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Chloride-induced corrosion of steel in cracked concrete—Part II: Corrosion rate prediction models

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ABSTRACT

Chloride-induced corrosion rate (i_{corr}) prediction models for RC structures in the marine tidal zone that incorporate the influence of crack width (w_{cr}), cover (c) and concrete quality are proposed. Parallel corrosion experiments were carried out for 2¼ years by exposing one half of 210 beam specimens (120 × 130 × 375 mm long) to accelerated laboratory corrosion (cyclic wetting and drying) while the other half underwent natural corrosion in the tidal zone. Experimental variables were w_{cr} (0, incipient crack, 0.4, 0.7 mm), c (20, 40 mm), binder type (PC, PC/GGBS, PC/FA) and w/b ratio (0.40, 0.55). The two proposed models (one each for accelerated and natural i_{corr}) can aid not only in quantifying the propagation phase, but also provide a novel way to select c, w_{cr} and concrete quality.

1. Introduction

Chloride-induced corrosion is the main cause of deterioration of reinforced concrete (RC) structures in chloride-laden environments. Consequently, much research effort has been put towards the prediction of chloride-induced corrosion damage in RC structures in the propagation phase, and relatively conservative, accurate and/or reliable prediction models have been proposed in the literature [1–7]. However, it is acknowledged that the development of corrosion rate prediction models has not been given the focus it deserves despite being one of the main input parameters (directly or indirectly) in existing corrosion-induced damage prediction models. In most cases conservative approaches where a representative corrosion rate is adopted for the entire propagation phase, such as those proposed in DuraCrete [8] and EN 206-1 [9], are used. These approaches have been adopted mainly because corrosion rate during the propagation phase is a function of many interrelated factors, which change during the corrosion propagation phase, and whose quantification in in-service RC structures is not easy. Nevertheless, there have been attempts to model corrosion rate as a function of the combined effect of the various relevant factors affecting it such as cover depth, condition of the concrete cover (e.g., cracking), concrete quality, temperature, concrete resistivity and moisture content of the concrete. However, even though not covered in this paper, the main challenges still remaining are the quantification of the inherent temporal and spatial variability of corrosion rate.

In the past, both empirical and numerical approaches have been used to develop corrosion rate prediction models [10–14]. Each of these approaches has inherent strengths and shortcomings and hence should be considered as complementary to each other. On the one hand, empirical models are usually simple and straightforward with respect to quantification of the input parameters but are, in most cases, limited with respect to their scope of practical applicability outside the boundaries of the experimental setup used in their development. On the other hand, numerical models are relatively input intensive in terms of incorporating the factors affecting corrosion rate in the prediction model but do not find wide practical applicability mainly due to difficulty in quantifying some of the input parameters such as Tafel slopes and limiting current density. This, to a large extent, is not the case with empirical models where the input parameters are usually relatively easily quantifiable. However, despite empirical corrosion rate prediction models being limited in applicability, they can be improved using numerical methods, and can form a strong foundation for mathematical models. This study focused on the development of empirical chloride-induced (accelerated and natural) corrosion rate prediction models in cracked RC.

2. Research significance

The need for accurate and reliable corrosion rate prediction models cannot be sufficiently emphasized especially with the current trend towards quantifying the propagation phase of corrosion-affected RC structures. Even though corrosion rate prediction models have been proposed in the past, none has explicitly incorporated the influence of

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Table 1
Chloride conductivity indexes (CCI) and corresponding diffusion coefficients.

Mix label	90-day CCI (mS/cm)	Corresponding diffusion coefficient, D_{90}* (cm^2/s) × 10^{-10}
PC-40	1.10	47.4
FA-40	0.24	9.6
FA-55	0.70	14.8
SL-40	0.15	7.0
SL-55	0.35	8.4

* Determined based on an empirical correlation between CCI and diffusion coefficient [23].

pre-corrosion (load-induced) cover cracking on corrosion rate. This is despite the fact that past studies [15–20], including the one reported in this paper, have shown that cover cracking accelerates both corrosion initiation and propagation. The models proposed in this paper incorporate the combined influence of cover cracking, cover depth and concrete quality on chloride-induced corrosion rate.

In this part (Part II) of this publication, the experimental results presented in Part I [21] will be used to establish correlations between corrosion rate and the experimental variables – cover depth, crack width and concrete quality. These will then be used in the model development.

3. Correlation between concrete quality and corrosion rate

Correlations between average corrosion rate (i_{corr}) and concrete quality (quantified using chloride diffusion coefficient, D_{90} (Table 1), obtained from the 90-day chloride conductivity index (CCI) value [22,23]) are presented in Figs. 1–4. These figures show that in both the field and laboratory specimens, irrespective of binder type, there exists a good correlation (R^2 generally > 0.7) between the D_{90} and corrosion rate for a given crack width and cover depth. For a given binder type and the corresponding D_{90} value, corrosion rate increases with increasing crack width. However, even though there is a high correlation between corrosion rate and D_{90}, the latter cannot be used in isolation to predict durability performance especially in cracked concrete. Other factors affecting corrosion rate such as cover depth and crack width must also be taken into account. In general, the trends shown in Figs. 1–4 between i_{corr} and D_{90} can be expressed as follows:

$$i_{corr} = k_1 e^{A_1 (D_{90} \times 10^{10})} [\mu A/cm^2] \quad (1)$$

where k_1 ($\mu A/cm^2$) and A_1 (s/cm^2) are coefficients whose values are dependent on cover depth (20 or 40 mm), crack width (0.4 or 0.7 mm) and exposure environment (laboratory and field). As mentioned previously, the CCI value used to determine the diffusion coefficient, D_{90}, is obtained using uncracked concrete specimens, and though high correlation factors can be obtained between corrosion rate and D_{90} even in the cracked specimens, the influence of cracking (and cover depth) should be taken into account to predict a realistic durability performance.

4. Correlation between c/w_{cr} ratio and corrosion rate

The concept of c/w_{cr} ratio has been covered in previous publications by the current authors and others [24,25]. Its use was motivated by the need to quantify the combined effect of crack width (w_{cr}) and cover thickness (c) on corrosion rate in order to obtain a suitable combination of these parameters during design. In this study, the quantified crack widths were 0, 0.4 and 0.7 mm while two cover depths, 20 and 40 mm, were used. The respective c/w_{cr} ratios for the crack widths and cover depths used are summarized in Eq. (2). The incipient-cracked specimens (see Part I of this publication [21]) are not used because their widths were not quantified. The c/w_{cr} ratio is also not applicable to uncracked concrete.

$$c/w_{cr} = \begin{cases} 50(\text{for } c = 20 \text{ mm}, \ w_{cr} = 0.4 \text{ mm}) \\ 29(\text{for } c = 20 \text{ mm}, \ w_{cr} = 0.7 \text{ mm}) \\ 100(\text{for } c = 40 \text{ mm}, \ w_{cr} = 0.4 \text{ mm}) \\ 57(\text{for } c = 40 \text{ mm}, \ w_{cr} = 0.7 \text{ mm}) \end{cases} \quad (2)$$

The relationship between corrosion rate and c/w_{cr} ratio for the various concretes is presented in Figs. 5 and 6. The results show similar trends between corrosion rate and c/w_{cr} ratio for both the laboratory and field specimens. For a given c/w_{cr} ratio, a range of corrosion rates is possible depending on the concrete quality. These figures also underscore the superior performance of blended cement concretes in comparison to PC concretes discussed earlier. The results show that it is possible to objectively use the c/w_{cr} ratio in the selection of cover depth, crack width (and concrete quality) to control corrosion rate. In general, the trends shown in Figs. 5 and 6 between corrosion rate and c/w_{cr} ratio can be expressed as follows:

$$i_{corr} = k_2 \left(\frac{c}{w_{cr}}\right)^{-A_2} [\mu A/cm^2] \quad (3)$$

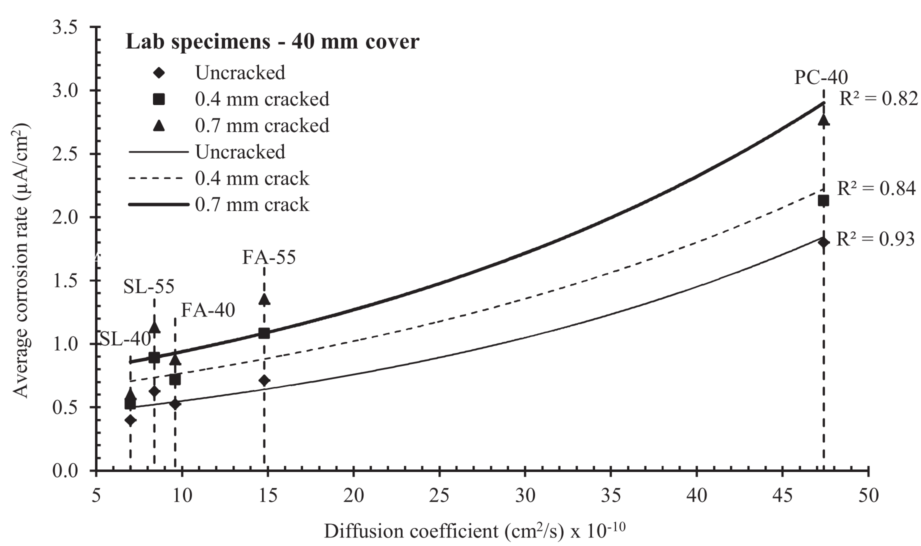

Fig. 1. Average corrosion rate vs. diffusion coefficient (lab specimens, 40 mm cover).