

**Critical Localized Corrosion Penetration of Steel Reinforcement  
for Concrete Cover Cracking**

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**ABSTRACT**

Corrosion of steel in concrete causes cracking of the concrete cover (C), when the metal loss reaches a critical penetration depth  $X_{crit}$ . The value of  $X_{crit}$  is important to formulate reliable models of the corrosion propagation stage. Corrosion of steel in concrete is commonly localized in nature especially in high quality concrete structures. Localized corrosion can occur due to preexisting cracks in cover concrete, concrete joints or defects in steel coatings. It has been shown previously that the value of  $X_{crit}$  increases as corrosion becomes more localized, but scarce data did not enable reasonable extrapolation to the cases of small corroding lengths as may be encountered at the intersection of rebar with preexisting narrow cracks. This investigation determines  $X_{crit}$  for cases of small corroding lengths (L), up to a highly localized case of  $C/L=5$ , including tests with conditions overlapping those of the earlier work to provide the basis for a more precisely established relationship. The tests were conducted with reinforced concrete cylinders having a central composite reinforcement rod of diameter ( $\emptyset$ ) with a short plain steel central segment bounded by highly corrosion resistant UNS06022 alloy bars. Corrosion was induced by impressed anodic current, and quantified by total charge and gravimetric determinations. The present results confirmed the trend of increasing values of  $X_{crit}$  as  $C/L$  increased. A refined functional relationship was proposed for  $X_{crit}$ ,  $\emptyset$ , C and L based on the added findings.

**Key words:** Corrosion propagation, Durability, Service Life, and Spalling.

## INTRODUCTION

Estimating the remaining service life of corrosion-affected reinforced concrete (RC) structures is required by asset owners and practicing engineers for repair and maintenance planning.

Corrosion durability of RC structures exposed to chloride-containing environments is measured by the length of corrosion initiation and propagation phases.<sup>1</sup> Various service life predictive models (e.g. Life 365,<sup>(A)</sup> Stadium,<sup>(B)</sup> etc.) are customarily developed to forecast the corrosion initiation stage with a pre-set fixed value for the corrosion propagation period.<sup>2</sup> However, once corrosion has initiated, the corrosion propagation period becomes predominant. The corrosion propagation phase represents the length of time from the onset of corrosion to the onset of corrosion-induced cover cracking.<sup>3</sup> Corrosion of embedded steel produces expansive corrosion products that have volumes several times larger than that of the original steel resulting in radial and hoop stresses that can ultimately lead to cracking and spalling of surrounding concrete. Therefore, a reliable prediction of the corrosion propagation period is required for a realistic estimate of the remaining service life of a corroding RC structure. Knowledge of the critical rebar corrosion penetration needed for cracking ( $X_{crit}$ ) along with a reliable estimate of the projected corrosion rate is crucial for the overall service life prediction for a corroding RC structure.

Most of the current research work is focused on developing models for determining  $X_{crit}$  assuming an approximately uniform distribution of corrosion along the length of rebar. However, localized corrosion is commonly encountered in practice, especially in high quality concrete structures. Localized corrosion can occur due to the presence of preexisting narrow cracks in cover concrete, concrete joints or coating defects in epoxy-coated steel. Very limited research was undertaken to examine the positive effect of corrosion localization on tolerance of increased critical penetration.

A previous investigation by Torres-Acosta and Sagüés proposed a relationship whereby when corrosion is localized to a short length there is a greater amount of  $X_{crit}$  compared to the case of more uniform corrosion.<sup>4</sup> The relationship, based on experiments where corrosion surface of the corroding segments was approximately uniform, states:

$$X_{crit} / \text{mm} \approx 0.011 \left( \frac{C}{\emptyset} \right) \left( \frac{C}{L} + 1 \right)^2 \quad (1)$$

Where; C is the concrete cover depth,  $\emptyset$  is the rebar diameter, and L is the length of the uniformly corroding segment. However, that investigation did not extend to small enough corroding lengths to ensure reasonable extrapolation to conditions representative of those typically encountered at the intersection of rebar with a preexisting narrow crack.

A more recent study Darwin et al proposed an alternative relationship based on experiments of epoxy-coated rebars with controlled areas of coating damage.<sup>5</sup>

$$X_{crit} / \mu\text{m} = 45 \left( \frac{(C/25.4)^{2-A_f}}{\emptyset^{0.38} L_f^{0.1} A_f^{0.6}} + 0.2 \right) \cdot 3^{A_f-1} \quad (2)$$

Where; C and  $\emptyset$  are in mm, and  $L_f$  and  $A_f$  are the fractional corroding length and area relative to that of the entire rebar, respectively. The experimental findings however were based on corrosion damage results calculated solely by Faradaic conversion, and not confirmed by gravimetric measurements. The current investigation sought to experimentally determine the effect of sufficiently small corroding lengths on  $X_{crit}$  and to compare the findings to those of the previous studies.

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(A) Trade name.

(B) Trade name.

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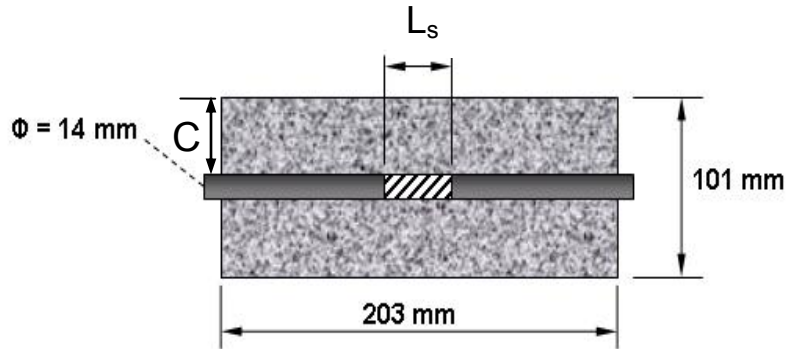
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## EXPERIMENTAL PROCEDURE

### Materials Used and Specimen Preparation

Reinforced concrete 4 in x 8 in (101 mm x 203 mm) cylindrical specimens were tested with controlled uniform concrete cover,  $C=1.72$  in (43 mm), having a composite metallic reinforcing smooth rebar of diameter,  $d=0.56$  in (14 mm) as illustrated in Figure 1. The concrete cover in the cylindrical geometry used represents the concrete face having the minimum cover in reinforced concrete members. The rebar is composed of an axial central carbon steel segment of length  $L_s$  representing the active anodic region. The carbon steel segment is bounded by two segments of a highly corrosion resistant Nickel-based alloy (UNS06022) representing the passive non-corroding regions. The UNS06022 alloy contains ~ 56% Ni, 21% Cr, 13% Mo and 3% W. The carbon steel segments were machined from a deformed carbon steel rebar (ASTM-A615 M- 03A.<sup>6</sup> designation No.7) to match the diameter of the as-received UNS06022 alloy bar. The UNS06022 alloy was used for its high corrosion resistance to avoid the artifacts associated with pitting of stainless steel used in previous investigations.<sup>4</sup> The length of anodic region,  $L_s$ , was designed to have small values approaching the narrow corroding spots expected at the bottom of pre-existing narrow cracks.<sup>7</sup> The values of  $L_s$  were selected such that the ratios of cover to anode length ( $C/L_s$ ) were  $C/L_s=1, 2, 3, 4$  and  $5$ , simulating cases of highly localized corrosion. The test included cases with conditions overlapping those of the earlier work to provide the basis for a more precisely established relationship. The three rebar segments were held together by a 5/16 in (8 mm) – 18 threaded Type 316 stainless steel rod passing through a central hole in the carbon steel and tightened into threaded holes in the UNS06022 alloy segments to minimize crevice formation at the joints. Specimens with the entire length of embedded rebar being carbon steel (anodic) were also tested to represent the case of uniform corrosion.



**Figure 1: Cylindrical specimen configuration**

The concrete as-cast mixture proportions and the 28-day compressive strength are given in Table 1. A modest chloride ion contamination level, 1.1% by weight of cement, was introduced by adding the corresponding amount of NaCl to help promote active corrosion of the anodically polarized carbon steel segment. Plastic cylindrical molds were used for specimen preparation and kept vertical during concrete casting to avoid bleeding and formation of bubbles at the rebar surface.

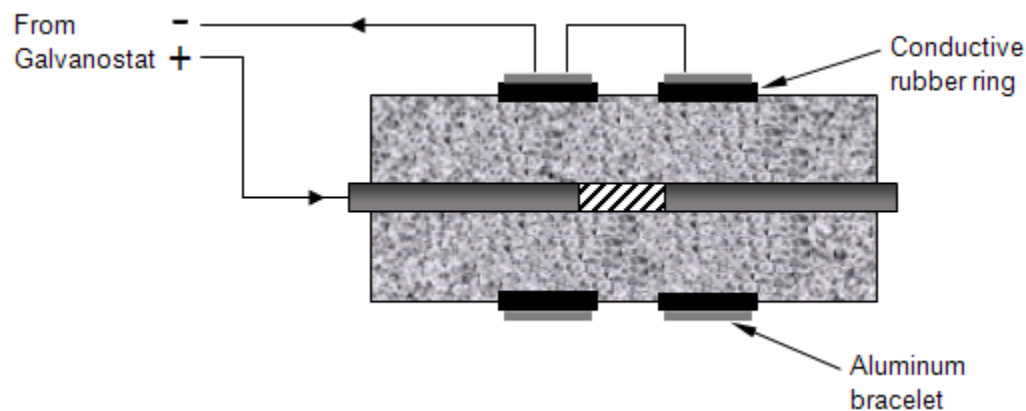
The carbon steel segments were 800-grit sand paper finished and cleaned with acetone before casting according to the requirements of ASTM G01-03.<sup>8</sup> Testing included 5 groups in triplicate covering the five ratios of concrete cover to anode length indicated above. The specimens were cured in their molds for 7 days, removed from molds and placed in a ~95% relative humidity (RH) chamber for 4 weeks then placed in an  $85 \pm 5\%$  RH test chamber to stabilize for a further ~ 6 months before starting anodic polarization in the same chamber. The 85% RH was selected partly because it is the point at which corrosion risk is expected to be highest.<sup>9</sup> RH was controlled by forcing air on the surface of a saturated potassium chloride (KCl) solution in a beaker inside the chamber.<sup>10</sup> The average test temperature was ~ 22°C. The specimen configuration, concrete composition, curing procedure and test conditions were selected to mimic those of a similar previous work to allow for comparisons.<sup>4</sup>

**Table 1**  
**Concrete mixture composition and compressive strength**

| Cement<br>kg/m <sup>3</sup> | Water<br>kg/m <sup>3</sup> | W/C  | Coarse<br>Aggregate<br>kg/m <sup>3</sup>    | Fine<br>Aggregate<br>kg/m <sup>3</sup> | Chloride ion<br>content,<br>% by weight of<br>cement | Entrained<br>air<br>content<br>% | 28 days<br>Compressive<br>Strength<br>(ASTM C-39) <sup>12</sup><br>Mpa |
|-----------------------------|----------------------------|------|---------------------------------------------|----------------------------------------|------------------------------------------------------|----------------------------------|------------------------------------------------------------------------|
| Type I                      |                            |      | Lime Stone # 89<br>(ASTM C33) <sup>11</sup> | Silica sand                            | (As part of Sodium<br>Chloride)                      |                                  |                                                                        |
| 426                         | 201                        | 0.47 | 949                                         | 676                                    | 1.1                                                  | 5.7                              | 38.93                                                                  |

### Accelerated Corrosion

A constant anodic current was applied to cause the carbon steel segments to corrode. The target applied anodic current density was 100  $\mu\text{A}/\text{cm}^2$ . This value was adopted in previous investigations and thought to produce results not far from those of natural corrosion.<sup>4, 13-15</sup> The amount of current to achieve the target current density was calculated by assuming that all the current would be directed to the carbon steel segments and that current demand by the passive UNS06022 alloy segments would be negligible. A galvanostat was specially designed with 15 channels to provide the required constant current values for the five groups. Figure 2 shows the counter electrode configuration used to pass the current through concrete, consisting of two conductive rubber rings pressed around each specimen by aluminum collars. The two counter electrode collars were spaced 1 in (~25 mm) apart at the center of rebar to allow for monitoring of crack appearance. The monitored currents remained within  $\pm 1\%$  of the target values with initial applied voltage in the order of 1.5 V between the anode and cathode. The possible influence of the counter electrode configuration on the uniformity of current distribution was evaluated using FEM modeling by comparison with a case where there was no gap between the two collars of the counter electrode. The numerical simulation, assuming that concrete resistivity was 10,000 ohm-cm (typical of the material used) and that the passive adjacent two UNS06022 alloy segments demanded no current, showed no substantial difference in current distribution between both cases.



**Figure 2: Illustration of accelerated corrosion test setup**

### Monitoring of Corrosion Cracking

The specimens were left to corrode under impressed current, monitoring applied current and voltage nearly daily, until a corrosion-induced crack of  $\sim 0.1$  mm appeared on the concrete surface. Monitoring for appearance of surface cracks was conducted at least twice a week as follows: a) Specimens were disconnected and a microscopic check for cracks was conducted using a graduated optical microscope having a magnification of 100X. b) Monitoring the applied voltage which tended to remarkably increase

before cracking presumably due to the resistance increase when substantial cracks began to develop at the steel/concrete interface.<sup>13</sup>

#### Evaluation Criteria and Estimation of Critical Penetration (Xcrit)

Once a surface crack reached a width of ~ 0.1 mm, the crack was traced on transparent paper for subsequent comparison of crack orientation with corrosion distribution on steel surface. The specimen was then demolished to retrieve the carbon steel segment and to visually observe the extent of corrosion product transport into concrete. The corrosion product was removed from the carbon steel segment following ASTM G1-03 by chemical cleaning, wire brushing and drying then weighing repeatedly.<sup>8</sup> The measured mass loss in grams,  $\Delta m$ , was compared with that theoretically calculated based on Faraday's law,  $\Delta m_F$ , as given by:

$$\Delta m_F = \frac{I.M.t}{n.F} \quad (3)$$

Where; I is applied current in Ampere, M is the atomic mass of iron (55.847 g/mol), t is the accelerated corrosion time in seconds, F is Faraday's constant, (96,485 coul/equivalent) and n is the effective valence corresponding to assuming that iron dissolves as divalent ions, (2).

The corrosion morphology and distribution along the rebar and around rebar perimeter were visually examined and detailed pictures taken. When significant corrosion metal loss was not occurring on the entire surface area of the carbon steel segment, the corroded surface area was measured using image analysis software (Image J). The corroded surface area was estimated to be the area covered by corrosion product only on the carbon steel segment and confirmed after removal of corrosion product and adjusted if necessary. For the cases where the entire surface of anode segment was corroded, the average critical penetration, Xcr, was estimated as follows:

$$X_{cr}/\mu m = \frac{\Delta m.10^4}{\rho \pi \emptyset L_s} \quad (4)$$

Where;  $\rho$  is the steel density (7.858 g/cm<sup>3</sup>) and  $\emptyset$  &  $L_s$  are the carbon steel segment diameter and length in cm, respectively. Implicit in the above is neglecting the effect of the curvature of the steel rod surface on the depth-volume relationship since usually Xcrit is much smaller than  $\emptyset$ .

For the instances where the surface area of the carbon steel segment was only partially corroded, over an area A that is less than  $\pi \emptyset L_s$ , two alternative approaches were followed to propose approximately equivalent cases where the entire surface of the segment would be corroding:

##### Case 1.

The crack-inducing effect of the partially corroded segment having a length  $L_s$  and a diameter  $\emptyset$  was assumed to be equivalent to that of a segment of the same diameter with its entire surface experiencing corrosion, but with a shorter length  $L_{eq}$  given by

$$L_{eq} = A/(\pi \emptyset) \quad (5)$$

And an average critical penetration,  $X_{cr_{eq}}$ , such that the total volume of metal consumed corresponds to the amount measured. Hence:

$$X_{cr_{eq}}/\mu m = \frac{\Delta m.10^4}{\rho.A} \quad (6)$$

Where; the geometric effect of surface curvature was neglected as indicated earlier.

### Case 2.

The crack-inducing effect was assumed to be the same as that of a segment of diameter  $\emptyset$  , length equal to  $L_s$  (designated here as  $L^*$  for consistency with the rest of the nomenclature), with its entire surface experiencing corrosion, but undergoing a smaller equivalent critical penetration,  $X_{cr^*_{eq}}$  given by

$$X_{cr^*_{eq}}/\mu m = \frac{\Delta m \cdot 10^4}{\rho \cdot \pi \cdot \emptyset \cdot L^*} \quad (7)$$

Where;  $L^*=L_s$ . And, as in Case 1, the segment having an average critical penetration,  $X_{cr^*_{eq}}$  reflects the total volume of metal consumed.

The above approaches were used later on for comparison with findings derived by previous work where corrosion in the segments was approximately uniform. In the following, the generic term  $X_{crit}$  will be used to indicate  $X_{cr}$  from the case of entirely distributed corrosion over anodic segment and also  $X_{cr_{eq}}$  as well as  $X_{cr^*_{eq}}$  from the two approaches for the partially distributed corrosion case. Likewise, the generic term  $L$  will be used to indicate the length of the corroding zone  $L_s$  in entirely corroding segments as well as the values  $L_{eq}$  and  $L^*$  under the Cases 1 and 2 treatments respectively.

### EDS Analysis

Energy Dispersive Spectroscopy (EDS) was employed to analyze the chemical composition for samples of slight tarnish-like scaling observed on some segments of UNS06022 alloy, and comparing with those of corrosion product samples taken from the surface of carbon steel. The purpose of the analysis was to determine whether the observed scale on UNS06022 alloy was resulting from steel corrosion product traveling along the rebar or from corrosion of the nickel alloy. The UNS06022 alloy-segments were examined under the optical microscope for signs of pitting before and after scale removal following ASTM G1-03.<sup>8</sup> Gravimetric measurement was also performed to determine the extent of any UNS06022 alloy bar metal loss and its possible source of error on the estimated values of  $X_{crit}$ .

## RESULTS AND DISCUSSION

### Crack Detection and Corrosion Morphology

Regular monitoring of applied anodic current and driving voltage provided a supplementary early sign of crack appearance. Figure 3a shows an example for a specimen having a ratio of  $C/L_s=3$  under galvanostatic control throughout the test, and showing a gradually increasing driving voltage before the appearance of surface cracking. The driving voltage increase was presumably due to concrete resistance increase as a result of developing micro cracks on or near the steel/concrete interface, but before terminal propagation to the external surface.

As anticipated, specimens with smaller ratios of  $C/L_s$  (i.e. greater corroding length) exhibited surface cracking of the specified ~ 0.1 mm-width criterion before those with the greater ratios (Table 2). The corrosion-induced concrete cover cracks were oriented in a longitudinal direction, parallel to the rebar, in the uniform corrosion specimens ( $C/L_s \approx 0$ ) where the entire length of rebar was subject to corrosion. In contrast, each of the specimens with localized corrosion ( $C/L_s = 1, 2 \text{ \& } 3$ ) exhibited a circumferential surface crack over the central corroding spot, extending around one half of the perimeter. The circumferential cracks were bounded by short longitudinal cracks having a similar length to that of the corroding steel segment in the cases of ( $C/L_s = 1 \text{ \& } 2$ ).

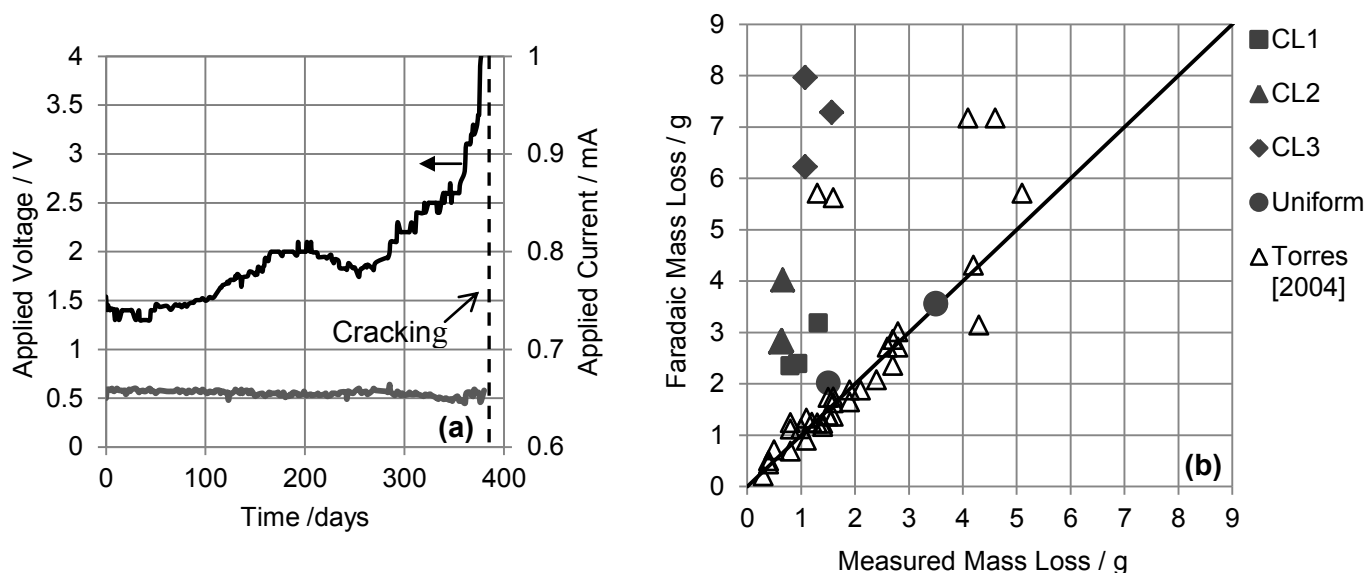
The concrete specimens were demolished and the rebars retrieved for examination. The corrosion products on the central steel segment were found to be non-uniformly distributed around the rebar perimeter in the specimens having  $C/Ls=1$  and 2. Table 2 shows the percentage of the entire surface area of each anode segment that experienced corrosion. After subsequent rust removal, metal loss was found, as expected, to have taken place beneath the corrosion product regions. The partially corroded regions, while limited to part of the steel perimeter, were approximately extending along the entire length of anodic segments. The steel central segments of the specimens with  $C/Ls=3$  showed entirely corroded surfaces. Visual examination showed that some steel corrosion products transport had taken place along the rebar length to cover the ends of the UNS06022 alloy bar on both sides of the anodic steel segment, to a distance of about half the rebar radius. This effect was also evident in the concrete immediately surrounding the rebar. There was also evidence that corrosion products filled the steel/concrete interfacial transition zone (ITZ) and diffused into the concrete matrix surrounding the anodic segment. Some steel segments showed corrosion pits up to about 4 times deeper than the average corrosion penetration which is in agreement with similar pitting behavior under natural corrosion reported in the literature.<sup>16</sup> However, the calculated depth of penetration referred to hereinafter, is the penetration value averaged over the corroded surface area.

### Accelerated Corrosion Efficiency

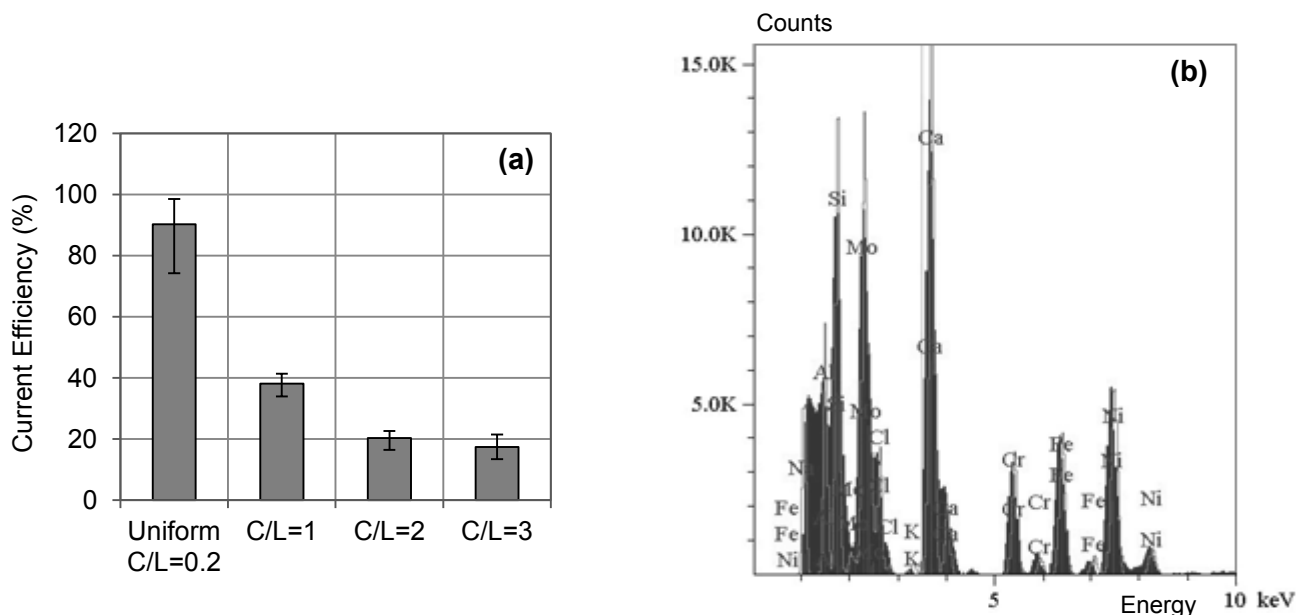
Figure 3b compares the measured steel mass loss values shown in Table 2 with the Faradaic values calculated using equation (3). The correlation gives an idea on how much of the applied anodic current is equivalent to actual mass loss which is known as current efficiency. The latter was calculated by dividing the measured steel mass loss by the theoretically estimated (Faradaic) mass loss. Figure 3b shows a reasonable agreement between the Faradaic and measured values of steel mass loss in the case of specimens having entirely corroding length of rebar ( $C/Ls \approx 0$ ). Whereas, in the case of specimens having locally corroding length of rebar ( $C/Ls = 1, 2$  and 3), the Faradaic prediction overestimated the actual mass of lost steel. The latter may partly be attributed to the smooth surface finish of the steel specimens that is expected to elevate the chloride corrosion threshold compared to that of regular deformed rebars. The electric charge would therefore be consumed in transporting the chloride ions to the steel surface before corrosion occurs. It may also be due to one of the following reasons: 1) the measured instant-off rebar potential was found to be ranging between + 600 to + 900 mV versus SCE reference. Therefore, oxygen evolution is expected to be another electrochemical reaction responsible for exchange of charge on the steel surface (in addition to the iron dissolution reaction) as well as on the surface of UNS06022 alloy segments. The oxygen evolution on UNS06022 alloy explains why the current efficiency shown in Figure 4a decreases as the length of anodic steel segment decreases relative to that of the UNS06022 alloy segments, 2) drying out of concrete resulting from flow of current for relatively long periods can decrease the accelerated current efficiency.<sup>11</sup> 3) Uncommon ion valence from iron dissolving into  $Fe^{3+}$  or presence of impurity elements such as copper which was confirmed by EDS in the steel corrosion product.<sup>17</sup> 4) Slight corrosion of UNS06022 alloy as was observed on one UNS06022 alloy segment of specimen CL 303. Figure 4b shows an EDS analysis of a layer of tarnish-like deposits observed on the surface of UNS06022 alloy which provided evidence of corrosion of the UNS06022 alloy. Examination of the tarnished surface of the UNS06022 alloy segment under optical microscope showed that the corrosion was uniform over the surface and very minimal. Gravimetric calculations of the nickel alloy mass loss indicated that the corrosion rate was less than  $2 \mu m / y$ .

Results from a previous investigation in Figure 3b showed a better agreement between the measured and estimated values.<sup>4</sup> That investigation involved the use of actual deformed rebars in the as-received surface condition with chloride ion concentration of 2% by weight of cement. The agreement may also be due to the relatively less current-induced dryness effect of concrete specimens due to shorter test durations than those of the present work. Since all Xcrit values were calculated based on the actual measured values of steel mass loss, deviation from the Faradaic mass loss estimates does not affect the significance of the results in the present work. The deviation is noted nevertheless as it illustrates a

potentially important source of uncertainty in the interpretation of results from investigations based only on Faradaic conversion estimates of metal loss.



**Figure 3: (a) Constant current and gradually rising voltage close to cracking for a specimen having a ratio of C/Ls= 3, (b) Measured versus Faradaic values of steel mass loss**



**Figure 4: (a) Decrease of anodic current efficiency with decreasing the exposed area of steel, (b) Energy dispersive spectroscopy (EDS) analysis of the light tarnish observed over a UNS06022 alloy segment in specimen CL303 showing evidence of slight corrosion of UNS06022 alloy**

Table 2 shows the measured mass losses in grams and the percentage of carbon steel area that experienced corrosion with respect to the entire area of carbon steel segments. For the cases of partially corroded surface area of steel segment, the values of  $L_{eq}$  and  $C/L_{eq}$  are shown. It also shows the  $X_{crit}$  values for the case of entirely corroded area of anode segment as well as those for the cases of partially corroded areas in accordance with the two approaches.

**Table 2**  
**Experimental results and values of equivalent geometric parameters**

| Specimens | C/Ls  | Length of Carbon Steel Ls /cm | Applied Current /mA | Xcrit /μm                         |       |        | Measured Mass Loss / g | % Area Corroded | Leq /cm | C/Leq | Time to crack /days |
|-----------|-------|-------------------------------|---------------------|-----------------------------------|-------|--------|------------------------|-----------------|---------|-------|---------------------|
|           |       |                               |                     | Xcr                               | Xcreq | Xcr*eq |                        |                 |         |       |                     |
| U1        | 0.215 | 20.32                         | 9                   | 49                                | -     | -      | 3.5                    | 100             | -       | -     | 16                  |
| U2        |       | 20.32                         |                     | -                                 | 24    | 21.40  | 1.5                    | 88              | 17.78   | 0.246 | 9                   |
| U3        |       | 20.32                         |                     | 50                                | -     | -      | 3.5                    | 100             | -       | -     | 16                  |
| 101       | 1     | 4.37                          | 1.951               | -                                 | 103   | 51.84  | 0.8                    | 51              | 2.21    | 1.98  | 48                  |
| 102       |       | 4.37                          |                     | -                                 | 133   | 85.48  | 1.32                   | 64              | 2.81    | 1.55  | 65                  |
| 103       |       | 4.36                          |                     | -                                 | 100   | 60.83  | 0.94                   | 61              | 2.64    | 1.65  | 49                  |
| 201       | 2     | 2.16                          | 0.967               | -                                 | 95    | 87.19  | 0.66                   | 92              | 1.99    | 2.2   | 166                 |
| 202       |       | 2.16                          |                     | -                                 | 100   | 81.49  | 0.62                   | 81              | 1.76    | 2.49  | 116                 |
| 203       |       | 2.17                          |                     | -                                 | 145   | 84.19  | 0.64                   | 58              | 1.26    | 3.47  | 117                 |
| 301       | 3     | 1.48                          | 0.656               | 206                               | -     | -      | 1.07                   | 100             | -       | -     | 380                 |
| 302       |       | 1.46                          |                     | 304                               | -     | -      | 1.57                   | 100             | -       | -     | 443                 |
| 303       |       | 1.48                          |                     | 206                               | -     | -      | 1.07                   | 100             | -       | -     | 485                 |
| 401       | 4     | 1.07                          | 0.478               | No cracking at 560+ days exposure |       |        |                        |                 |         |       |                     |
| 402       |       | 1.06                          |                     |                                   |       |        |                        |                 |         |       |                     |
| 403       |       | 1.05                          |                     |                                   |       |        |                        |                 |         |       |                     |
| 501       | 5     | 0.86                          | 0.384               |                                   |       |        |                        |                 |         |       |                     |
| 502       |       | 0.86                          |                     |                                   |       |        |                        |                 |         |       |                     |
| 503       |       | 0.86                          |                     |                                   |       |        |                        |                 |         |       |                     |

### Progress in Predicting Critical Penetration

The results from this investigation, incorporating data for higher C/Ls values than previously available, were examined together with those of earlier work to propose an updated relationship between  $X_{crit}$  and the system variables. The existing Torres-Acosta relationship, equation (1), was used as a starting formulation, with  $X_{crit}$  and  $L$  substituted depending on the case by the equivalent parameters defined above. Initial examinations showed that the expanded results obtained here could be approximated using the equation (1) form but with the exponent 2 of the term  $(1+C/L)$  replaced by a number  $n$  obtained by a fitting procedure. Thus:

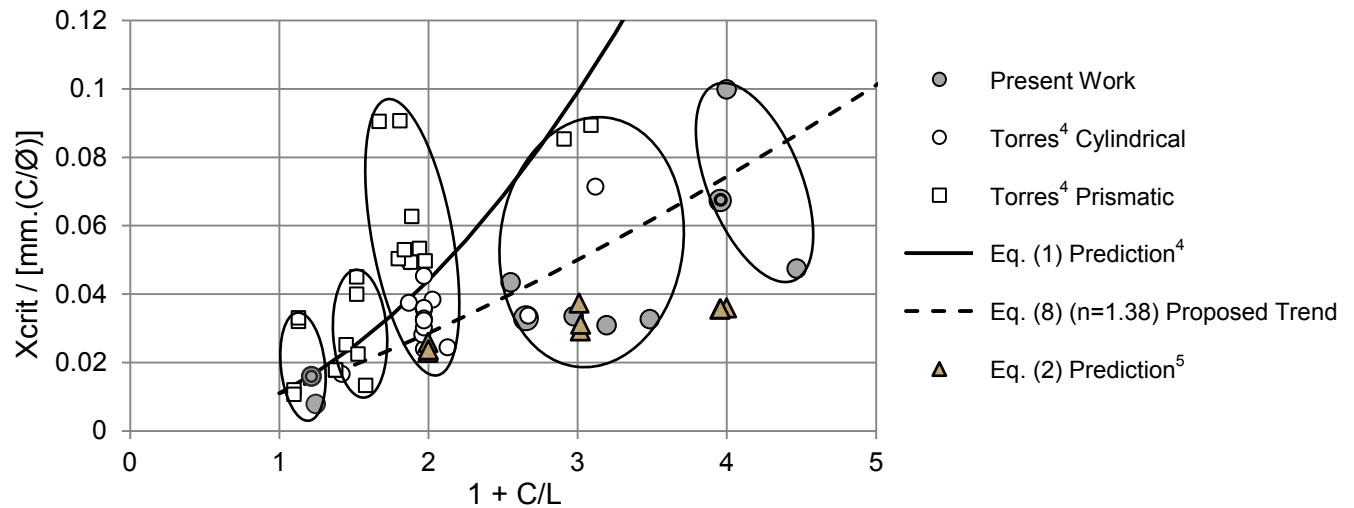
$$X_{crit} / \text{mm} \approx 0.011 \left( \frac{C}{\emptyset} \right) \left( \frac{C}{L} + 1 \right)^n \quad (8)$$

Preliminary analysis also revealed that for the case of corrosion affecting the entire length of the rebar (i.e.  $C/L \approx 0$ ) equation (1) reasonably accounted from data of previous investigators as well as of the present investigation. Since in those instances  $X_{crit}$  is directly proportional to  $C/\emptyset$ , it was chosen to evaluate the behavior for all conditions by using the normalized ratio  $X_{crit} / (C/\emptyset)$ . In the following, the ability of equation (8), with the appropriate value of  $n$ , to predict  $X_{crit}$  is examined for cases of corrosion affecting the full length of the rebar, or only short segments with surfaces either fully or partially affected by corrosion.

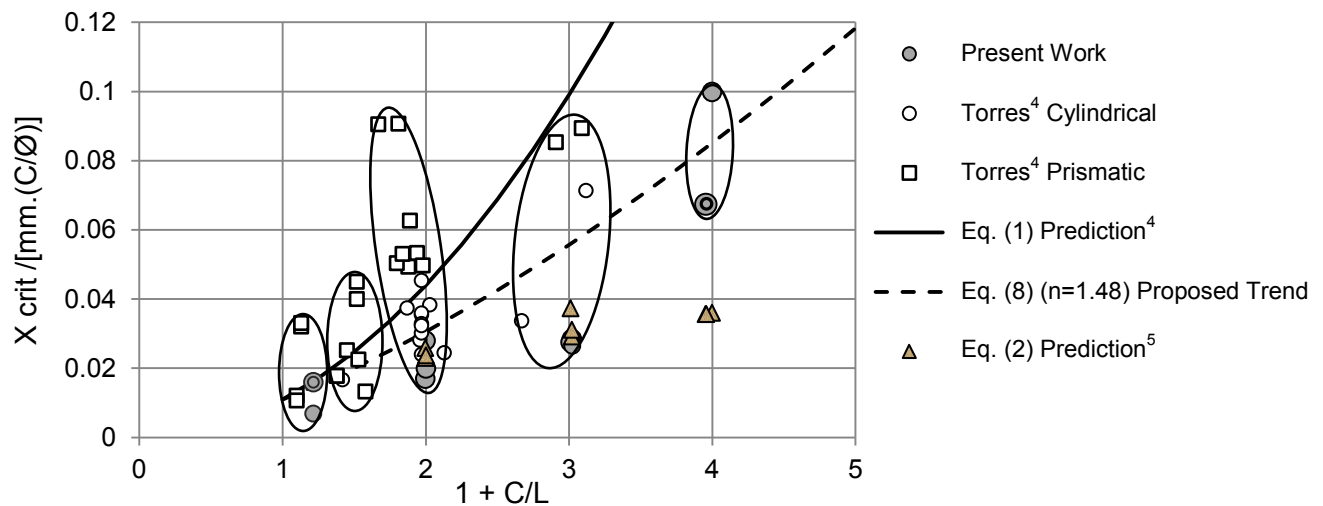
For the latter situations, the relative merits of the Case 1 and 2 alternatives to treat the extent of corrosion in the segment are investigated. Comparison with the predictions of equation (2) is made as well.

Figure 5 shows the estimated critical penetrations  $X_{crit}$ , for both partially and entirely corroded surface areas of anode segments using the Case 1 equivalent parameters. That means that  $L$  in this case is equal to  $A/(\pi\emptyset)$ , and that  $X_{crit}$  is the average corrosion penetration in the area  $A$  affected by corrosion. Figure 5 also shows the data obtained by Torres-Acosta from similar testing of cylindrical and prismatic specimens for comparison.<sup>4</sup> Examination of those results showed that the values of  $X_{crit} / (C/\emptyset)$  for prismatic specimens tended to be significantly greater than those for the cylindrical ones, which shared the same geometry as those used in the present work. That differentiation was not emphasized in that previous work but merits consideration here. In particular, Figure 5 shows that the present results tend to follow a general trend comparable to that in the previous work for cylindrical specimens. The similarity of trends was confirmed when numerically analyzing the results. A fit of equation (8) to the present data by itself yielded  $n=1.23$ , and when combined with that of Torres-Acosta for cylindrical specimens yielded  $n=1.26$ , an essentially similar result. The Torres-Acosta data for only cylindrical specimens yielded  $n=1.56$ , so extending the data set to the greater values of  $C/L$  probed here moderated somewhat the exponent relating the increase in  $X_{crit}$  with the degree of corrosion localization. Likewise, a reduction in exponent took place when the present data were combined with those of Torres-Acosta for both prismatic and cylindrical specimens, which yielded  $n=1.38$ . The corresponding relationship is plotted in Figure 5 as a proposed trend based on the combined data set and the Case 1 approach to treat partially corroding segments. Analysis of Torres-Acosta's data only yielded  $n=1.90$  for the combined cylindrical and prismatic specimens and  $n=2.02$  for the prismatic specimens only; both values consistent with the published rounded-off exponent in equation (1).<sup>4</sup> The corresponding prediction by equation (1) clearly overestimates the present results obtained for the cases with  $C/L > 2$ .

Figure 6 shows the estimated critical penetrations  $X_{crit}$ , for both partially and entirely corroded surface areas of anode segments using the Case 2 approach equivalent parameters. That means that  $L$  in this case is the length of the segment affected by corrosion, and that  $X_{crit}$  is the average of corrosion penetration in the segment. As in Figure 5, results from previous work are included for comparison. Proceeding similarly as for Case 1 a fit of equation (8) to the present data by itself, but following the Case 2 approach, yielded  $n=1.22$ . When the present data were combined with those of Torres-Acosta for cylindrical specimens a value  $n=1.25$  was obtained, an essentially similar result. When the present data were combined with those of Torres-Acosta for both prismatic and cylindrical specimens, the analysis yielded  $n=1.48$ . These results are on the whole quite comparable to those noted in the Case 1 analysis and the same comments apply here as well.



**Figure 5: Comparison of present experimental results of  $X_{crit}$  (Case 1 approach) with literature data and alternative predictions including proposed trend based on equation (8). Equation (2) is prediction only shown for the localized corrosion cases of the present work.**



**Figure 6: Comparison of present experimental results of  $X_{crit}$  (Case 2 approach) with literature data and alternative predictions including proposed trend based on equation (8). Equation (2) prediction is only shown for the localized corrosion cases of the present work.**

In both Figures 5 and 6 the predicted values of  $X_{crit}$  as predicted by equation (2) by Darwin<sup>5</sup> are presented as well, for the values of  $C/L$  and  $C/\phi$  corresponding to the present data set. Since as noted earlier the corroding length in the present experiments coincided closely with  $L_s$ , that value was used for  $L_f$ . The value of  $A_f$  was as that corresponding to the % Area corroded in Table 2 and the size of the steel segment relative to that of the entire bar. Equation (2) in both cases tends to agree with the experimental results for cylindrical specimens of both the present and Torres-Acosta's investigation for  $C/L = 1$  and 2, but it significantly underestimated those obtained in the present work with  $C/L=3$ . Equation (2) consistently underestimated the values of  $X_{crit}$  that were obtained by Torres-Acosta<sup>4</sup> for prismatic specimens and consequently also the predictions based on equation (1).

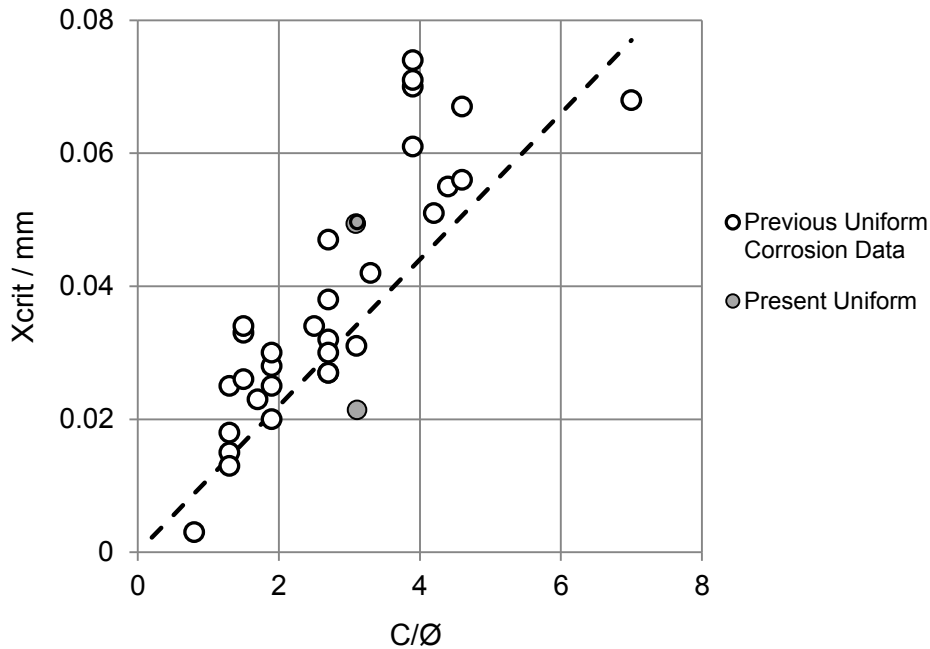
As an additional evaluation of the present results, it is recalled that equations (1) and (8) reduce to equation (9) for  $C/L=0$ .

$$X_{crit}/mm \approx 0.011(C/\emptyset) \quad (9)$$

As shown in Table 2, even the cases of full length rebar exposure did not result in corrosion penetration over the entire surface of the rebar in the present case. Nevertheless, conformity of the present results with the above expectation for the limit  $C/L=0$  condition was examined, using as an example the Case 2 approach to equivalent penetration depth. Figure 7 shows a graphic display of the comparison, showing reasonably close agreement with expectations given the typical experimental scatter prevalent in these tests.

The present results, extending to more localized corrosion cases than those probed earlier, agree with previous work in finding that more corrosion penetration is needed to induce cracking when the corrosion is localized. The new results suggest that the increase in  $X_{crit}$ , while still significant, proceeds following a smaller exponent than that proposed earlier by Torres-Acosta at least for tests with cylindrical specimens.<sup>4</sup> In contrast the relationship in equation (2) tended to underestimate, at the highest values of  $C/L$ , even the cylindrical specimen data obtained at present.<sup>5</sup>

The analysis of results obtained using the Cases 1 and 2 parametric descriptions, for instances where only part of the segment perimeter was affected by corrosion, were not strongly differentiated at least given the size of the data set and the extent of scatter. In general, the present findings support considering the use of equation (8) for application over an extended range of  $C/L$  values than previously available, with alternative values of  $n=1.38$  for a Case 1 treatment of partial corrosion of an anodic segment, and  $n=1.48$  when the Case 2 approach is used.



**Figure 7: The experimental  $X_{crit}$  data for cases of uniform corrosion ( $C/L \approx 0$ ) from present and previous investigations are compared.<sup>4</sup> The dashed line represents the prediction of  $X_{crit}$  by equation (8) for the case of rebar corroding along its entire length, using the case-2 approach where necessary.**

## CONCLUSIONS

1. The experimental findings confirmed the trend of increasing critical penetration,  $X_{crit}$ , induced by locally corroding reinforcement with increasing the ratio of concrete cover to corroding length,  $C/L$ . The present study involved testing of cases having  $C/L$  ratios approaching those typically encountered at the bottom of narrow cracks.
2. The amount of corrosion penetration in a uniformly corroding reinforcing bar required for a 0.1mm-wide crack to appear on the concrete cover surface was 50  $\mu\text{m}$  or less, as anticipated. Whereas, the amount of critical penetration in the case of localized corrosion was up to about 300  $\mu\text{m}$  (6 times greater) for a ratio of  $C/L=3$ .
3. In the case of localized corrosion, steel corrosion products transported along the rebar length to an average distance of one half of rebar radius on each side of the corroding segment. That corrosion product had to fill the adjacent space in the rebar-concrete interface which is thought to have contributed to slowing down the pressure build-up and therefore increased  $X_{crit}$ .
4. The surface crack in the case of uniform corrosion was oriented parallel to the embedded rebar, whereas in the case of localized corrosion was mainly oriented in a circumferential direction (transverse crack) around the corroding spots.
5. A modified functional relationship was proposed to provide a better estimate of the critical rebar penetration needed for concrete cover cracking resulting from localized corrosion of embedded steel. The relationship may be applied for cases where corrosion is not occurring around the entire rebar perimeter. Previous models were found to be only suitable for predicting  $X_{crit}$  up to a  $C/L = 2$  or less and they tend to provide either overestimated or underestimated amounts for greater values of  $C/L$ .
6. Faradaic conversions can result in erroneous estimations of actual mass losses induced by impressed current in accelerated corrosion experiments of steel in relatively dry concrete environments.

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