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Chloride Penetration into Reinforced Concrete Structure

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ABSTRACT

This research investigates the chloride penetration in reinforced concrete under flexural load. In this paper, the chloride penetration in cracked and uncracked concretes in plain concrete as well as in reinforced concrete were experimented and modelled. In reinforced concrete, cracks often appear as the V-shaped crack. The proposed models predicted the chloride ingress in cracked concrete follow two-dimensional diffusivity, one from the exposed surface and another one perpendicular to crack plane. In the present paper, the natural crack was investigated, while crack width and crack depth were recognized as the key parameters influencing on the coefficient of chloride diffusion and the chloride profile. The ANSYS program was employed to simulate the chloride profiles in cracked reinforced concrete and they were validated by comparing with experimental results obtained by conventionally chemical analysis. The predicted results fitted quite well with the experimental ones.

Keywords. Chloride Penetration, Reinforced Concrete, Cracked Concrete, Model.

INTRODUCTION

Nowadays, the durability of reinforced concrete structures in marine environment has been concerned as a serious problem in concrete construction technology. However, the corrosion of reinforced concrete is considered one of the major deterioration mechanisms where chloride attack as main factors. In marine structure, the chloride may attack in the pore structure by the transport of diffusion mechanism accompanying with chemical reactions (Sugiyama et al. 2003; Sugiyama et al. 2008b).

A large number of prior researchers have investigated the chloride penetration into reinforced concrete; in addition, numerous models to predict transport properties and service life have been introduced. However, it has a disadvantage that all simulations are conducted with the pure concrete or uncracked concrete. In fact, in the real structure, most reinforced concrete structures are often exposed with involving the cracks that will reduce the durability of reinforced concrete faster than the uncracked concrete.

An appearance of crack due to service loading causes an increase in rate of chloride ingress into reinforced concrete. Up to now, many researches have tried to take into account the influence of crack width on the chloride penetration into cracked concrete (Takewaka et al.

2003; Ismail et al. 2004; Kato et al. 2005; Djerbi et al. 2008; Ismail et al. 2008; Wang and Ueda 2010). In addition to crack width, crack depth is also a key parameter; especially, under loading the crack depth will rise during all stages in the life of a concrete structure which it strongly affects the chloride penetration depth. However, studies about crack depth affecting on the chloride penetration have not been clear and complete. Furthermore, the loading is also a parameter having the influence on the chloride penetration in concrete (Lim et al. 2000). Because of embedding reinforcing steel in concrete structure, the visible cracks often appear and stabilize or propagate under loading.

Conclusively, the current research will propose the models to predict the chloride penetration into plain concrete and reinforced concrete under marine environment. Especially, the effects of microcrack and visible crack caused by external load on the chloride penetration will be investigated.

CHLORIDE PENETRATION INTO PLAIN CONCRETE UNDER CYLIC LOADING

Prediction of chloride diffusion coefficient under fatigue

Considering a simple case of chloride flow through cracked concrete, total flow of chloride can be expressed as the sum of the flow through crack and flow through uncracked part of homogeneous material. Thus, total flux of chloride through the entire cracked concrete can be written as follow (Gérard and Marchand 2000):

$$J_{tot} = \frac{J_{ucr} A_{ucr} + J_{cr} A_{cr}}{A_{ucr} + A_{cr}} \tag{1}$$

where J_{tot} is the total flux of chloride through entire cracked concrete, mole/m^{2}s. J_{ucr} is the flux of chloride through uncracked concrete, mole/m2s, and Jcr is the flux of chloride through cracks. A_{ucr} and A_{cr}, m^2, are the areas, which are perpendicular to the chloride flow, of cracks and uncracked concrete, respectively.

The equation (1) can be modified as follows:

$$D_{tot} = \frac{A_{ucr} D_{ucr} + A_{cr} D_{cr}}{A_{ucr} + A_{cr}} \tag{2}$$

where D_{ucr} and D_{cr}, m^2/s, are the chloride diffusion coefficient of the uncracked concrete and through cracks, respectively. D_{tot}, m^2/s, is the apparent chloride diffusion coefficient of the cracked concrete.

Kato (Kato et al. 2005) proposed that Dcr increases with increasing the crack width and becomes almost constant when the crack width is 0.075mm or more. D_{cr} is approximately 2.51×10^{-7} m^2/s as the crack width is smaller than 0.075mm.

For crack due to flexural cyclic load, we adopt the simple assumption that a single-edge crack occurs; the crack shape is straight; the crack length at the edge side is equal to that at the bottom side of the beam. Hence, crack area, A_{cr}, can be expressed simply as:

$$A_{cr} = W_e a h \tag{3}$$

where W_e, m, is the effective crack width. However, the actual crack due to flexural cyclic load is not simply straight, it is tortuous. In order to account for tortuous effect in an actual crack, W_e can be related to crack mouth opening δ and the tortuosity parameter, τ ($1<\tau \leq 5$):

$$W_e = \frac{\delta}{\tau} \tag{4}$$

Experimental verification for model

Test of flexural cyclic load. The test of the flexural strength of concrete beam was conducted by ASTM C78 for determination of flexural ultimate load, P_{ult}. Then, the flexural cyclic test was performed with different load levels, SR, which is ratio of maximum applied load, P_{app}, max, to ultimate load, P_{ult}. In the test of flexural cyclic load, Instron machine 1200kN was used to apply third-point bending cyclic loads to concrete beams over span of 300mm. Deflection values of beams at middle bottom position were measured by LVDT. The load control test with low frequency of 0.01Hz and load levels, SR, of 0.5, 0.6, 0.7 and 0.8 was used in this research. The load levels, SR, flexural ultimate load, P_{ult}, and maximum applied load, P_{app}, max, of different mixture series are shown in Table 3. Bending load was ramped up to the desired P_{app}, max over about 20 cycles, then one-stage constant applitude fatigue loading between P_{app}, max and P_{app}, min, where P_{app}, min equals to zero, was conducted. Based on curves of relationship of load and deflection shown in Fig. 6, in each load level, the specific number of cycles where the curves of relationship of load and deflection (herein after it is referred as to L-D curve) changed or not changed was determined. At cycles that L-D curve not changed and changed (N = 2000, 2500, 3000, 3200, 3500 and 3800), cubic specimens of 100mm were taken from the middle bottom position of beams by sawing, see Fig. 7. Using these sawn specimens, crack widths of plain concrete in tension zone were measured by optical microscopy, and the chloride diffusion coefficients of plain concretes under different number of cycles and load levels were determined. A modified chloride migration test, which combines ASTM C1202 and NTBUILD 492, was applied for determination of the chloride diffusion coefficient. The chloride diffusion coefficient was calculated from this penetration depth through Equation (5). The detail of this test can refer to (Northtest-NTBuild-492 1999).

$$D = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \tag{5}$$

where D is chloride diffusion coefficient, m2/s, U is absolute value of the applied voltage, V, T is average value of the initial and final temperatures, oC, L is thickness of the specimen, mm, xd is average value of the penetration, mm, t is test duration, hour.

Fatigue crack width and crack length. In the fatigue test under load control procedure, bending load was ramped up to the desired Papp, max over 20 cycles, the elastic displacement at this desired Papp, max, with SR=0.7, was about 0.01mm (Gontar 2000). So, the numerical analyses of the fatigue deformation adopt 0.007, 0.008, 0.01 and 0.011mm as the initially ramped up crack width, wi, these fatigue deformations are corresponding to SR of 0.5, 0.6, 0.7 and 0.8, respectively. Numerical analyses of relationships between crack width and the number of cycles for plain concrete beam subjected to fatigue tests with different SR are shown in Figure 1.

The theoretically calculated fatigue crack lengths of concrete beams under different load levels with the minimum applied load, Papp,min, equal to zero are shown in Figure 2. The fictitious crack width and crack length increased with increasing either the number of cycles or the load level, SR. The numerical simulation clearly showed that fictitious crack growth, in terms of crack width and crack length, can be divided into three stages; a decelerated stage; a steady stage; an accelerated stage towards fracture.

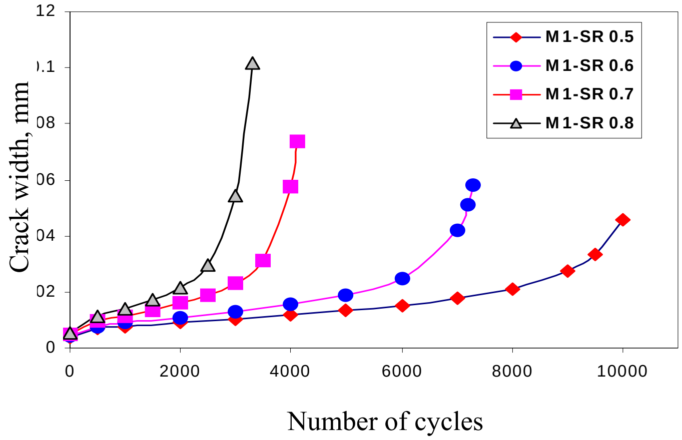

Figure 1. Predictions of relationships of crack width and number of cycles

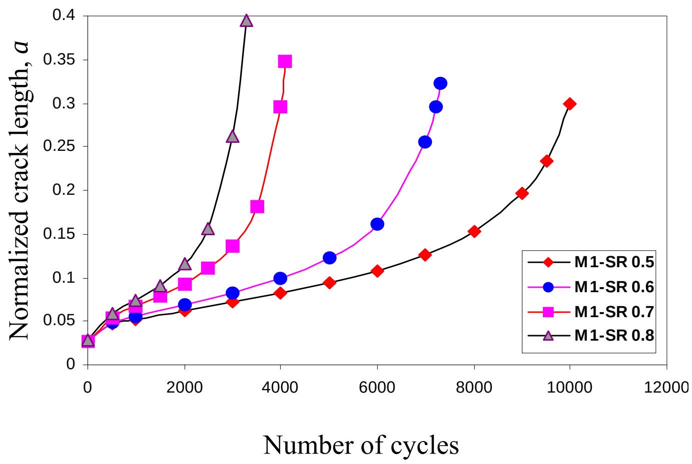

Figure 2. Predictions of relationships of crack length and number of cycles

However, as shown in Figure 3, the numerical results of crack widths do not fit well with experimental data obtained by optical microscopy. One reason for this is that the fatigue load may cause multiple microcracks in concrete than results of the numerical prediction with a single crack. Indeed, the numerical predicted crack width is larger than the measured crack width. Good fitting between the model estimation and experimental data is found when the authors introduce a so-called crack density parameter, μ, which takes into account microcracks beside the main crack. μ is a function of the number of cycles, N, and load level, SR, as below:

$$\mu = \left(\frac{1}{SR}\right)^2 \log(N) + 2.2 \quad (6)$$

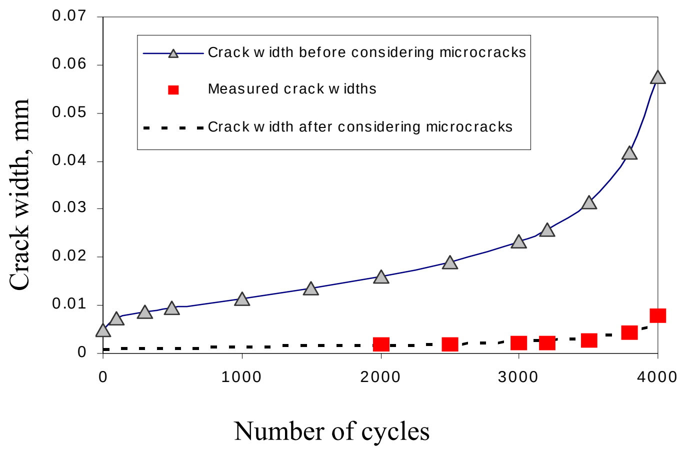

Figure 3. Relationships of crack width and number of cycles, model prediction and experimental results, *SR*=0.7

Chloride diffusion coefficient under fatigue. With actual concrete structures, consequently, the equation of chloride diffusion coefficient should be rewritten to account for the effects of loadings as:

$$D_i = D_{i,ref} \,.\, f(SR) \tag{7}$$

Where, f(SR) is a function of the dependence of Di on the load levels, SR.

The effect function, f(SR), generally has been formulated based on the load level and the kinds of loads. Undergoing flexural cyclic load, the stress of the beam is divided into a tension zone and a compression zone. The effects of the flexural cyclic load level on the diffusion coefficients of plain concrete in the tension and the compression zone are shown in Figure 4. The chloride diffusion coefficients in the tension zone increased, whereas, it showed a decreasing trend in the compression zone (Figure 4.).

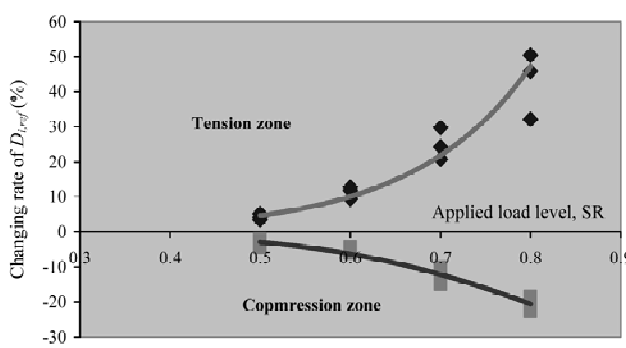

Figure 4. The effect of applied load levels on chloride diffusion coefficient of concrete both in tension and compression

Particularly, the effect of the flexural cyclic load on the chloride diffusion coefficient could be expressed as an exponential function in the tension zone as below:

$$f(SR) = 0.0985e^{7.71SR} \tag{8}$$

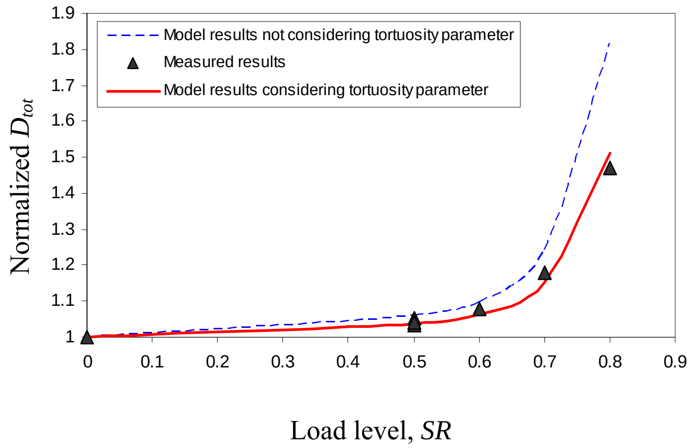

Figure 5. Relationships of load level and normalized Dtot, model prediction and experimental results, N=3500

The effect of fatigue load level on the chloride diffusion coefficient in tension zone is shown in Figure 5. As can be seen in Figure 5, with the same mixture series and the same number of cycle, the experiments show an increasing tendency of the chloride diffusion with increasing the load level. The chloride diffusion increases significantly when we apply fatigue test with load level SR at 0.6, 0.7 and 0.8, especially at 0.7 and 0.8. The model prediction shows the same tendency of the chloride diffusion with measurements. However, at any the load level of fatigue test, the normalized Dtot (against the control without fatigue test, SR=0) predicted by the model is always higher than that measured by the experiment. A main reason is that we use the assumption of the singly straight crack developed with the number of cycles.

Practically, with the number of cycles, the crack is tortuous and the width of the crack along the path varies significantly. When we introduce tortuosity parameter, τ, with τ=1.65, to account for the intrinsic tortuosity of the crack, good agreement between model predictions and measured results, simulated crack width after considering the crack density divided by τ, can be found.

MODEL FOR CHLORIDE DIFFUSION AT A CRACK LOCATION OF REINFORCED CONCRETE

Development of Model

With macro view, in tension surface of reinforced concrete structure, there are two zones obtaining the crack or uncrack locations. The crack and uncrack locations are defined as Figure 6.

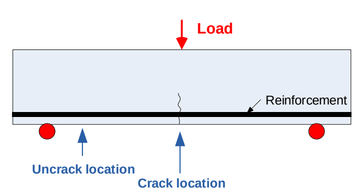

Figure 6. Definition for crack and uncrack locations.

At a crack location, the chloride profile is different with that at an uncrack location, more chloride concentration is found at the crack location than at the uncrack location, that also induces more damage due to reinforcement corrosion than the uncrack location. A simple approach is proposed to predict the chloride profile at crack locations of cracked reinforced concrete by updating the Fisk's second Law :

$$\frac{\partial C_t}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \tag{9}$$

For the plain concrete, under coupling cyclic load, the apparent diffusion coefficient of concrete was modified by Mien (Mien et al. 2009) as:

$$D_a = D_{c,ref} . f_1(T). f_2(t). f_3(h). f_4(SR) / \phi \tag{10}$$

$$f_4(SR) = 0.0985 e^{7.71SR} \tag{11}$$

The equation (9) was applied to model the chloride penetration in plain concrete under cyclic load in case of appearing invisible crack. However, in the real structure, with the embedded steel reinforcement in concrete the visible crack will occur on the reinforced concrete structure under varying load lever. Many previous conclusions have pointed out that the crack width played the role of increasing the chloride penetration into cracked concrete. Moreover, with the cylinder specimens, they also pointed out when the traversing crack width reached to the threshold value, the chloride diffusion coefficient of cracked concrete could be considered constant or independent with the crack width. These proposed threshold value of crack width are 0.60 µm (Wang and Ueda 2010), 0.075 mm (Kato et al. 2005) or higher 0.08 mm (Djerbi et al. 2008).

Moreover, in the real reinforced concrete under flexural load, the cracks appear on the surface of tension zone and propagate from the surface to the neutral axis due to the increasing magnitude of loading or number of load cycles etc. In a naturally cracked reinforced concrete (tapered crack or V-shaped crack), crack width had an important role in chloride penetration, but the crack depth should also be recognized as a key parameter affecting chloride penetration and chloride profile (Vu et al. 2011). The different depths of cracks can influence on the chloride penetration depth and causing the differences of the chloride diffusion coefficients. For instance, a deeper crack depth will have a deeper chloride penetration depth than a shallower crack depth, although these cracks have the same crack width and concrete proportion. Consequently, the chloride diffusion coefficient has to be modified to become the chloride diffusion coefficient at crack locations of reinforced concrete, that the influences of crack characteristics should be included as follows:

$$D_a^{cr} = f(W, L, D_{uncr}) \tag{12}$$

Where: D_a^{cr} is the chloride diffusion coefficient at crack location, is a function considering the dependence of chloride diffusion coefficient at crack location on that at uncrack location (D_{uncr}), the crack width (W) and crack depth (L).

The chloride ions will diffuse in cracked concrete following two states. Firstly, the chloride ions will diffuse through the crack region and are governed by the chloride diffusion coefficient at crack region (D_{cr}). Then, the chloride ions continually diffuse in the un-cracked concrete region at the tip of crack and governed by the chloride diffusion coefficient of un-cracked concrete ($D_{un\text{-}eff}$) corresponding with an effect of crack depth on it. In this research, the crack depth is defined as the straight length from the crack mouth along crack plane to where that has a crack width of 30 µm. Because when the crack width less than 30 µm, there is insignificant for chloride diffusion (Djerbi et al. 2008; Ismail et al. 2008).

By the assumption above, an average of chloride diffusion coefficients (D_{av}) is proposed as follows:

$$D_a^{cr} = D_{av} = \frac{D_{cr} + D_{un-eff}}{2} \tag{13}$$

Where: D_{cr} is the chloride diffusion coefficient through a crack is calculated basing on the crack width (w) proposed by Djerbi (Djerbi et al. 2008), following equation below:

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

However, in the research of Djerbi (Djerbi et al. 2008) the traversing crack was observed with crack walls are separate and parallel, but in this research, the cracks of reinforced concrete is a tapered crack with the crack width is reduced in correlation to the crack depth. Therefore, the average crack width (W_{av}) is proposed as equation (30) and is approximately calculated by average of W_1 and W_2:

$$w_{av} = \frac{w_1 + w_2}{2} = \frac{w_1 + 30}{2} \tag{15}$$

Where: w_1 is crack mouth (μm). w_2 = 30 μm.

With the effect of crack depth, the chloride diffusion coefficient of uncracked concrete region, which is the region above the crack tip, will be a function of crack depth:

$$D_{un-eff} = f(L, D_{uncr}) \tag{16}$$

Where: L (mm) is the respective crack depth; D_{uncr} is the chloride diffusion coefficient at uncracked location of concrete.

Experimental

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 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 volt for testing was 60 V. The duration time of testing was 10 hours. After testing STDT, the cubic specimens were split 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 crack tip.

Figure 7 shows the experimental results of the influence of crack depth on the chloride diffusion coefficient by STDT. The results also indicate 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 govern by effects of concrete proportions, typically, water-cement ratios. Because the chloride diffusion takes place in the crack and in the matrix of concrete, the different performances of matrix concrete govern by concrete proportions cause the varying chloride diffusion coefficient. Normally, a higher concrete performance will bring out a lower chloride diffusion coefficient (Suryavanshi et al. 2002). 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 diffusion coefficient of chloride, when the crack depth varies, is independent with 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:

$$D_{un-eff} = 0.58L * 10^{-12} + D_{uncr} \tag{17}$$

Where: L is respective crack depth (mm).

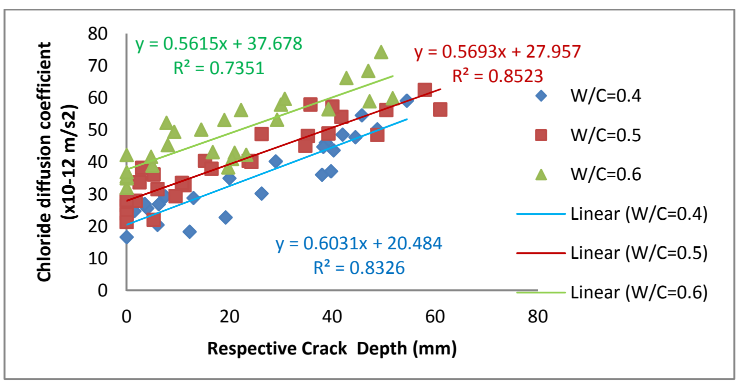

Figure 7. The influence of crack depth on the chloride diffusion coefficient

Testing the Chloride Profile at Uncrack Location and Crack Location. The back-to-back pair of reinforced concrete beams containing a single crack was immerged into salt solution of Nacl 10%. After immersion periods, 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. To verify the proposed model for predicting chloride profile at crack location, the concrete powder samples on crack location were obtained, they were then analyzed by the conventional chemical analysis (ASTM-C1152 1997). The concrete powder samples at uncrack location would be also collected to find out the apparent chloride diffusion coefficient at uncracked zone.

Verification for model

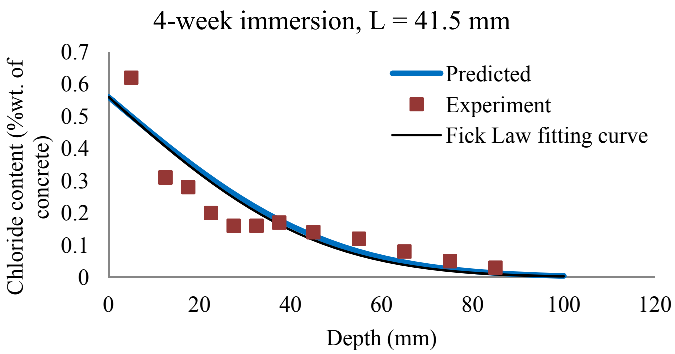

Figure 8. Comparison between predicted and experimental results (W/C = 0.6).

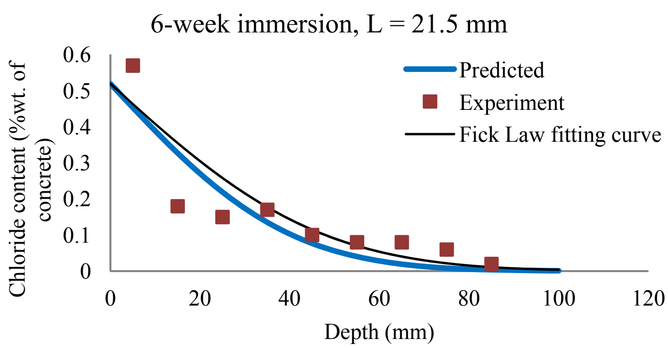

Figure 9. Comparison between predicted and experimental results (W/C = 0.4).

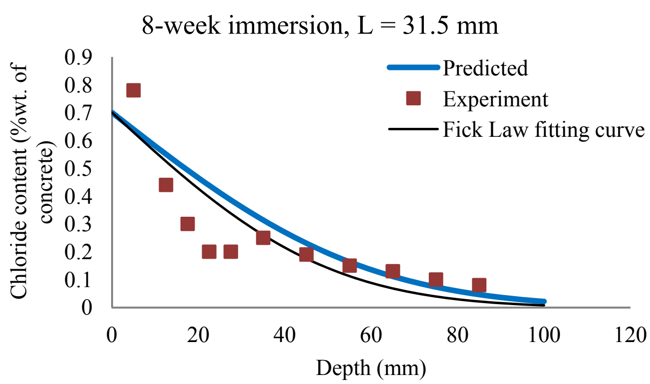

Figure 10. Comparison between predicted and experimental results (W/C = 0.5).

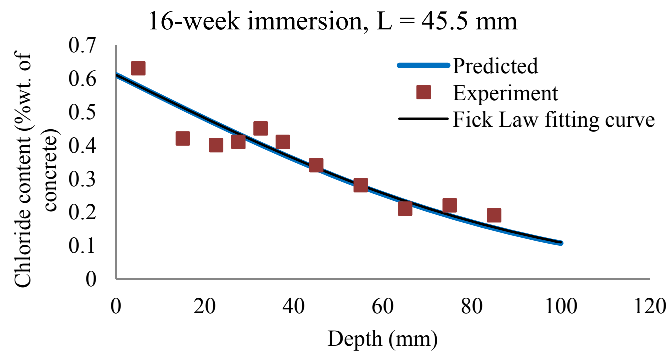

Figure 11. Comparison between predicted and experimental results (W/C =0.5).

By applying the Fick's Second Law, and the chloride diffusion coefficient at a crack location of reinforced concrete, equation (12), the chloride profile at crack location is calculated. Subsequently, the comparisons between the predicted and experimental results in the different immersion periods are shown in Figure 8 to Figure 11. The proposed model used the surface chloride concentration at crack location and average chloride diffusion coefficient (D_{av}) to predict the chloride profile at crack location of reinforced concrete. There is a good agreement between the experimental results and predicted results, since the immersion periods were larger than 4 weeks.

TWO DIMENSIONAL CHLORIDE DIFFUSIVITY MODEL OF CRACKED REINFORCED CONCRETE

The Model

In modelling two-dimensional chloride diffusion, equation (8) will be modified to become a given equation as follows:

$$\frac{\partial C_t}{\partial t} = D_a\left[\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right] \qquad (18)$$

Thus, it is very difficult and complicate to model or measure the chloride concentration, chloride diffusion coefficient inside and around crack because characteristics of crack are tortuous and roughness. Moreover, the chloride diffusion coefficient of cracked concrete varies continuously corresponding to crack width along the crack plane. Therefore, when a cracked concrete is immerged into salt solution, the mechanisms of chloride penetration are assumed, including moving mechanism of bulk salt solution in whole crack in an initial stage by capillary suction, then, a diffusion mechanism of chloride ions from exposed surface into the whole crack and uncracked concrete region takes place. This assumption will be investigated as a simple approach (Vu et al. 2012).

The movement mechanism of bulk salt solution. The movement mechanism of bulk salt solution is to transport the bulk salt solution from the exposed surface to inside whole crack by capillary suction. Then, this solution volume will present and occupy among the crack planes. To approach simply, the movement mechanism of bulk salt solution by capillary suction will be instead by an assumption that the salt solution always present in the whole crack as a boundary condition. Because the time for moving of bulk salt solution from the exposed surface through crack wall to crack tip is very short when comparing with the exposed duration of structures, the movement of bulk salt solution depended with time will be ignored. By this assumption, the moving mechanism of bulk salt solution at initial stage is replaced by the chloride surface content located along the crack plane as the boundary condition for the second dimensional diffusion. In this assumption, the chloride surface content located along the crack plane will be also assumed to be dependent to crack width:

- When the crack width is larger than 60 μm, the environment in whole crack can be considered as the environment on exposed surface. So, in this section, the chloride concentration depth, perpendicular to crack plane, could be assumed to equal the chloride concentration depth from exposed surface of un-cracked concrete (Figure 12). This assumption was also proved by (Win et al. 2004). It also means the surface chloride content at crack plane is similar to that at exposed surface.
- In addition, when the crack width reduces from 60 μm to zero along crack plane, the magnification of surface chloride content could be linearly reduced from chloride concentration on exposed surface to zero following equation below:

$$\begin{cases} C_s^y = C_s^x = C_s \ \text{when } w \geq 60\ \mu\text{m} \\ 0 \leq C_s^y < C_s \ \text{when } 0\ \mu\text{m} \leq w < 60\ \mu\text{m} \end{cases} \quad (19)$$

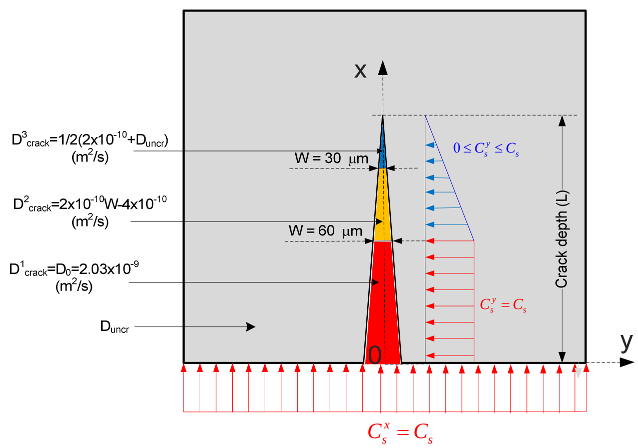

Figure 12. The concept of the 2D surface content and diffusion coefficient of chloride for cracked concrete

The diffusion mechanism of chloride ions into cracked concrete. After the movement of bulk chloride solution took place in whole crack, the diffusion mechanism for chloride ions through the crack would begin. In the diffusion mechanism, the chloride ions will be diffused into concrete member by diffusion mechanism due to higher chloride concentration of the exposed environment to lower that. It takes place at cracked concrete and matrix (un-cracked concrete) at the same time, and specified by the chloride diffusion coefficients.

The chloride diffusion through a crack of concrete was very complicated and depended on the crack width opening. The chloride diffusion coefficients of cracked concrete (D_{crack}) are assumed based on the lower and upper threshold values of crack width. In this assumption, the chloride ions will diffuse into concrete through whole crack having three zones divided by the lower and upper threshold values of crack width. In this research, the lower threshold value of crack width chosen is 30 μm and the upper threshold value of crack width chosen is 60 μm, Figure 12.

- In zone 1, from exposed surface to the crack width of 60 μm, the environment is considered as the environment on exposed surface and the diffusivity of chloride ions in crack is assumed as in bulk water. So, the chloride diffusion coefficient in this zone will equal the diffusion coefficient of ions in bulk water (D_0), approximately 2.03 x 10^{-9} (m^2/s) (Kato and Uomoto 2005; Sun et al. 2011).

$$D^1_{crack} = D_0 = 2.03 \times 10^{-9}\ (m^2/s) \tag{20}$$

- For zone 2, where the crack width reduce from 60 μm to 30 μm, the chloride diffusion coefficient is assumed to reduce linear with reduce in the crack width, expressed by equation below (Djerbi et al. 2008):

$$D^2_{crack} = 2E\text{-}11*W - 4E\text{-}10\ (m^2/s),\ \text{with } 30\mu m \le W < 60\mu m. \tag{21}$$

- With the zone 3, where the crack width reduce from 30 μm to crack tip ($0\mu m \le W < 30\mu m$). In previous researches, the influence of crack on the chloride diffusion phenomenon can be ignored; it means the chloride diffusion coefficient in this zone will equal that in uncracked concrete. In fact, the chloride diffusion coefficient must reduce linear from D^2_{crack} (at crack with (W) = 30 μm) to the chloride diffusion coefficient of un-crack concrete (D_{uncr}). However to simply calculate, it is calculated as the average of D^2_{crack} (at W = 30 μm) and D_{uncr}.

$$D^3_{crack} = (2E\text{-}11*30 - 4E\text{-}10 + D_{uncr})/2 = (2E\text{-}10 + D_{uncr})/2\ (m^2/s). \tag{22}$$

Conclusively, in this research the initial and boundary conditions for the chloride penetration into cracked reinforced concrete is applied as follow:

$$\begin{cases} \dfrac{\partial C_t}{\partial t} = D_a \left[\dfrac{\partial^2 C}{\partial x^2} + \dfrac{\partial^2 C}{\partial y^2} \right] & x > 0,\ t > 0, \\ C(0, 0 \le y < L, 0) = C_s & \text{L: crack depth} \\ C(x, y, 0) = 0 & x > 0,\ y > 0. \end{cases}$$

Numerical analysis by ANSYS program

The equation describing the two dimensional diffusivity of chloride ions has the form being similar to the thermal equation. In order to derive this equation, the ANSYS program based on the finite element method is employed. By using thermal module of ANSYS program, the input data include the chloride diffusion coefficient of cracked and uncracked concrete, the chloride surface content of uncracked concrete, and crack characteristics. In ANSYS program, the analysis type of transience is chosen to calculate the chloride concentration at a given point in the medium with time dependent. The solid 2D - 4 node liner element was chosen to mesh the model. With the size of 100 mm for beam model, the element size of 1mm was chosen to modelling.

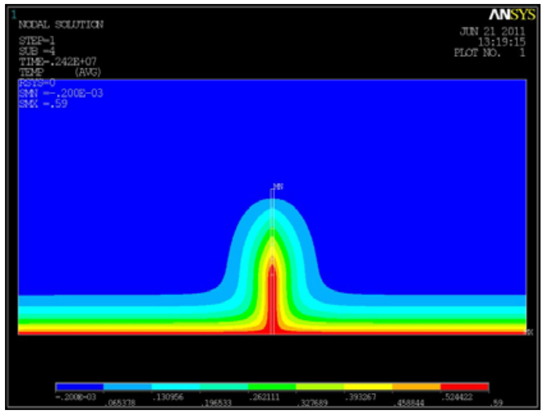

Figure 13. The 2D chloride diffusivity model of cracked concrete beam 1

In this model, the boundary conditions of exposed surfaces will be attributed by the surface chloride content. The experimental diffusion coefficient at uncracked location is used for two -dimensional analysis of chloride penetration using finite element formulation from ANSYS program. The crack plane is treated as an exposed surface having the surface chloride content is a function of crack width varying along crack plane, while chloride concentration at the exposed surface is assumed constant. A typical analytical computation result is illustrated in Figure 13.

Verification for proposed 2D model

It is very difficult to validate the two dimensional diffusivity of chloride by the complication of preparing and comparing with the experimental results. Furthermore, because the distributions of chloride concentration around the crack are extremely complicate, these are a lack for finding a method to determine the chloride concentration around the crack plane. In this research, an experimental program is proposed for determining chloride concentration distribution in cracked concrete. These experimental results will be used to compare with the predicted results for validating the proposed model. The concrete powder samples were collected at locations close to crack plane of cracked beams. On each cracked reinforced concrete beams, drilled holes for collecting concrete powder have the different distances from the crack plane. Then, the conventional chemical analysis method (ASTM-C1152 1997) was employed to find out the total chloride content at interval depth in each concrete samples.

The predicted results of chloride content were extracted from model of ANSYS program. The advantage of ANSYS program is able to plot the magnitude of chloride content of computation model at any wanted points. Then, these predicted results of chloride content are compared with the experimental results of that of concrete powder samples around the crack plane. They are expressed in figures below:

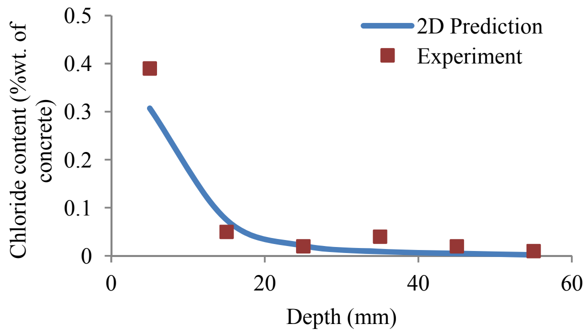

Figure 14. The predicted and experimental results at 30mm away from crack plane

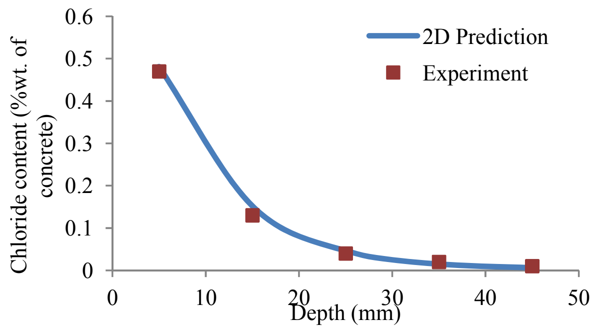

Figure 15. The predicted and experimental results at 41mm away from crack plane.

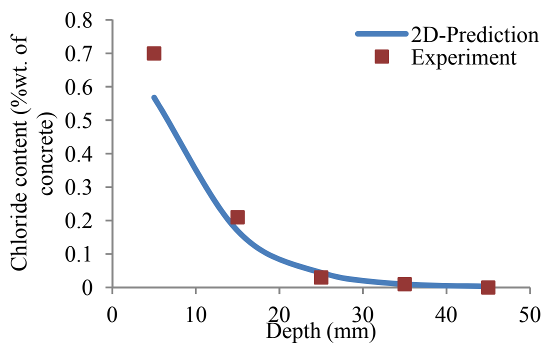

Figure 16. The predicted and experimental results at 50mm away from crack plane.

By applying the proposed 2D chloride diffusivity model, the experiment results of the surface chloride content (Cs) at the uncrack location, chloride diffusion coefficient of uncrack concrete and the crack characteristics, the distribution of chloride content around the crack plane of reinforced concrete could be predicted. Regarding figures above, it could be recognized that both the experiment results and predicted results show the chloride content corresponding to the depth of concrete were reducing from exposed surface to inner concrete. In addition, the experiment results and predicted results of chloride content fit well for most cases. Their deviations are accepted although the errors could be obtained by the influence of crack tortuosity. From the verify program and comparison with the experiment results, the reliability of the proposed model could be accepted because of the tortuosity, unity, straight of crack plane that can influence on accuracy of the experimental results at compared locations.

CONCLUSIONS

1. A model for the calculation of the chloride diffusion coefficient at cracked reinforced concrete beams was proposed. In this model, the chloride diffusion coefficient at crack was updated from the chloride diffusion coefficient of uncrack concrete and was described as a function of the crack width and crack depth. Applying the proposed model of chloride diffusion coefficient, a model for chloride diffusion at crack location of reinforced concrete under marine environment was also proposed base on the basic of Fick's Second Law. An experiment program was prepared to verify the proposed model. The predicted results of chloride profile fitted very well with the experimental results.
2. With another view, the chloride diffusion into cracked reinforced concrete was recognized following two-dimensional (2D) diffusivity. Therefore, a model of 2D chloride diffusion into cracked reinforced concrete was proposed and was analyzed by ANSYS program. This model assumed the crack plane acted as the second exposed surface in addition to tension surface. Two new experiments were also conducted to observe the chloride diffusion through a crack of reinforced concrete under flexural loading. In the first experiment, the chloride profiles were obtained by conventionally chemical analysis. The analytical results of model fitted well to experimental results.
3. In most cases, cracks are not able to reduce the load carry capacity of reinforced concrete or cause collapse of reinforced concrete because of the small crack width, less than maximum threshold crack width or crack residue upon elastic stage. However, the cracks may unprofitably effect on the durability and damage of reinforced concrete structure by providing the free access for movements of chloride ions from marine environment.
4. The benefits of research is providing the models, which can be used to predict the chloride threshold induced corrosion of the reinforced concrete, evaluate the durability of concrete structure or the service life of reinforced concrete structure when chloride ions attack via cracks of reinforced concrete.

REFERENCES

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

Djerbi, A., S. Bonnet, A. Khelidj and V. Baroghel-bouny (2008). "Influence of traversing crack on chloride diffusion into concrete." *Cement and Concrete Research*, 38(7.

Gérard, B. and J. Marchand (2000). "Influence of cracking on the diffusion properties of cement-based materials: Part I: Influence of continuous cracks on the steady-state regime." *Cement and Concrete Research*, 30(1), 37-43.

Ismail, M., A. Toumi, R. Francois and R. Gagne (2004). "Effect of crack opening on the local diffusion of chloride in inert materials." *Cement and Concrete Research* 34 (4), 711-716.

Ismail, M., A. Toumi, R. François and R. Gagné (2008). "Effect of crack opening on the local diffusion of chloride in cracked mortar samples." *Cement and Concrete Research*, 38(8-9), 1106-1111.
Kato, E., Y. Kato and T. Uomoto (2005). "Development of Simulation Model of Chloride Ion Transportation in Cracked Concrete." *Journal of Advanced Concrete Technology*, 3(1), 85-94.
Lim, C. C., N. Gowripalan and V. Sirivivatnanon (2000). "Microcracking and chloride permeability of concrete under uniaxial compression." *Cement & Concrete Composites*, 22(5), 353-360.
Mien, T. V., B. Stitmannaithum and T. Nawa (2009). "Simulation of chloride penetration into concrete structures subjected to both cyclic flexural loads and tidal effects." *Computers and Concrete*, 6(5), 15.
Northtest-NTBuild-492, *Chloride Migration Coefficient from Non-steady-state Migration Experiments*, 1999.
Sugiyama, T., W. Ritthichauy and Y. Tsuji (2003). "Simultaneous transport of chloride and calcium ions in hydrated cement systems." *Journal of Advanced Concrete Technology*, 1(2), 127-138.
Sugiyama, T., W. Ritthichauy and Y. Tsuji (2008b). "Experimental investigation and numerical modeling of chloride penetration and calcium dissolution in saturated concrete." *Cement and Concrete Research*, 38(1), 49-67.
Sun, G., Y. Zhang, W. Sun, Z. Liu and C. Wang (2011). "Multi-scale prediction of the effective chloride diffusion coefficient of concrete." *Construction and Building Materials*, 25(10), 3820-3831.
Suryavanshi, A. K., R. N. Swamy and G. E. Cardew (2002). "Estimation of Diffusion Coefficients for Chloride Ion Penetration into Structural Concrete." *ACI Materials Journal*, 99(5), 441-449.
Takewaka, K., T. Yamaguchi and S. Maeda (2003). "Simulation Model for Deterioration of Concrete Structures due to Chloride Attack." *Journal of Advanced Concrete Technology*, 1(2), 139-146.
Vu, H. Q., B. Stitmannaithum and S. Takafumi, (2011), "Experimental Study on Chloride Penetration Depth of Cracked Concrete", In: S. R. Lee, L. J. Leu, S. T. Quek, W. Teparaksa and H. Shirato, editors, *The Twenty-Fourth KKCNN Symposium on Civil Engineering*, Hyogo, Japan, pp. 269-272.
Vu, H. Q., B. Stitmannaithum and S. Takafumi, (2012), " Experimental and Numerical Study on Two-Dimensional Chloride Diffusivity in Cracked Reinforced Concrete ", In: editors, *The 5th International Conference of Asian Concrete Federation*, Thailand.
Wang, L. and T. Ueda, (2010), "Nummerical determination of the chloride difusion coefficient in cracks and cracked concrete", In: H. Yokota, T. Sugiyama and T. Ueda, editors, *The 2nd International Conference on Durability of Concrete Structures ICDCS2010*, Sapporo, Japan, Hokkaido University Press.
Win, P. P., M. Watanabe and A. Machida (2004). "Penetration profile of chloride ion in cracked reinforced concrete." *Cement and Concrete Research*, 34(7), 1073-1079.