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

Hoang Quoc Vu[1], Boonchai Stitmannaithum[2], and Takafumi Sugiyama[3]

[1] Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand, e-mail: vqhoang@hcmut.edu.vn

[2] Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand, e-mail: boonchai.s@chula.ac.th

[3] Environmental Materials Engineering Laboratory, Faculty of Engineering, Hokkaido University, Hokkaido, Japan, e-mail: takaf@eng.hokudai.ac.jp

Received Date: June 5, 2012

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.

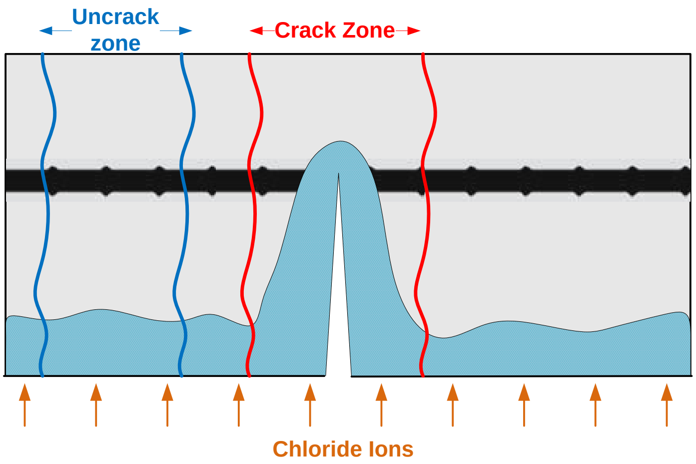


Figure 1. Collecting chloride profile at crack and uncrack zones

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:

$$\frac{\partial C_t}{\partial t} = D_a \frac{\partial^2 C_t}{\partial x^2} \tag{1}$$

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

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

where $C(x,t)$ is chloride concentration at time t at depth x; C_s is surface chloride content; $erf()$ 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:

$$D_a = f(W, L, D_{uncr}) \quad (3)$$

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_{uncr}) 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 ($D_{un\text{-}eff}$) 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.

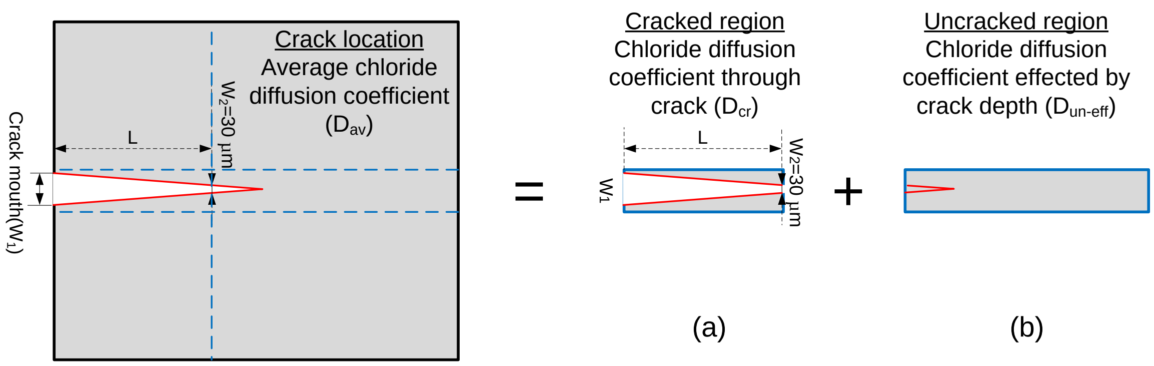


Figure 2. The concept for chloride diffusion coefficient at a crack location of reinforced concrete

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

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

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

$$\begin{cases} D_{cr}(m^2/s) = (2x10^{-11})W - 4x10^{-10}, & \text{when } 30\mu\text{m} \le W \le 80\mu\text{m} \\ D_{cr}(m^2/s) \approx 14x10^{-10}, & \text{when w} > 80\mu\text{m} \end{cases} \tag{5}$$

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:

$$W = \frac{W_1 + W_2}{2} = \frac{W_1 + 30}{2} \tag{6}$$

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:

$$D_{un-eff} = f(L, D_{uncr}) \tag{7}$$

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_{uncr} 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.

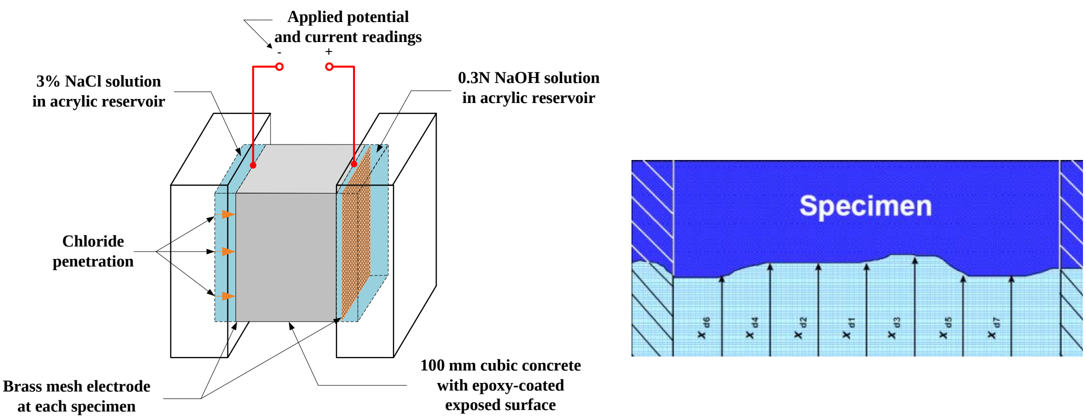


Figure 3. Set up of short-term diffusion test combined by ASTM C1202 and Nordtest NT build 492

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_{uncr} is the chloride penetration depth at uncrack zone, L is the crack depth, $x_{cr\text{-}eff}$ is the chloride penetration depth at crack zone (crack tip), affected by the crack depth.

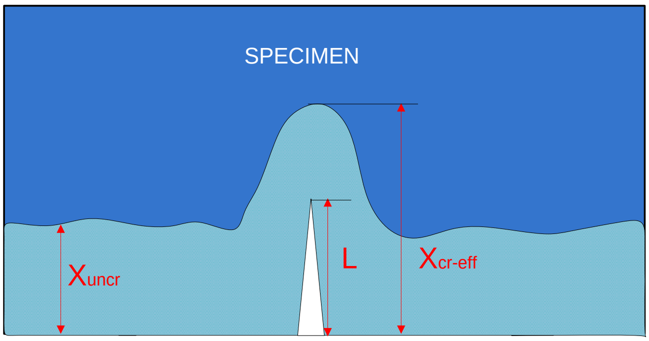


Figure 4. The concept of the chloride penetration depth at crack and uncrack zones of reinforced concrete

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

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

And:

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

Where:

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

z: absolute value of ion valence, for chloride, z = 1; F: Faraday constant, F = 9.648 ×104 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 anolyte 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:

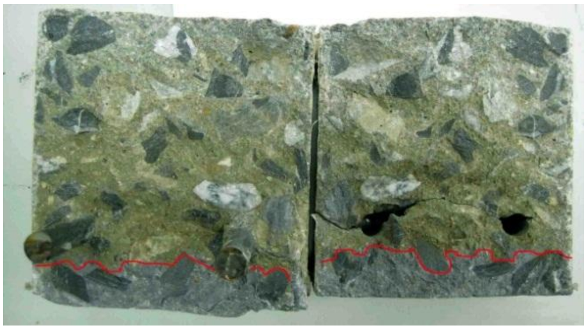
- To observe the influence of crack depth on the chloride diffusion coefficient (D_{un-eff}).
- To validate the prediction model of chloride profile at tapered cracks of reinforced concrete.

Table 1. Mix Proportion and Properties of Concrete

Mix	W/C	Cement (kg)	Water (kg)	Sand (kg)	Coarse Agg. (kg)	Av. Comp. Str. (MPa)	Av. Slump (cm)
1	0.4	513	205	664.14	1,024	48.1	7.5
2	0.5	410	205	748.62	1,024	39.3	8.5
3	0.6	342	205	804.93	1,024	32.8	8

Testing the Influence of Crack Depth on the Chloride Diffusion Coefficient

The cubic specimens containing a single crack were sawed from the pre-cracked reinforced concrete beams. Before conducting the chloride diffusion test, the correlation of the crack depth to crack width along crack plane of the cubic specimen is measured on both crack sides of the cubic specimen by a digital microscope. The crack mouth on the tensile surface of cubic specimen was measured at 9 points of interval distance of 1 cm. The applied voltage for testing was 60 V. The duration time of testing was 10 hours. After testing STDT, the cubic specimens were split along the crack plane into two parts. The silver nitrate 0.1 M was then sprayed on the split surface of the concrete. After 15 minutes, the chloride penetration depth was measured as visible white precipitation of silver chloride at the crack tip (x_{cr-eff}). Figure 5 shows an experimental result of the chloride penetration depths in uncrack and crack zones.



(a)

(b)

Figure 5. Chloride penetration depth in uncrack zone, xun (a) and crack zone, xcr-eff (b)

Testing the Chloride Profile in Uncrack Zone and Crack Zone

The back-to-back pair of reinforced concrete beams (Figure 6) containing a single crack were immerged into salt solution of NaCl 10%. After immersion periods of 2, 4, 6, 8, 16 weeks, these beams were kept at room temperatures for 7 days to thoroughly dry the surface. Then, a drill bit having a diameter of 1 inch was used to drill a hole on the tensile surface of reinforced concrete beam to collect the concrete powder. The samples of the concrete powder of 10 gram will be collected in an interval depth of 5 - 10 mm. To verify the proposed model for predicting chloride profile in the crack zone, the concrete powder samples in crack zone were obtained, and were then analyzed by the conventional chemical analysis [16]. The concrete powder samples in uncrack zone were also collected to find out the apparent chloride diffusion coefficient in uncracked zone following the standard instructions [17]. The experimental results, such as the crack width, crack depth and the apparent chloride diffusion coefficient in uncrack zone, are showed in Table 2.

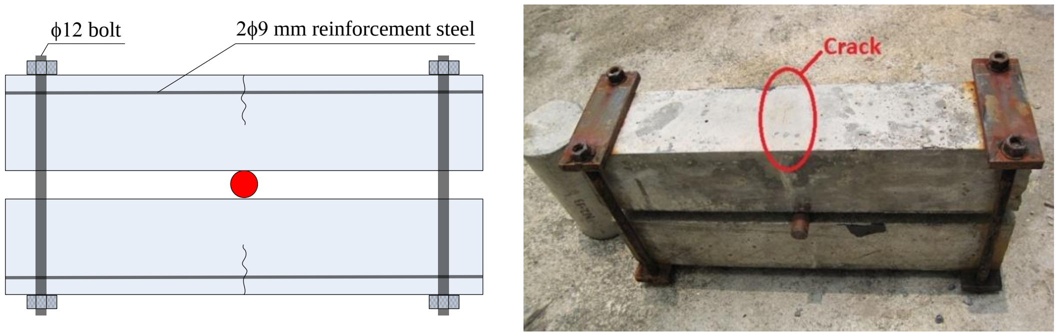


Figure 6. The back-to-back pair of reinforced concrete beams immersed into salt solution

Table 2. Experimental Results of Crack Characteristics and Chloride Diffusion Coefficient

Immersion Periods (week)	W/C	Crack No.	Crack Mouth (W_1, mm)	Respective Crack Depth (L, mm)	Apparent Chloride Diffusion Coefficient at Uncrack Zone (D_{uncr}), (m^2/s)
2	0.4	1	0.058	32.5	3.77E-11
	0.5	1	0.077	36	5.33E-11
	0.6	1	0.081	32	8.87E-11
4	0.5	1	0.093	41.5	3.16E-11
	0.6	1	0.083	41.5	4.74E-11
6	0.4	1	0.045	21.5	2.43E-11
	0.5	1	0.052	27.5	2.19E-11
	0.6	1	0.072	33	2.28E-11
8	0.4	1	0.089	42	2.47E-11
	0.5	1	0.074	31.5	2.43E-11
	0.6	1	0.080	40.5	3.25E-11
16	0.5	1	0.107	45.5	1.65E-11
		2	0.101	45	

Results and discussions

The Influence of Crack Depth on the Chloride Diffusion Coefficient

Figure 7 shows the experimental results of the influence of crack depth on the chloride diffusion coefficient by STDT. The results also pointed out that the values of chloride diffusion coefficient for W/C of 0.6 were higher than W/C of 0.5 and 0.4 at the same depths of cracks. At the same depths of cracked concrete, the chloride diffusion coefficients are still governed by the effects of concrete proportions, typically, water-cement ratios. Because the chloride diffusion takes place in the crack and in the matrix of concrete together, so the varying chloride diffusion coefficient in the matrix concrete is affected by the matrix concrete performances and concrete proportions. Normally, a higher concrete performance will bring out a lower chloride diffusion coefficient [18]. Furthermore, in the experimental results, the trends of increasing chloride diffusion coefficient in the correlation of crack depth are similar when the water-cement ratios are varied. It can be concluded that the trend of increasing the penetration depth and diffusion coefficient of chloride, when the crack depth varies, is independent on the proportion of concrete (W/C). From the linear regression of experimental results, an equation describing the influence of crack depth (L) on the chloride diffusion coefficient at crack zone of reinforced concrete is presented as follows:

$$D_{un-eff} = 0.58L * 10^{-12} + D_{uncr} \tag{10}$$

where L is crack depth (mm).

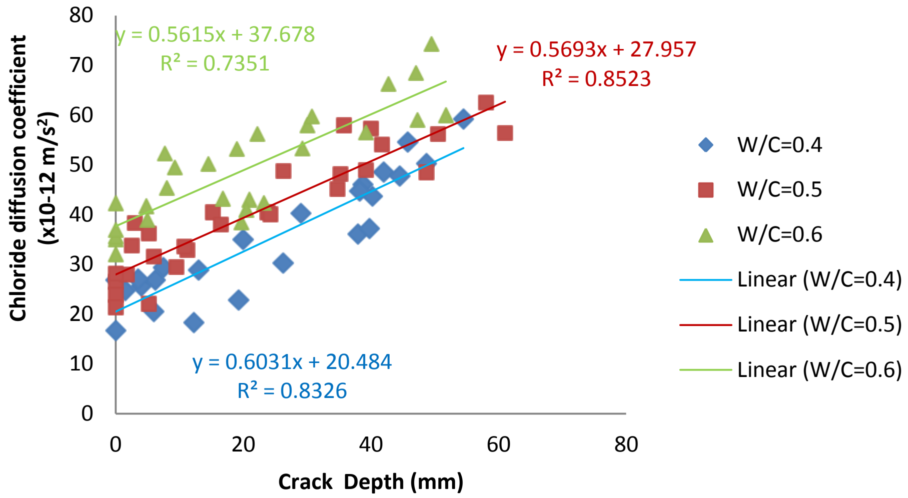


Figure 7. The influence of crack depth on the chloride diffusion coefficient by STDT

Validation of Proposed Model

The equation (5) describes the effective chloride diffusion coefficient (D_{cr}^{eff}). In the calculation of chloride profile, the effects of chloride binding capacity and the hydration time on the chloride diffusion have to be included in equation (5) to become the apparent chloride diffusion coefficient (D_{cr}^{app}) as follows:

$$D_{cr}^{app} = D_{cr}^{eff} * \left(\frac{28}{t}\right)^{a} / \phi \tag{11}$$

where t is the age of concrete (day); a is the experiment coefficient, 0.3 for OPC [2]; ϕ is the chloride binding capacity of a cement [9].

$$\phi = (1+\alpha) \tag{12}$$

$$\alpha = 0.56 + 0.025 C_3A \tag{13}$$

C_3A is a hydration compound of the cement.

By applying the Fick's Second Law, equation (2) and the chloride diffusion coefficient at a crack zone of reinforced concrete, equation (4), the chloride profile at crack zone is calculated. Subsequently, the comparisons between the predicted and experimental results in the varying immersion periods are shown in Figure 8 to Figure 20.

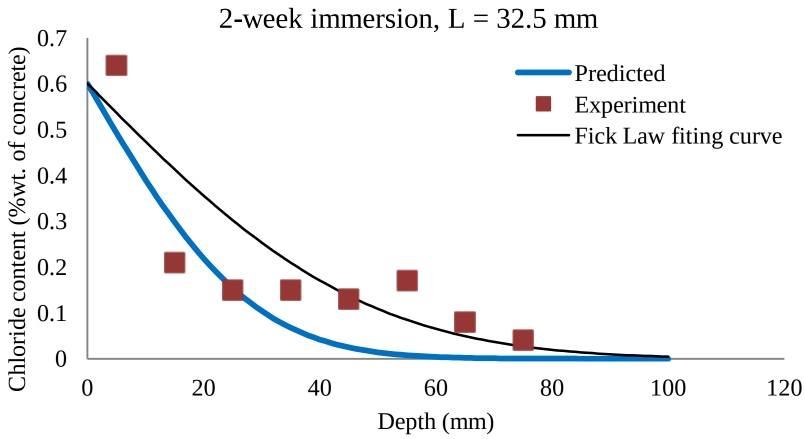


Figure 8. Comparison between predicted and experimental results (W/C = 0.4)

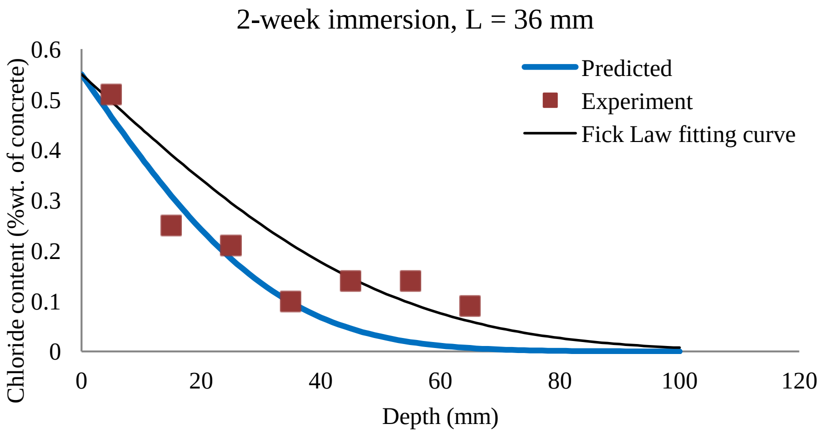


Figure 9. Comparison between predicted and experimental results (W/C = 0.5)

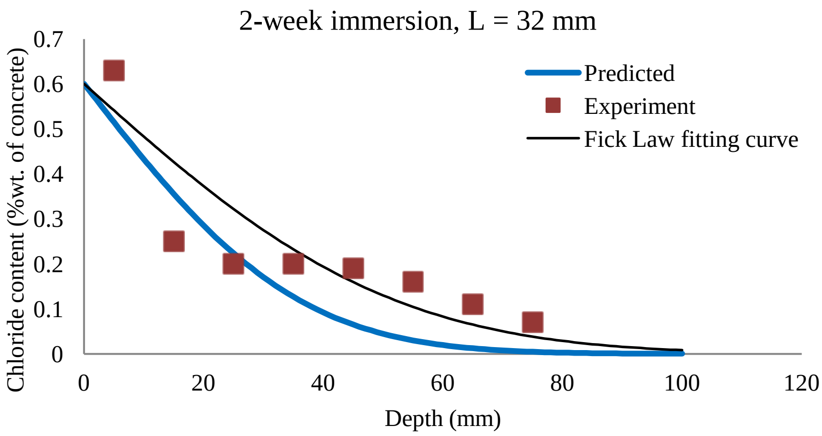


Figure 10. Comparison between predicted and experimental results (W/C = 0.6)

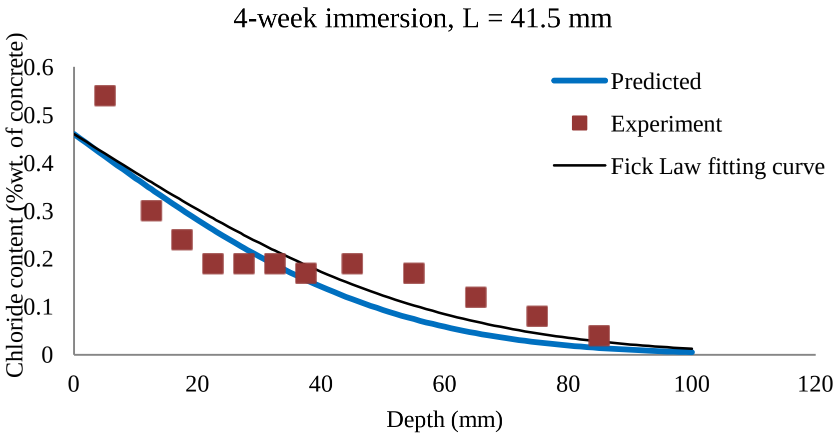


Figure 11. Comparison between predicted and experimental results (W/C = 0.5)

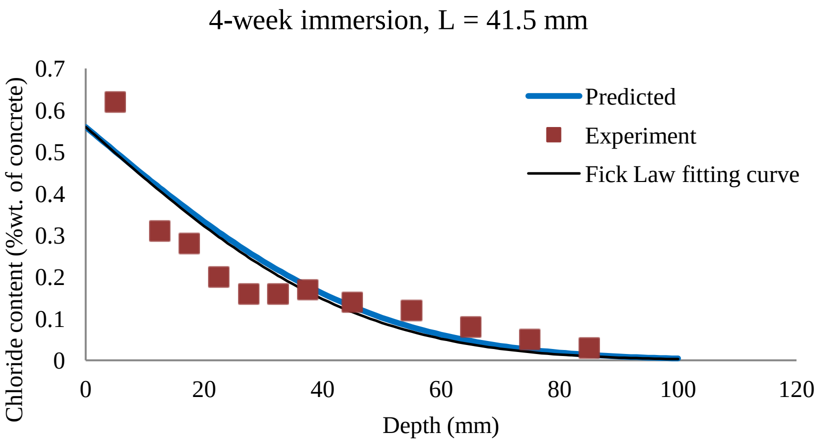


Figure 12. Comparison between predicted and experimental results (W/C = 0.6)

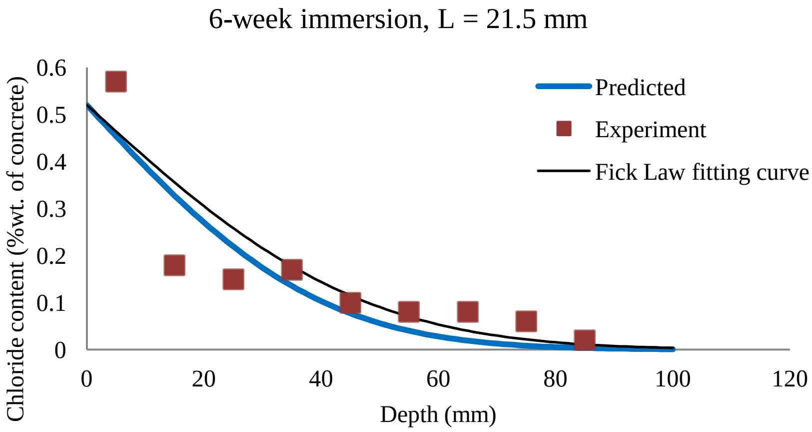


Figure 13. Comparison between predicted and experimental results (W/C = 0.4)

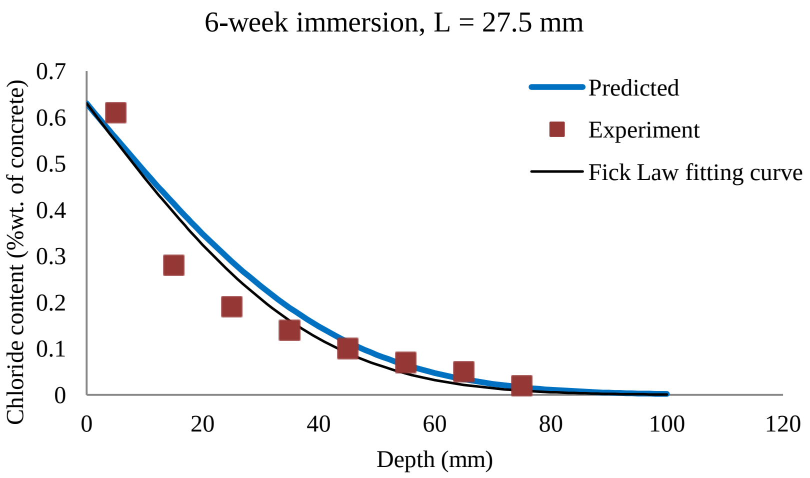


Figure 14. Comparison between predicted and experimental results (W/C = 0.5)

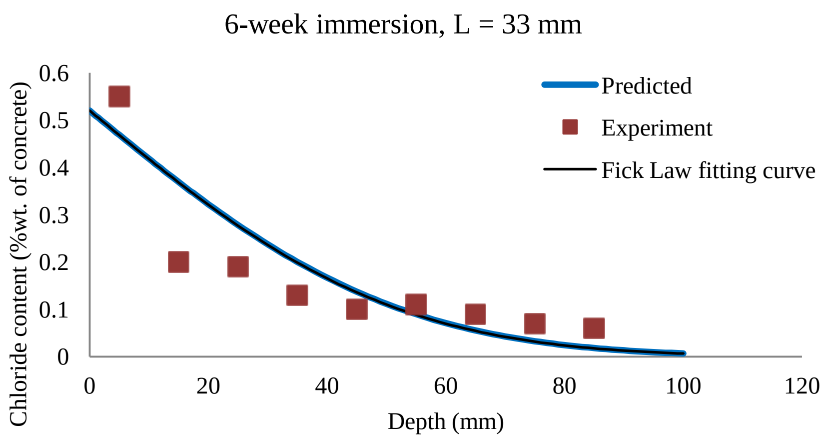


Figure 15. Comparison between predicted and experimental results (W/C = 0.6)

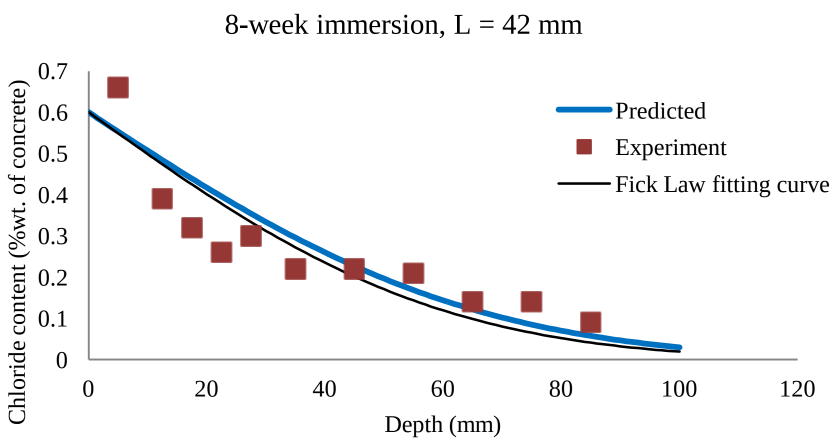


Figure 16. Comparison between predicted and experimental results (W/C = 0.4)

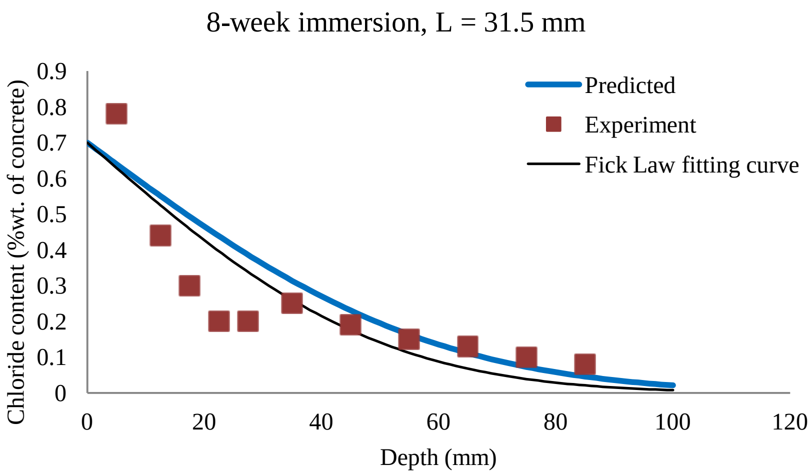


Figure 17. Comparison between predicted and experimental results (W/C = 0.5)

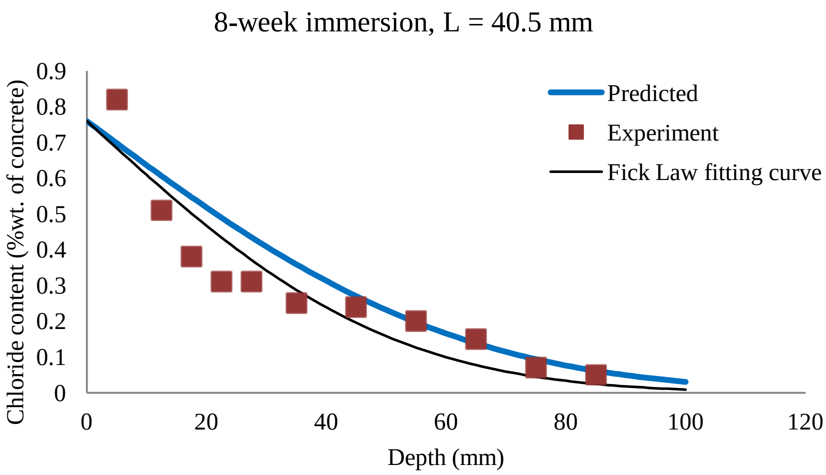


Figure 18. Comparison between predicted and experimental results (W/C = 0.6)

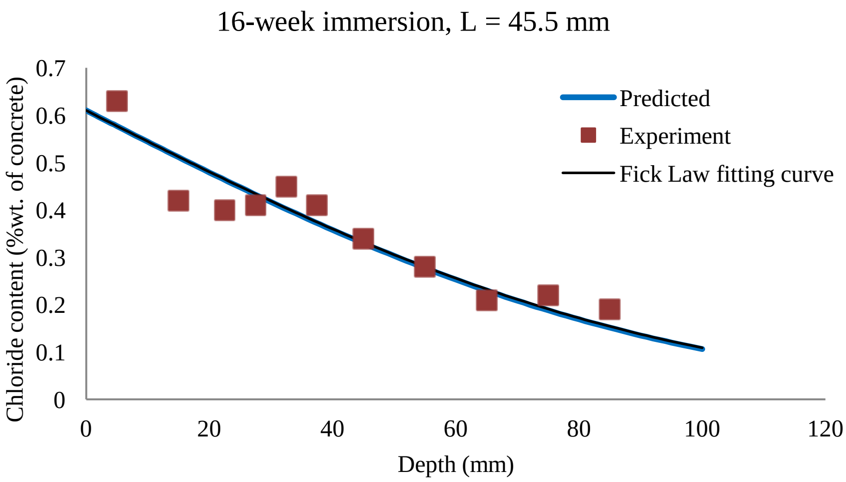


Figure 19. Comparison between predicted and experimental results (W/C =0.5; Crack 1)

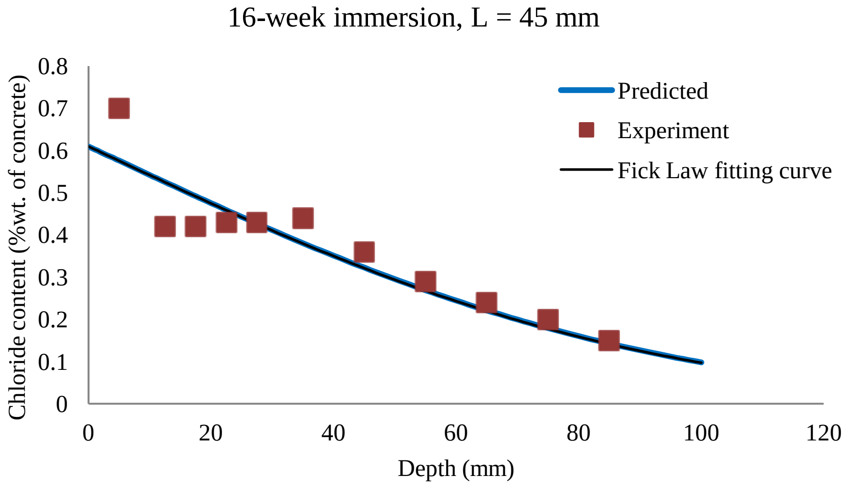


Figure 20. Comparison between predicted and experimental results (W/C =0.5; Crack 2)

The proposed model used the surface chloride concentration in crack zone and average chloride diffusion coefficient (D_{av}) to predict the chloride profile at the locations of crack zones. The predicted results fitted very well with the experimental results, except for the samples immerged in salt solution during the initial weeks (2 weeks). In this case, an explanation is provided that the experimental results for chloride penetration are governed by the mechanism of movement of bulk chloride solution due to capillary suction. This capillary suction is assumed to primarily control the chloride transport through the whole crack at the initial ages of immersion periods. Then, the mechanism of chloride diffusion would be taken as following Fick's second law. Inversely, the predicted results are obtained by the derivation of Fick's second Law equation, which is applied for only diffusion mechanism. However, in case of immersion periods larger than 4 weeks, only the diffusion mechanism still controls the chloride penetration into concrete. That is why there is a good agreement between the experimental results and predicted ones.

Conclusions

- The research proposed a simple approach to predicting chloride profile in crack zone of reinforced concrete. The results of numerical calculation fit well with the experimental results. This developed model will become an important solution to evaluate the remaining service life of concrete structure when cracks appeared.
- Effects of crack characteristics, such as crack width and crack depth, were investigated on the chloride profile and chloride diffusion coefficient at the cracks of reinforced concrete structure. In addition to the crack width, the crack depth should be taken into account as an influence on chloride penetration into cracked reinforced concrete.
- The chloride penetration into cracked concrete increased as an increase of the crack depth and their rate trends were independent on the proportion of concrete, but dependent on the geometric of crack. The study also indicated that the service load had a significant role in increasing the chloride penetration due to a varying crack depth.
- The experimental results also showed the influence of the capillary suction mechanism on the chloride penetration into cracked concrete during the early periods of immersion by the movement of bulk chloride solution.

Acknowledgments

This research has been conducted at Chulalongkorn University, Thailand and Hokkaido University, Japan. Support from Japan International Cooperation Agency (JICA) through AUN/SEED-Net Program is greatly appreciated.

References

[1] T. Sugiyama, W. Ritthichauy, and Y. Tsuji, "Experimental investigation and numerical modeling of chloride penetration and calcium dissolution in saturated concrete," *Cement and Concrete Research*, Vol. 38, No. 1, pp. 49-67, 2008.

[2] M.A. Bermudez, and P. Alaejos, "Models for chloride diffusion coefficients of concretes in tidal zone," *American Concrete Institute Materials Journal*, Vol. 107, No. 1, pp. 3-11, 2010.

[3] K. Takewaka, T. Yamaguchi, and S. Maeda, "Simulation model for deterioration of concrete structures due to chloride attack," *Journal of Advanced Concrete Technology*, Vol. 1, No. 2, pp. 139-146, 2003.

[4] M. Ismail, A. Toumi, R. Francois, and R. Gagne, "Effect of crack opening on the local diffusion of chloride in inert materials," *Cement and Concrete Research*, Vol. 34, No. 4, pp. 711-716, 2004.

[5] E. Kato, Y. Kato, and T. Uomoto, "Development of simulation model of chloride ion transportation in cracked concrete," *Journal of Advanced Concrete Technology*, Vol. 3, No. 1, pp. 85-94, 2005.

[6] A. Djerbi, S. Bonnet, A. Khelidj, and V. Baroghel-bouny, "Influence of traversing crack on chloride diffusion into concrete," *Cement and Concrete Research*, Vol. 38, No. 6, pp. 877-883, 2008.

[7] M. Ismail, A. Toumi, R. François, and R. Gagné, "Effect of crack opening on the local diffusion of chloride in cracked mortar samples," *Cement and Concrete Research*, Vol. 38, No. 8-9, pp. 1106-1111, 2008.

[8] L. Wang, and T. Ueda, "Numerical determination of the chloride diffusion coefficient in cracks and cracked concrete," In: H. Yokota, T. Sugiyama, and T. Ueda, eds., *Advances in Concrete Structural Durability: Proceedings of the 2nd International Conference on Durability of Concrete Structures ICDCS2010*, Hokkaido University Press, Sapporo, Japan, 2010.

[9] T.V. Mien, B. Stitmannaithum, and T. Nawa, "Simulation of chloride penetration into concrete structures subjected to both cyclic flexural loads and tidal effects," *Computers and Concrete*, Vol. 6, No. 5, pp. 421-435, 2009.

[10] C.C. Lim, N. Gowripalan, and V. Sirivivatnanon, "Microcracking and chloride permeability of concrete under uniaxial compression," *Cement & Concrete Composites*, Vol. 22, No. 5, pp. 353-360, 2000.

[11] R. François, A. Toumi, M. Ismail, A. Castel, T. Vidal, and R. Gagné, "Effects of cracks on local diffusion of chloride and long-term corrosion behavior of reinforced concrete members," In: T. Zhao, F.H. Wittmann, and T. Ueda, eds., *Proceedings of International Workshop on Durability of Reinforced Concrete under Combined Mechanical and Climate Loads*, Qingdao, China, 2005.

[12] Vu, H.Q., B. Stitmannaithum, and S. Takafumi, "Experimental Study on Chloride Penetration Depth of Cracked Concrete", In: S.R. Lee, et al., editors, *The Twenty-Fourth KKCNN Symposium on Civil Engineering*, Hyogo, Japan, pp. 269-272, 2011.

[13] Mien, T.V., B. Stitmannaithum, and T. Nawa "Prediction of chloride diffusion coefficient of concrete under flexural cyclic load." *Computers and Concrete*, Vol. 8, No. 3, 2011.

[14] C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, American Society for Testing and Materials (ASTM), 1997.

[15] 492, *Chloride Migration Coefficient from Non-steady-state Migration Experiments*, Northtest-NTBuild, 1999.

[16] C1152, *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*, American Society for Testing and Materials (ASTM), 1997.

[17] C1556, *Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion*, American Society for Testing and Materials (ASTM), 2004.

[18] Suryavanshi, A.K., R.N. Swamy, and G.E. Cardew "Estimation of Diffusion Coefficients for Chloride Ion Penetration into Structural Concrete." *ACI Materials Journal*, Vol. 99, No. 5, pp. 441-449, 2002.