Paper No.
PP5

Short term test methods to determine chloride threshold using macrocell and lollipop type specimens

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ABSTRACT

Chloride induced corrosion is one of the serious mechanism of deterioration of reinforced concrete structures. Chloride threshold (Cl_{th}) is one of the important parameters to estimate the corrosion initiation time. Chloride ions from external/surrounding atmosphere travel into the concrete (mostly through diffusion process) and reach the rebar level. When sufficient amount of Cl_{th} reaches the rebar, chloride ions disrupts the protective passive layer on the steel surface. Though, Cl_{th} is an important parameter to be consider to estimate the service life; Practitioners/engineers generally do not evaluate the Cl_{th} before planning/construction. In other words, the performance based approach for durability design of reinforced concrete structure is not adopted. This conservative approach can be because of following reasons, i) the standard methods (say, ASTM G 109) requires a long time for determination of Cl_{th} of steel cementitious system, ii) Chloride threshold cannot be generalized for steels; It also depends on many factors like steel type, concrete mix, water to binder ratio, and steel - concrete interface properties and iii) conservative approach of contractors and practicing engineers. This paper introduces the short term chloride threshold test methods for uncoated and cement polymer composite (CPC) coated rebar. For this, macrocell (similar to ASTM G 109) and lollipop type specimens (for linear polarization resistance technique) were cast for following set of steel specimens, i) 'as – received' steel, ii) CPC coating on 'as – received' steel, iii) rust free/sand - blasted steel surface, iv) CPC coating on sand – blasted steel. Chloride concentration near to the exposed steel surface was determined using guidelines given in SHRP – 330. Using both the test methods, chloride threshold determined for each steel type was found to be approximately same. The test duration to determine Cl_{th} was found approximately 30 - 90 days in case of Lollipop type specimens and 50-175 day in case of macrocell specimen.

Keywords: Chloride threshold, Reinforced Concrete, short term test method

INTRODUCTION

We have built a large number of reinforced concrete structures in last two decades. Almost all of these structures are constructed without performance based design. Recently structures are been proposed for a specific service life. For this, contractor and practitioners should check the quality and long term performance of materials. However, quality check for many important material properties is not done. Because many of these techniques require longer duration. ASTM G 109 is one the test method widely used to determine the chloride threshold. But this method takes very long time (say, more than 2 years). Therefore, practitioners cannot afford to wait this long to determine the Cl_{th} values. In this work, Authors try to compare and propose a short term test method, which can be used to determine Cl_{th} within a short time period. However, test duration will depend on the variables involved (say, type of steel, admixtures used, coating type). Chloride threshold depends on many factors like type of steel (Hurley et al., (2006)), surface condition [Pillai and Trejo (2005), (Bertolini and Redaelli 2009)]. Therefore, test variables chosen in this study are steel surface condition (rusted/as - received and rust free/sand - blasted) and with and without CPC coating. To quantify the performance of cement polymer composite (CPC) coating and to check the validity of these methods on coated rebars, CPC coating was applied and tested in this work. Many researchers [Angst et al., (2011), (Burstein 1996), Briet (2001), and Zimmermann (1999)] have reported that size of specimen plays an important role in determining the chloride threshold. The decrease in specimen size may result in more scatter of data and an increase in specimen size may lead to pitting corrosion (angst et al (2011)). Specimen size can also alter interfacial transition zone (between steel and concrete). This alteration can result in formation of unexpected corrosion cells. To overcome these effects, mortar was used instead of concrete. In concrete, the aggregates are supposed to be the inert material but presence of aggregates can create unnecessary nonuniformity in the specimen. Use of mortar can improve the uniformity at the steel concrete (S – C) interfacial zone. This paper introduces and compares the two short term test methods to determine chloride threshold of steel with and without CPC coating.

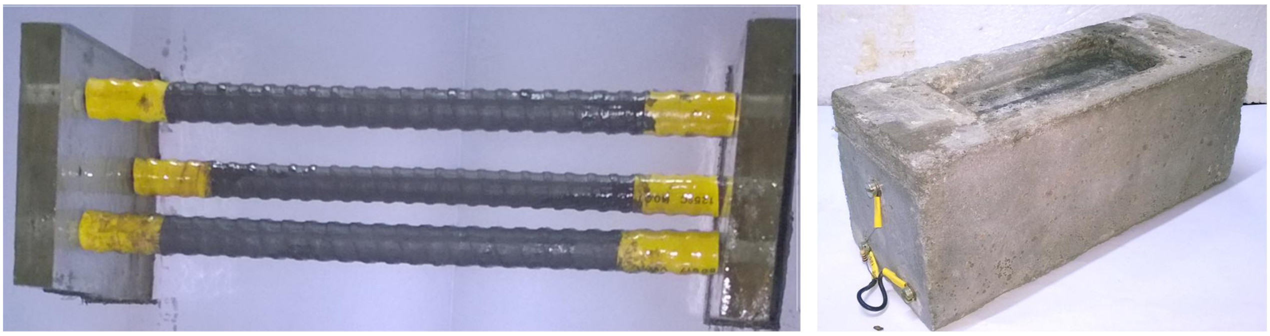
EXPERIMENTAL PROCEDURE

This experimental study was conducted in two parts: i) Determination of chloride threshold using macrocell specimen, ii) Determination of chloride threshold value using Linear Polarization Resistance (LPR) technique on Lollipop type specimen.

MACROCELL SPECIMEN

Figure 1 (a) shows the photograph of a set of three rebars arranged similar to ASTM G 109 type of specimen. Figure 1 (b) shows the photograph of macrocell specimen (modified ASTM G109) with a dimension of (200 × 75 × 75) mm. Three steel bars were installed in each specimen; top rebar acts as an anode and bottom rebars act as a cathode. A 100 Ω resistor was connected between the top (anode) and bottom (cathode) rebars to complete the macro cell circuit as in ASTM G109 – indicating an anode-to-cathode ratio of 1:2.

Three specimens of each type for coated and uncoated steel specimens with and without rust removal were cast for this study: following type of specimens were cast and tested i) 'As-received' TMT steel rebar (AR/WOC), ii) 'Sand-blasted steel rebar (SB/WOC)' iii) CPC coating applied on TMT rebar (AR/WC), and iv) CPC coating applied on sand-blasted rebar (SB/WC). This makes a total of twelve specimens. Mortar was used in this study. By doing this, irregularities due to aggregates in concrete can be avoided. Effect of Interfacial Trasition zone (ITZ) can still be accounted by ITZ effect of fine aggregate and cement paste in the mortar.



(a) (b)

Figure 1 Photograph of (a) reabr set ready for embedding in mortar and (b) Test specimen ready for testing

These specimens were subjected to alternate two day wet (using 15% NaCl solution) and five days dry regime. The macrocell potential (potential difference across 100 Ω resister) was recorded at the end of each wet regime. Later these potentials were used to calculate the total corrosion.

Steel rebar and specimen preparation

For macrocell specimen, Quenched and self-tempered steel (also known as thermo mechanically treated (TMT) steel) with two different surface condition [rusted and clean (by sand blasting)] was used with and without CPC coating for this test. The rebars were cut to 200 mm length and drilled on the both the side to make electrical connections and positioning during the casting of specimens. Epoxy coating was done for 25 mm at the each end of the rebar and was covered with heat shrink tube to prevent moisture from entering into this region. Then, these steel specimens were arranged in a fashion as shown in Figure 1 (a). Mortar was placed in the mould with steel rebar cage embedded. The specimens were moist cured for 28 days. Then, these set of specimens were exposed to chloride solution by placing 15 % NaCl solution in the prebuilt dam.

Lollipop type specimens (LPR test specimens)

Specimen preparation

Lollipop type specimens, the rebars were cut to 70 mm length and drilled on one side to make electrical connections and positioning during the casting of specimens. Once the mortar was placed, it was allowed atmospheric curing for 24 hours and then specimens were moist cured for next 14 days. Then epoxy coating was applied to the lower part of 35 mm mortar in the specimens to avoid chloride ingress to this region (see Figure 2 (a)). Later these specimens were exposed to two days wet (with 3.5 % NaCl solution) and five days dry regime. The specimens were immerged in NaCl solution to a specific level to avoid the entry of solution to the junction of stainless steel and TMT steel rebar. Figure 2 (b) shows the corrosion cell used for the LPR testing. The test specimen (working electrode) is placed in the center and Nichrome mesh is placed around the specimen with an approximate distance of 50 mm. Ions rich concrete simulated pore solution was used as an electrolyte during the test.

Figure 2 shows the photograph of Lollipop type specimen. Linear polarization test was conducted at the end of each wet regime. Polarization resistance (R_p) was measured and the $1/R_p$ value was calculated. Because $1/R_p$ value is proportional to corrosion rate (see Equation 1), the chloride exposure was stopped when spikes in the $1/R_p$ were observed.

(1)

Where I_{corr} is the corrosion current density, B is stern – Geary constant, A is the surface area (in cm^2), and R_p is the polarization resistance.

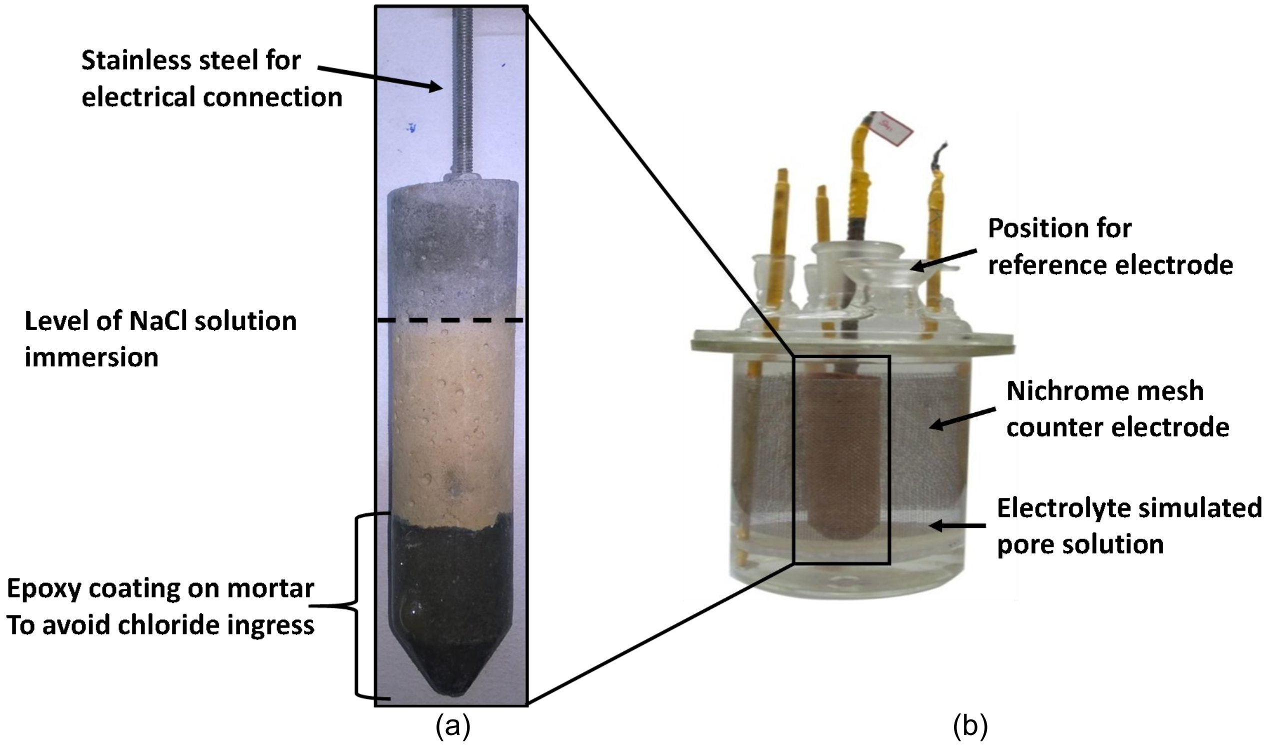


Figure 2: Photograph of (a) Lollipop type specimen and (b) Linear polarization resistance test setup

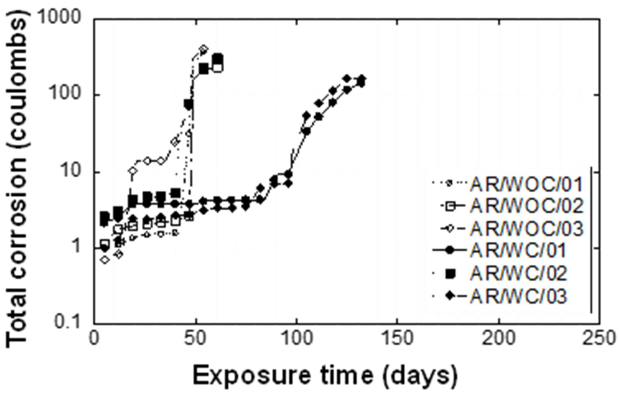
RESULTS

This section summarizes the test results obtained for all types of specimens using macrocell and lollipop type LPR test methods.

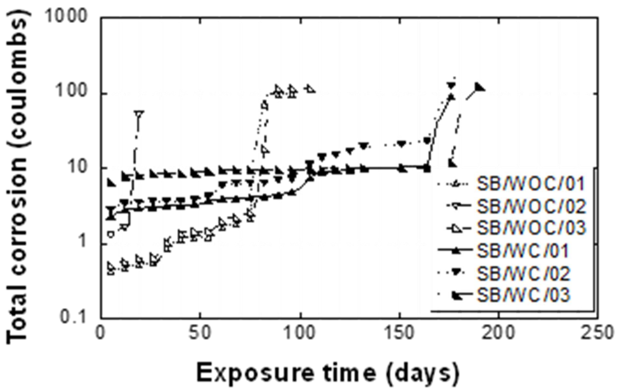
Total corrosion using macrocell specimens

Figure 3 shows the results obtained from modified ASTM G109 (macrocell specimens) test performed (for 250 days). The corrosion initiation was identified as per ASTM G-109 (when total charge passed is more than 150 coulombs). Corrosion resistance of all the three AR/WOC specimens is observed to be very poor. Corrosion initiation was observed within 40 days (see Figure 3 (a)).Corrosion initiation was observed in As-Received/With Coating (AR/WC) specimens on or before 100 days of alternate wet and dry exposure (see a sudden increase in Total Corrosion in Figure 3 (a)). Corrosion initiation in specimen AR/WC/01 was observed along with uncoated specimen. This could be due to the presence of discontinuity in the coating when applied on rusted steel surface. Whereas, all the three SB/WC specimens could prolong corrosion initiation beyond 200 days of cyclic exposure. It is interesting to note that macrocell specimens could capture the corrosion initiation for both coated and uncoated steel rebar specimen (spikes/peaks of Total corrosion).

Also, it should be noticed that the corrosion performance of CPC coating was best exploited when used without rust layer (or application of CPC coating after sand blasting). Premature corrosion of specimens 'as – received' and 'sand – blasted' without coating (AR/WOC and SB/WOC) was observed (within 100 days of exposure). There was no or very less advantage of CPC coating when applied on rusted steel surface ('as receivced' condition). Whereas, when CPC coating is applied on sand blasted specimen, it can adhere to the steel surface and can prolong the corrosion initiation significantly (Ababneh et al., 2012).



(a) Steel type 1 – 'as – received' steel



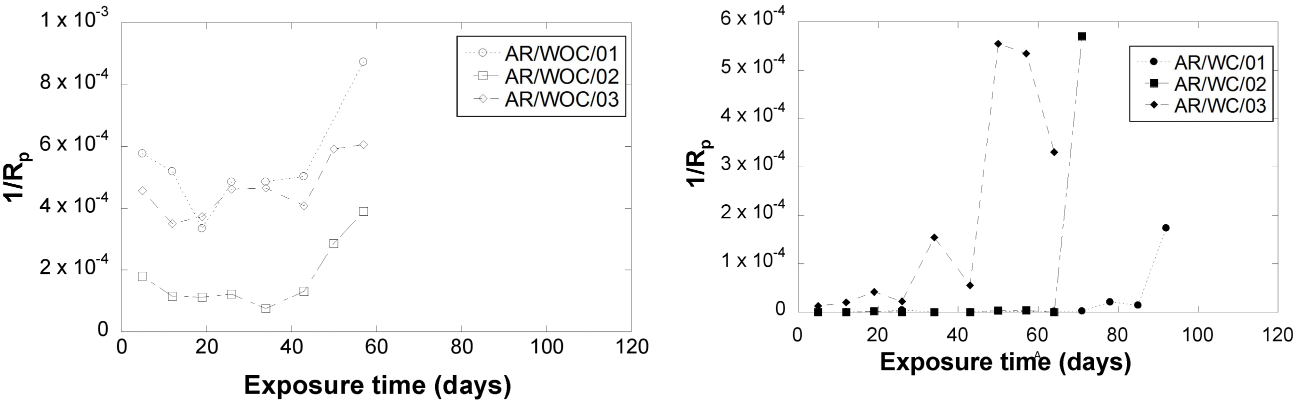
(b) Steel type 2 – Clean/rust free steel

Figure 3: Total corrosion values

Linear polarization resistance using Lollipop type specimen

Figure 4 (a) and (b) shows the $1/R_p$ values for 'as – received' specimens, without and with CPC coating respectively. Exposure to NaCl solution was stopped when increase in $1/R_p$ value was observed. Because $1/R_p$ is proportional to corrosion current density (see Equation 1), corrosion initiation was detected when sudden increase in ($1/R_p$) value was observed. Figure 5 (a) and (b) shows similar test results for the rust free steel rebar without and with the coating. Exposure to chloride exposure was stopped when a sudden increase in $1/R_p$ value was observed.

Exposure to AR/WOC was stopped at around 60 days (see Figure 4 (a)). When AR/WOC specimens were autopsied after 60 days of exposure, severe corrosion was observed, which was not noticed in $1/R_p$ plot. Therefore, Cl_{th} reported here for AR/WOC specimens are overestimated than actual. For specimens AR/WC, corrosion initiation was observed over a range of 40 – 80 days (see Figure 4 (b)). This variation might be due to small discontinuities in the coating. Whereas, corrosion initiation for specimens SB/WOC and SB/WC was observed nearly at 60 and 100 days of exposure respectively. Similar to the case of macrocell specimens, SB/WC type of specimens showed the best corrosion performance among four types of steel. It should be noticed that determination of Cl_{th} for steel with very high corrosion resistance (SB/WC) was also possible to be estimated within 100 days (approx. 3 months).



(a) Steel type 1 – w/o coating

(b) Steel type 1 – w/ coating

Figure 4: $1/R_p$ value for 'as - received' specimen (steel type 1)

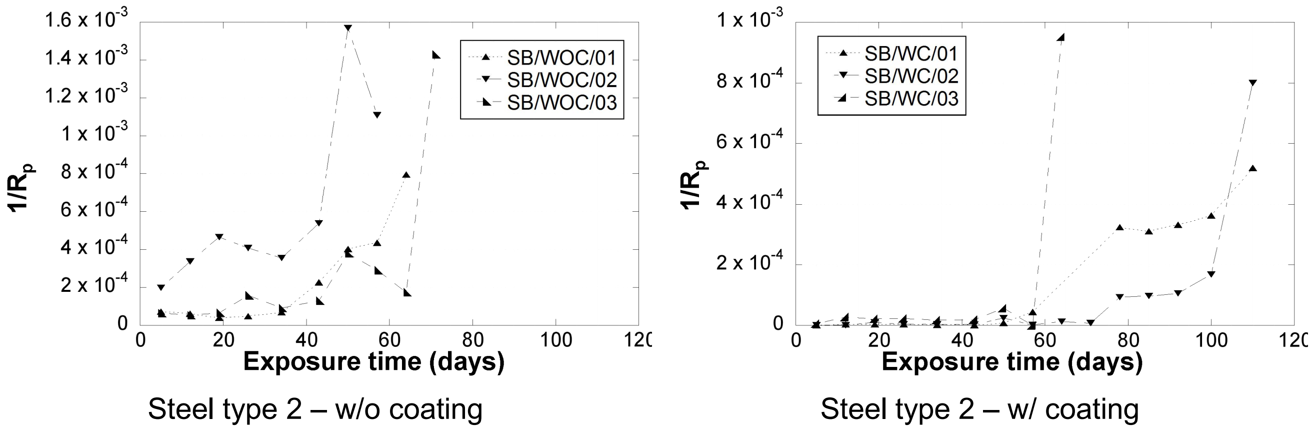


Figure 5: 1/Rp value for 'sand - blasted" specimen (steel type 2)

Chloride threshold value

Once corrosion initiation was identified, specimens were autopsied near the exposed rebar (top rebar in macrocell specimens). Chloride concentration near to the steel rebar was determined using SHRP – 330 for specimens of both types of the test methods. Figure 6 shows the chloride threshold values of all four types of steel determined using macrocell specimen and Lollipop type specimen. It can be seen that chloride threshold determined by both the methods are approximately same. Authors also observed that chloride ingress in Lollipop type specimen is multidimenional, whereas it is unidimentional in the case of macrocell specimens. Therefore, Cl_{th} from macrocell specimens can be considered more reliable. However, some minor modification in Lollipop type specimen geometry can also help in giving more accurate results. Average Chloride threshold values for AR/WOC, AR/WC, and SB/WC type of specimen was found approximately equal from both types of the test method.

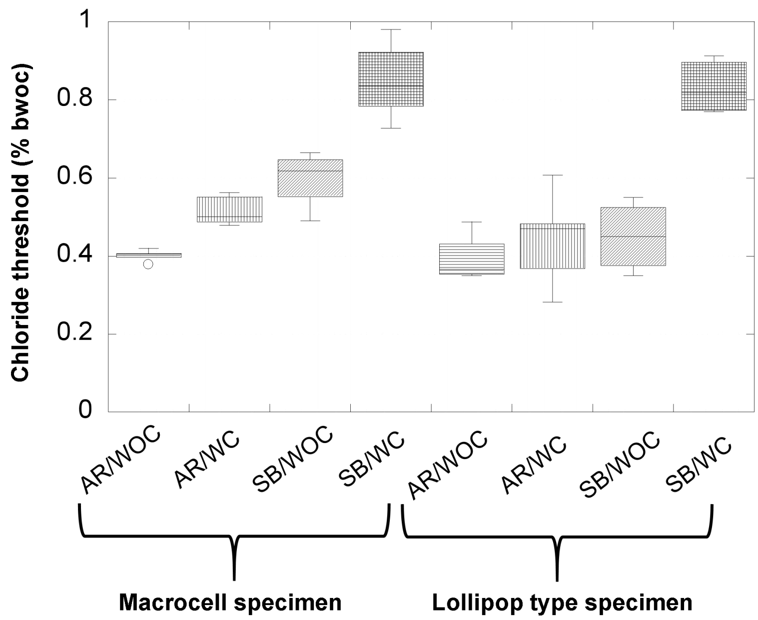


Figure 6: Chloride threshold value

CONCLUSIONS

1. Average Chloride threshold values for AR/WOC, AR/WC, SB/WOC, and SB/WC was found to be (0.4, 0.5), (0.5, 0.45), (0.6, 0.3), and (0.85, 0.84) [representation (Cl_{th} using macrocell, $Cl_{th\ using}$ Lollipop type specimen)].

2. New modified test methods (macrocell specimens and Lollipop type specimen) can be used for assessing chloride threshold of uncoated and coated steel in a short time.

3. If such short term test methods are used to assess the material quality, then performance based design for reinforced concrete can be adopted for upcoming projects,

4. The performance of CPC coating was fully exploited when it is applied on rust free / sand-blasted surface.

ACKNOWLEDGMENTS

The authors acknowledge the support from MHRD and BTCM Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India to carry out this research.

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