

PREDICTION OF CHLORIDE PROFILE AT CRACK LOCATION IN REINFORCED CONCRETE UNDER FLEXURAL LOADING

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Abstract

The chloride penetration into concrete is one of the most popular topics and very exciting in the field of concrete durability. The chloride ion acts as a main factor in causing the corrosion of the reinforcement in concrete structure. Moreover, chloride transport mechanisms in concrete are very complicated. Specifically, the cracks were recognized as one of the primary reasons causing an increase in the corrosion rate of reinforcements due to chloride attack. The aim of this research is to propose models for predicting the chloride profile at crack locations of reinforced concrete. In the present paper, the tapered crack (V-shaped crack) was introduced as a natural crack due to flexural loads. In addition to the crack width, the crack depth also played as a factor influencing the chloride penetration depth and chloride profile. Finally, the validity of the proposed model was verified by comparing with experimental results under the influence of crack characteristics. The research results showed that the predicted results fitted well with experimental ones when the immersion periods were larger than 4 weeks.

Keywords: Chloride Penetration, Chloride Profile, Cracked Concrete, Crack Depth, Crack Width

Introduction

The durability of reinforced concrete structures in marine environment has been considered as a serious problem in concrete construction technology. The principle cause of reduction in durability of reinforced concrete is the reinforcement corrosion in the chloride-laden environments. Generally, the chloride ions are able to attack in the pore structure [1] and were recognized as a main factor for corrosion of the reinforcing steel in a marine environment [2]. Normally, the reinforcement is protected away from corrosion by a passive film. Once the chloride concentration at the surface of the reinforcement reach a threshold value, this passive film will be destroyed and the corrosion process is initiated. A prediction for chloride concentration at the reinforcement surface in concrete member is very necessary for the durability and service life design.

Furthermore, the cracks occurring on reinforced concrete due to external loads are unavoidable during the service life of concrete member. Like a fast access slot, the cracks may take chloride ions from the marine environment into the concrete structure. Up to now, many researchers have tried to take into account the influence of crack width on the chloride penetration into concrete structure [3-8]. They concluded that the crack width strongly influenced on the chloride diffusion and its coefficient was considered as a function of the crack width. In addition to the crack width, the crack depth is also a key parameter; especially, under external loading the crack characteristics will rise during all

stages in the life of a concrete structure and they can strongly influence on the chloride penetration [9]. However, studies about crack depth affecting the chloride penetration have not been clear and complete. On the other hand, the loading is also a parameter having an influence on the chloride penetration in concrete [10]. Mien [9] investigated and modeled the chloride penetration in plain concrete with invisible crack under combined actions of cyclic loading and tidal environment. Because of the embedded reinforcing steel in the concrete structure, the visible cracks such as tapered cracks often appear and stabilize or propagate under external loading.

In the field, the reinforced concrete structure is under the influence of combined factors, such as natural crack characteristics due to the external loading and marine environments. Particularly, when the crack occurs in the concrete cover, the rate of chloride ion is accelerated to diffuse into the concrete structure hence the durability, as a result, will be reduced quickly. For this reason, this research will carry out the effects of tapered crack characteristics, crack width and crack depth, on the chloride diffusion into cracked reinforced concrete structure under saturated condition. A numerical model was proposed to predict the chloride profile at tapered cracks of reinforced concrete structure and this model will become an important solution to evaluate the remaining service life of concrete structure when cracks appear.

Development of Model

Flexural loading is able to cause zones with cracks and uncrack on the tension surface of reinforced concrete, as shown in Figure 1. The chloride profile in crack zone is different with that in uncrack zone, furthermore it accumulates chloride concentration in crack zone more than in uncrack zone. From this reason, the steel reinforcement will be found in more damage in crack zone than in uncrack zone.

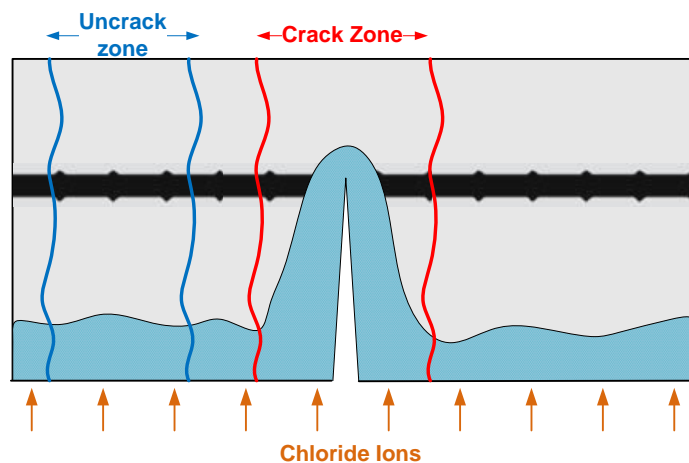


Figure 1. Collecting chloride profile at crack and uncrack zones

Generally, under saturated condition the chloride profile governed by the diffusion mechanism of chloride ions is calculated by Fick's second law, as shown by the equation below:

$$\frac{\partial C_t}{\partial t} = D_a \frac{\partial^2 C_t}{\partial x^2} \quad (1)$$

A solution to equation (1) is given by the compliment to the error-function:

$$C(x,t) = C_s \left(1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_a t}} \right) \right) \quad (2)$$

where $C(x,t)$ is chloride concentration at time t at depth x ; C_s is surface chloride content; $\operatorname{erf}()$ is error function; x is distance from concrete surface; t is exposure time; and D_a is apparent chloride diffusion coefficient.

Up to now, many researches have concluded that the crack width played a role of increase in the chloride penetration into cracked concrete [3-8, 11]. However, in the real reinforced concrete under flexural load, the crack depth also affects the chloride penetration depth and chloride profile along the crack zone in addition to the crack width [12].

Consequently, to predict the chloride profile in a tapered crack of reinforced concrete, the chloride diffusion coefficient (D_a) has to be modified and developed. It will become the chloride diffusion coefficient in the crack zone of reinforced concrete, so that the influences of crack characteristics should be included as follows:

$$D_a = f(W, L, D_{un-cr}) \quad (3)$$

where D_a is the chloride diffusion coefficient in crack zone, and is a function considering the dependence of chloride diffusion coefficient of uncrack zone (D_{un-cr}) on the crack width (W) and crack depth (L).

The concept of chloride diffusion through the crack is illustrated in Figure 2. The chloride ions will diffuse in cracked reinforced concrete following two states. First, the chloride ions will diffuse through crack region and are governed by the chloride diffusion coefficient of crack (D_{cr}), as shown in Figure 2a. Subsequently, the chloride ions continuously diffuse in the uncrack region of concrete at the tip of crack. The chloride profile in this uncrack region must correlate to the coordinate axis at the exposed surface. That is why the chloride diffusion coefficient of this uncrack region (D_{un-eff}) must have a correlation to crack depth, as shown in Figure 2b. In other words, the crack depth will have an influence on the chloride profile or chloride diffusion coefficient of the uncrack region.

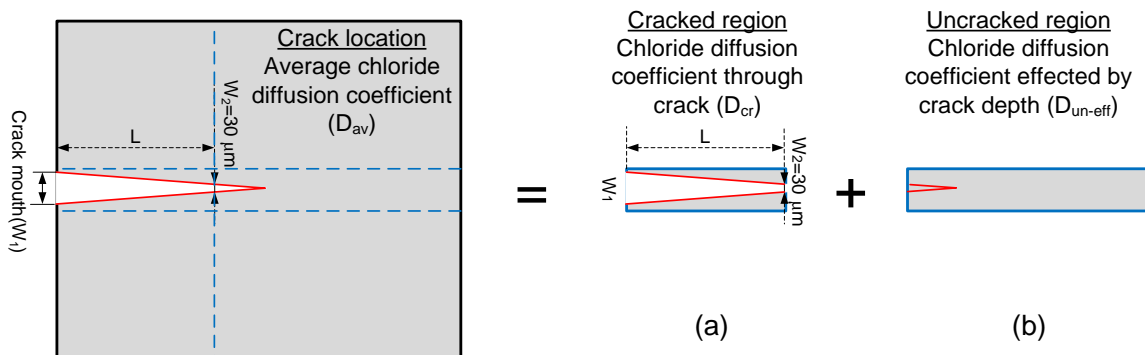


Figure 2. The concept for chloride diffusion coefficient at a crack location of reinforced concrete

With the assumption above, the chloride diffusion coefficient in cracked reinforced concrete is proposed as an average chloride diffusion coefficient (D_{av}) as follows:

$$D_a = D_{av} = \frac{D_{cr} + D_{un-eff}}{2} \quad (4)$$

where D_{cr} is calculated based on the crack width (W) by the following equation proposed by Djerbi [6]:

$$\begin{cases} D_{cr} (m^2 / s) = (2 \times 10^{-11})W - 4 \times 10^{-10}, & \text{when } 30 \mu\text{m} \leq W \leq 80 \mu\text{m} \\ D_{cr} (m^2 / s) \approx 14 \times 10^{-10}, & \text{when } w > 80 \mu\text{m} \end{cases} \quad (5)$$

However, in the research of Djerbi [6], the crack walls are transverse, separate and parallel, but in the real structure and present research, the crack normally occurs as tapered crack (V-shaped crack) that the crack width is reduced in correlation to the crack depth. So, to apply the equation (5), the crack width is approximately calculated by the average of W_1 and W_2 :

$$W = \frac{W_1 + W_2}{2} = \frac{W_1 + 30}{2} \quad (6)$$

where W_1 is the crack mouth (crack width on the tension surface), μm . $W_2 = 30$ (μm). Because of the effect of crack depth, the chloride diffusion coefficient of uncrack region, which is above the crack tip (Figure 2b), will be a function of crack depth as follows:

$$D_{un-eff} = f(L, D_{un-cr}) \quad (7)$$

where L (mm), crack depth, is assumed as a straight length from the crack mouth along the crack plane to where a crack width (W_2) is 30 μm ; D_{un-cr} is the chloride diffusion coefficient in uncrack zone.

A relationship of the crack depth (L) to the chloride diffusion coefficient D_{un-eff} will be found by an experiment. This experiment is based on the short-term diffusion test (STDT) a basis of chloride migration test [13]. Furthermore, STDT is modified by the combination of ASTM C1202 [14] and Nordtest NT build 492 [15], as shown in Figure 3. In addition, in this test, the shape of applied voltage cell is modified to change from cylinder-shape specimen to cubic-shape specimen.

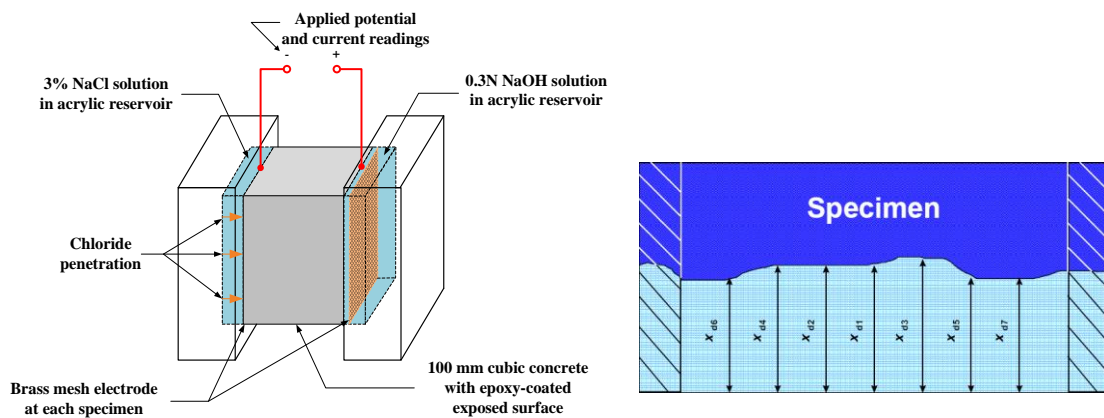


Figure 3. Set up of short-term diffusion test combined by ASTM C1202 and Nordtest NT build 492

The concept of this experiment reflects the relationship between chloride penetration depth in crack and uncrack zones in correlation to crack depth, as shown in Figure 4;

where x_{un-cr} is the chloride penetration depth at uncrack zone, L is the crack depth, x_{cr-eff} is the chloride penetration depth at crack zone (crack tip), affected by the crack depth.

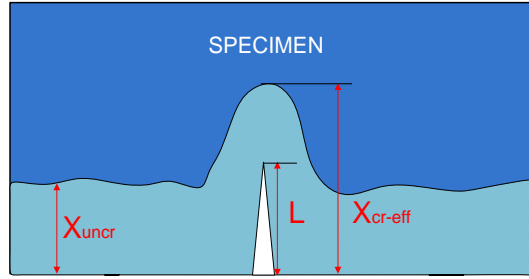


Figure 4. The concept of the chloride penetration depth at crack and uncrack zones of reinforced concrete

Based on Nordtest NT build 492, the chloride diffusion coefficient is determined as follows:

$$D_{un-cr} = \frac{Rt}{zFE} \cdot \frac{x_{un-cr} - \alpha \sqrt{x_{un-cr}}}{t} \quad (8)$$

And:

$$D_{cr-eff} = \frac{Rt}{zFE} \cdot \frac{x_{cr-eff} - \alpha \sqrt{x_{cr-eff}}}{t} \quad (9)$$

Where:

$$\alpha = 2 \sqrt{\frac{RT}{zFE}} \cdot \text{erf}^{-1} \left(1 - \frac{2c_d}{c_0} \right); \quad E = \frac{U - 2}{L_t}$$

z : absolute value of ion valence, for chloride, $z = 1$; F : Faraday constant, $F = 9.648 \times 10^4$ J/(V.mol); U : absolute value of the applied voltage, V; R : gas constant, $R = 8.314$ J/(K.mol); T : average value of the initial and final temperatures in the analyte solution, K; L_t : thickness of the specimen, m; t : test duration, seconds; erf^{-1} : inverse of error function; c_d : chloride concentration at which the color changes, $c_d \approx 0.07$ N for OPC concrete; c_0 : chloride concentration in the catholyte solution, $c_0 \approx 2$ N.

Experiment Testing

Preparation of Specimens

In this study, three types of water-cement ratio (W/C) - 0.4, 0.5 and 0.6 - in mixtures were investigated. The ASTM Type I Portland cement (OPC) was used; concrete proportions in study are presented in Table 1. The sand and coarse aggregate were washed and dried prior to casting to remove any initial chloride content. For each type of concrete proportions, the beams with size of 100x100x500 mm were cast. After curing for 28 days, the single crack on the tension surface of each beam was generated by the bending moment with a three-point load; the crack depth was modified by varying the magnitude of applied load. There pre-cracked reinforced concrete beams will be used for two experimental programs:

