8 and 7.3 kg/m<sup>3</sup> (18.1 and 12.3 lb/yd<sup>3</sup>), respectively. The standard deviation decreased slightly from 1.5 to 1.4 kg/m<sup>3</sup> (2.5 to 2.4 lb/yd<sup>3</sup>) when the as-received reinforcement was polished. Unlike the ASTM A 706, ASTM A 615, microcomposite, and SS304 reinforcements, the SS316LN reinforcement exhibited a significantly lower critical chloride threshold after removing the as-received surface. This reinforcement exhibited surface crevices similar to that of the SS304 reinforcement; these surface crevices, however, were filled with iron oxides

(likely, the mill scale). In conjunction with the composition (high chromium, nickel, and molybdenum contents), these filled surface crevices likely did not have a detrimental impact on the initiation of corrosion. Why the removal of the as-received surface reduced the critical chloride threshold of the SS316LN reinforcement is unknown. Possible reasons could include that a strong, robust passive film formed on the reinforcement surface as a result of the mill scale removal process or the large number of heterogeneities (microvoids) that were present in the microstructure resulted in the steel being more susceptible to chloride corrosion.

## SUMMARY AND CONCLUSIONS

The results of this research indicate that milling and polishing the surface of ASTM A 706, microcomposite, and SS304 reinforcement can improve the critical chloride threshold values of these reinforcement types. Although polishing the bars is not practical for field applications, based on these findings, removal of the mill scale or the as-received surface condition may improve the corrosion resistance of some reinforcement types when embedded in cementitious materials. It should be noted that the increase in the critical chloride threshold for the ASTM A 706 was small and the economic justification for removing the mill scale on this reinforcement type is likely not justified. The removal of the mill scale on the microcomposite steel reinforcement showed a significant improvement in the critical chloride threshold and removal of this mill scale may be economically justified. More research is needed to confirm this.

The critical chloride threshold of the ASTM A 615 and SS316LN reinforcements decreased with the removal of the as-received surface conditions. The tightly adhered, continuous, uniform mill scale on the ASTM A 615 reinforcement may serve as a protective barrier, thus increasing the critical chloride threshold of this steel reinforcement type. The significant reduction in the critical chloride threshold value of the SS316LN reinforcement was unexpected and thought to be a result of the removal of a strong, corrosion resistant passive film that possibly formed during the mill scale removal process or as a result of exposing the microstructure, which exhibited microvoids, to the chloride environment.

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## REFERENCES

- Alonso, C.; Andrade, C.; Castellote, M.; and Castro, P., 2000, "Chloride Threshold Values to Depassivate Reinforcing Bars Embedded in a Standardized OPC Mortar," *Cement and Concrete Research*, V. 30, No. 7, pp. 1047-1055.
- ASTM A 615/A 615M-01b, 2002, "Standard Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, Pa., 6 pp.
- ASTM A 706/A 706M-01, 2002, "Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement," ASTM International, West Conshohocken, Pa., 6 pp.
- ASTM C 150-97a, 1998, "Standard Specification for Portland Cement," ASTM International, West Conshohocken, Pa., 8 pp.
- ASTM C 778-97, 1998, "Standard Specification for Standard Sand," ASTM International, West Conshohocken, Pa., 3 pp.
- ASTM C 1202-97, 1997, "Standard Test Method for Electrical Indication of Concrete's Ability To Resist Chloride Ion Penetration," ASTM International, West Conshohocken, Pa., 6 pp.
- ASTM E 03-01, 2001, "Standard Practice for Preparation of Metallographic Specimens," ASTM International, West Conshohocken, Pa., 12 pp.
- Cady, P., and Gannon, E., 1992, "Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion," *SHRP Report No. SHRP-S-330*, Strategic Highway Research Program, Washington, D. C., Sept., pp. 85-105.
- Glass, G. K., and Buenfeld, N. R., 1997, "Presentation of the Chloride Threshold Level for Corrosion of Steel in Concrete," *Corrosion Science*, V. 39, No. 5, May, pp. 1001-1013.
- Li, L., and Sagues, A. A., 2001, "Metallurgical Effects on Chloride Ion Corrosion Threshold of Steel in Concrete," *FDOT Report No. WPI 0510806*, Florida Department of Transportation, Tallahassee, Fla., Nov.
- Mammoliti, L. T.; Brown, L. C.; Hansson, C. M.; and Hope, B. B., 1996, "The Influence of Surface Finish of Reinforcing Steel and pH of the Test Solution on the Chloride Threshold Concentration for Corrosion Initiation in Synthetic Pore Solutions," *Cement and Concrete Research*, V. 26, No. 4, Apr., pp. 545-550.
- Maslehuddin, M.; Al-Zahrani, M. M.; Al-Dulaijan, S. U.; Abdulquddus, Rehman, S.; and Ahsan, S. N., 2002, "Effect of Steel Manufacturing Process and Atmospheric Corrosion on the Corrosion-Resistance of Steel Bars in Concrete," *Cement and Concrete Research*, V. 24, No. 1, Feb., pp. 151-158.
- Mohammad, T. U., and Hamada, H., 2001, discussion of "Chloride Threshold Values to Depassivate Reinforcing Bars Embedded in a Standardized OPC Mortar," by C. Alonso, C. Andrade, M. Castellote, and P. Castro, *Cement and Concrete Research*, V. 31, No. 5, May, pp. 835-838.
- Pan, Q. Y.; Huang, W. D.; Song, R. G.; Zhou, Y. H.; and Zhang, G. L., 1998, "The Improvement of Localized Corrosion Resistance in Sensitized Stainless Steel by Laser Surface Remelting," *Surface and Coatings Technology*, V. 102, No. 3, Apr., pp. 125-134.
- Pantelis, D. I.; Bouyiouri, E.; Kouloumbi, N.; Vassiliou, P.; and Koutsomichalis, A., 2002, "Wear and Corrosion Resistance of Laser Surface Hardened Structural Steel," *Surface and Coatings Technology*, V. 161, No. 2-3, Dec., pp. 125-134.
- Tait, W. S., 1994, *An Introduction to Electrochemical Corrosion Testing for Practicing Engineers and Scientists*, Pair O Docs Publications, Racine, Wis., 139 pp.
- Trejo, D., and Miller, D., 2003, "Determination of Chloride Corrosion Threshold for Metals Embedded in Cementitious Material," U.S. Patent No. 6,646,427 B2.
- Trejo, D., and Pillai, R. G., 2003, "Accelerated Chloride Threshold Testing: Part I—ASTM A 615 and A 706 Reinforcement," *ACI Materials Journal*, V. 100, No. 6, Nov.-Dec., pp. 519-527.
- Trejo, D., and Pillai, R. G., 2004, "Accelerated Chloride Threshold Testing: Part II—Corrosion Resistant Reinforcement," *ACI Materials Journal*, V. 101, No. 1, Jan.-Feb., pp. 57-64.