

Scientific paper

Mesoscale Modelling of the Chloride Diffusion in Cracks and Cracked Concrete

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Received 19 May 2011, accepted 27 September 2011

Abstract

In service, cracks or microcracks are usually present in concrete as a result of several mechanisms, for example the drying shrinkage, thermal gradients, freezing-thawing cycles, alkali-aggregate reaction and external loading. It has been realized that cracking can significantly accelerate the ingress of chlorides into concrete since it provides preferential flow channels and allow more chlorides to penetrate. But it is also believed that cracking plays an important role on the penetration speed of chloride. The objective of this paper is to quantify the diffusion coefficient of chloride through cracks of concrete with different crack widths by means of the mesoscale modelling method based on the available experimental results from literatures. In the numerical models, the position and opening width of cracks are artificially prescribed based on geometrical layout of the samples used in test. Additionally, the Voronoi diagram technique is adopted to discrete the domain of a specimen in order to reduce the mesh bias. On the Voronoi diagram, a randomly distributed lattice network is constructed to represent the transport process of chlorides. The range of investigated crack width is from 20 to 600 μm covering the data in experimental program. The diffusion coefficients of chloride through cracks of different width, D_{cr} , are numerically determined by the trial and error method. It is concluded that chloride can penetrate into cracks with a much higher speed than that in free water. When the crack width is larger than a critical value, D_{cr} is determined as 10000 mm^2/h and independent of the crack width.

1. Introduction

Chloride-induced corrosion of steel reinforcement is one of the major deterioration mechanisms of reinforced concrete structures when they are exposed to the environment of seawater or de-icing salt. This is widely considered as the driving force in the past few decades that caused the growing interest in attempting to investigate the chloride movement within concrete. In addition, cracks or microcracks are usually present in concrete, as a result of the mechanical or environmental actions, or commonly of their combinations. Recent studies have indicated that cracks can significantly accelerate the diffusion speed of chlorides in concrete because it can provide additional flow channels and allow more chlorides to penetrate. As a result, there is no doubt that cracking of concrete can greatly affect the durability of reinforced concrete structures (Djerbi *et al.* 2008). Thereafter, it seems very important to investigate the effect of cracking on the transport property of chlorides in concrete in order to allow more accurate prediction of durability and service life of concrete structures (Wang and Ueda 2009a; Wang *et al.* 2008; Kato *et al.* 2005).

Unfortunately, the characteristics of chlorides penetration in cracked concrete, especially moving through an individual crack of various crack widths, have not yet been made clear and there are still much work to be done to give a quantitative representation of the chloride transport.

In the past, most previous works focused on experimental methods to evaluate the effect of cracking on the chloride diffusion property of concrete, as well as the diffusion features of chlorides in a single crack (Aldea *et al.* 1999; Samaha and Hover 1992; Gowripalan *et al.* 2000; Ismail *et al.* 2004, 2008; Rodriguez and Hooton 2003; Kim *et al.* 2010). In the tests, cracks were created naturally by loading a specimen or artificially formatted by cutting the specimen. For example, using the feedback controlled splitting test method. Wang *et al.* (1997) induced the single crack on a specimen and measured the permeability through the crack. It was reported that the permeability of cracked concrete depends on the value of the crack opening (or crack width), w_{cr} , in the concrete. But when a crack opening displacement was less than 50 μm , the crack opening had little effect on the permeability. When the crack opening displacement was increased from 50 to 200 μm , the cracked concrete permeability increased rapidly with a great magnitude in comparison with that corresponding uncracked concrete.

Chloride diffusion coefficients through cracks of concrete, D_{cr} , were evaluated using a steady-state migration test (Djerbi *et al.* 2008), in which the cracks were also generated by controlled splitting tests. It was pointed out that the maximum diffusion rate of chloride in a single crack approximated that diffusing in free bulk water

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(about 10^{-9} m²/s) when the crack width was 80 μ m or more. Based on the similar test method, Kato *et al.* (2005) concluded that D_{cr} increased with increases in the crack width and was almost constant when the crack width became wider than approximately 75 μ m, but this constant diffusion coefficient was in a range of 10^{-7} ~ 10^{-6} m²/s, which was about 10^2 ~ 10^3 times higher than that in free water. In the simulation model of Takewaka *et al.* (2003), if w_{cr} is less than 50 μ m, the cracks seldom affect diffusivity, but when w_{cr} is between 50 μ m and 100 μ m, D_{cr} was set 10 times of the sound part, and when w_{cr} is larger than 100 μ m, D_{cr} was set as 10^3 times of that of the sound part. Ismail *et al.* (2004; 2008), and Rodriguez and Hooton (2003) separately examined the penetration property of chlorides through an artificially formed crack, as well as the diffusion speed perpendicular to the crack surface. Their test results indicated that the rate of chloride penetration perpendicular to the crack surface was very similar to that from the exposed surface when w_{cr} was larger than the critical crack width. The critical crack width is considered as a material property and generally in a range of 50-80 μ m according to different tested materials and test methods, whose crack surfaces are completely separated and no stress can be transferred any longer (Ismail *et al.* 2004). This finding can be understood that chlorides penetrate through the crack with a very high rate, even faster than that in free bulk water when crack width is greater than the critical value. Because in the experimental study, the samples were saturated with lime water (Ismail *et al.* 2004; Rodriguez and Hooton 2003), cracks are approximately considered to be fully filled by water before exposed to chloride solution, and subsequently the chlorides move in water-filled cracks. During this testing procedure, the capillary mechanism induced by surface tension of thin pores or

microcracks can be neglected. Therefore, Ishida *et al.* (2009) stated that mass transport in the crack spaces is driven not only by concentration gradient of ions, but also by convection current due to the small temperature gradient and/or small hydraulic pressure gradient. In their analysis method, a single crack or multiple cracks are converted into a group of voids and the diffusion coefficient of chloride ions in the voids (converted from the cracks), is set to a value of fifty times larger than the value in free water.

From the review of previous studies, it can be found that the results differ too much, even up to a magnitude of 2nd to 4th power of 10. Therefore, the objective of current research is to quantify the diffusion coefficient of chloride through a single crack by numerical simulation method in terms of the mesoscale composite structure of concrete.

2 Lattice network model

2.1 Construction of the model

It has been proposed that on the mesoscale level, mass transport in concrete can be described by means of lattice-type model, which is a discrete numerical method and has the advantage of mesh-independence and accurate descriptions of basic properties of the continuum response (Sadouki and Van Mier 1997; Grassl 2009). Only an overview of the lattice network approach for modelling mass transport in concrete is given here. Additional details, such as those related to mesoscopic composite structure of concrete, Voronoi element construction and lattice element meshing method have been reported by Wang *et al.* (2008) and Wang and Ueda (2011).

As shown in Fig. 1, in the lattice network model, a

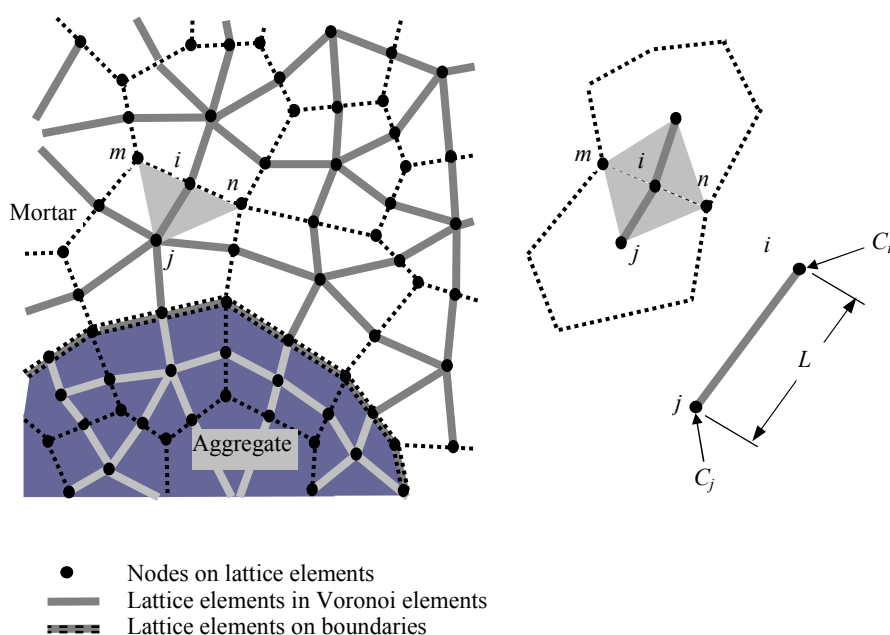


Fig. 1 Construction of the lattice network model.

continuous area is represented by a discrete lattice element. Each lattice element has its own cross-sectional area and diffusivity. For example, the diffusion area of Δjmn is represented by the one-dimensional lattice element ij with the length of L . As illustrated in **Fig. 1**, since the lattice element ij falls in the mortar cell, its diffusivity will be taken the value of that of mortar. In other words, the chloride penetrating across the area of Δjmn will be mathematically considered along the uni-directional lattice element ij as like through a “pipe”. Thus, for a one-dimensional nonstationary flow problem like that expressed by the Fick’s second law, the discrete form of the governing equation can be formulated by using the Galerkin method as follows:

$$AD \begin{Bmatrix} \frac{\partial C}{\partial x} \Big|_{x=x_i} \\ \frac{\partial C}{\partial x} \Big|_{x=x_j} \end{Bmatrix} + \frac{AD}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} C_i \\ C_j \end{Bmatrix} + \frac{1}{\omega} \frac{AL}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{Bmatrix} \frac{\partial C_i}{\partial t} \\ \frac{\partial C_j}{\partial t} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (1)$$

in which A and L are the area and length of the lattice element; C_i and C_j are the chloride concentration at the nodes i and j , respectively; D is the diffusivity of the corresponding material of the lattice element, i.e. mortar D_m , coarse aggregate D_a , and the interfacial transition zone (ITZ) D_{ITZ} ; ω is a parameter to account for the dimension conversion and is set as 2.0 for a two dimensional lattice element arrangement (Nakamura *et al.* 2006).

After introducing the discrete time increment Δt , the finite difference equation in time about Eq. (1) can be formed by a step-by-step procedure with the Crank-Nicholson finite-difference algorithm. Given the initial state of all lattice elements in a specimen, a system of equations is set up at each time step, and then solved for the new nodal potential values (Wang and Ueda 2009b).

2.2 Application and verification of the model

In order to verify the applicability and precision of the lattice network model in simulating chloride penetration in concrete, a pure diffusion process described by Fick’s second law is adopted herein because its analytical solution is available and usually written by an error function as:

$$C(x,t) = C_s \left(1 - \operatorname{erf} \left(\frac{x}{\sqrt{4D_c t}} \right) \right) \quad (2)$$

where $C(x,t)$ is the concentration of chlorides at distance x and time t ; C_s is the concentration of chlorides at $x=0$, $t>0$, i.e. the chloride surface concentration; D_c is the diffusion coefficient of concrete as a homogenous material; $\operatorname{erf}(\cdot)$ is the error function. The concrete model and its Voronoi diagram are shown in **Fig. 2**, in which the volume ratio of coarse aggregate is about 40%. On the diffusion boundary of exposed surface (top surface of the

sample in **Fig. 2**), the chloride concentration C_s is assumed as $4.86 \times 10^{-3} \text{ g/cm}^3$ unchangeably during the analysis, and the initial chloride content in the sample is assumed as 0. The diffusion coefficients of mortar D_m , and concrete D_c , have been determined as $2.392 \times 10^{-2} \text{ mm}^2/\text{h}$ and $1.971 \times 10^{-2} \text{ mm}^2/\text{h}$ for a certain mixture, respectively (Oh and Jang 2004). In addition, the coarse aggregate is assumed to be non-diffusible, i.e., the diffusion coefficient of lattice elements falling in aggregate is set as 0. It has been revealed that D_{ITZ} can be taken as 10 times of that of the mortar (Wang *et al.* 2008). The average chloride profiles along three lines as shown in **Fig. 2** are determined as the numerical results. **Figure 3** presents the chloride profiles after 200 days diffusion for both numerical and analytical solution. The good agreement proves that the lattice network model can be used to predict the chloride profiles in concrete.

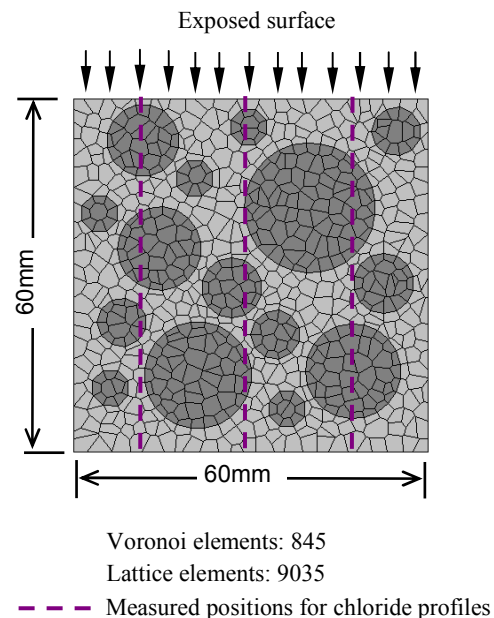


Fig. 2 The Voronoi model and analysis conditions of the specimen.

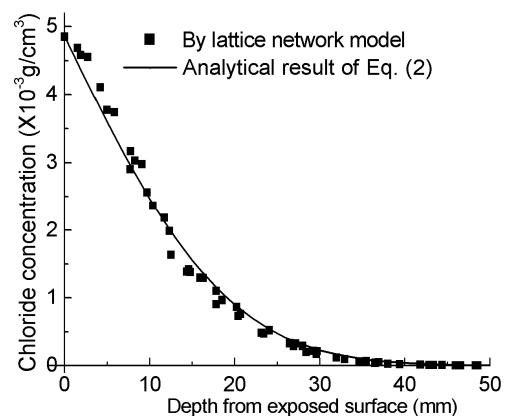


Fig. 3 Comparison of chloride profiles between numerical and analytical results.

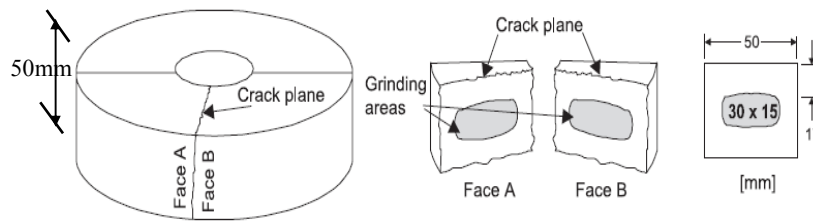


Fig. 4 Schematic illustration of the specimen used in test (Ismail *et al.* 2004).

3. Diffusion coefficient in single crack (D_{cr})

3.1 Brick specimen

The shape and size of specimen used in the test by Ismail *et al.* (2004) are shown in Fig. 4. In this experiment, in order to avoid the self-healing of cement-based material on local chloride penetration of the cracked sample, an inert material, i.e. brick, was used. The controlled cracking was achieved by adjusting the deformation of an expansive core and the confining force applied by the external steel ring. Because the crack width is not ideally consistent along the crack path, even on the top and bottom annular surfaces, its value of each sample is calculated by averaging 20 measurements taken on top and bottom surfaces separately. By this method, the obtained crack widths in experiment are 128, 60, 53, 34, and 21 μm . After reaching the required crack width, the specimen was firstly saturated with demineralized water and then moved to the chloride penetration cell to perform the chloride diffusion test. The top and bottom surfaces are left to be exposed to chloride solution but the cylinder side surface is sealed. As a result, the chloride penetration profiles, measured both from the sample surface and perpendicular to crack path, were synthetically used to evaluate the penetrating rate of chloride through the crack. The perpendicular-to-crack profiles were determined by vertically grinding the areas measuring 30×15 mm downward the crack surface, located in the center of the crack plane 17 mm below the exposed surface. One of a vertical plane perpendicular to the crack path is chosen to simulate the two-dimensional transport of chlorides: along or parallel to the crack pathway and perpendicular to the crack surface. The horizontal depth of this plane is set as 50 mm in the numerical simulation, in other words, the circumferential length to crack surface is 25 mm because the maximum depth of penetration is less than 15mm from test observation. The Voronoi diagram for this cracked surface is shown in Fig. 5 with 451 Voronoi elements and 5046 lattice elements (but for sake of clearness, the lattice elements are not depicted). In addition, the crack width along crack depth is set as constant of the value in test, which is the ideal approximation of Fig. 4. The diffusion coefficient of the brick D and the surface chloride concentration C_s are calculated as $0.396 \text{ mm}^2/\text{h}$ and $7.68 \times 10^{-3} \text{ g/cm}^3$ respectively, by means of the least square method with test data. The exposed time in the

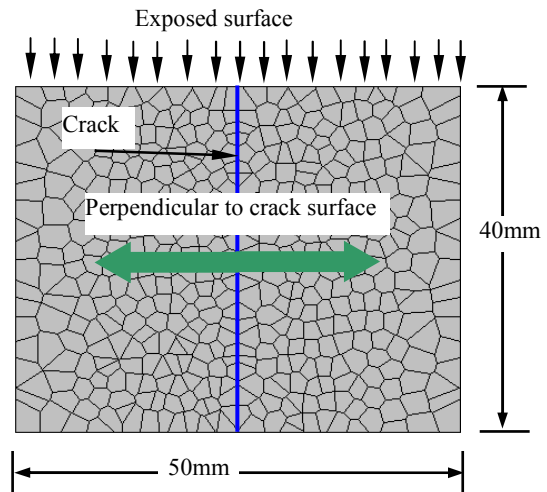


Fig. 5 Numerical model of the specimen in two dimensions.

experiment and current simulation is $T=10$ h. The initial chloride content is 0.01% weight of brick supplied by the material constituents, i.e. about $0.2 \times 10^{-3} \text{ g/cm}^3$ of volumetric content.

From Eq. (1), it is supposed that the incrementing time Δt may have an effect on the calculation results. Therefore, to investigate the sensitivity of chloride profiles on Δt , a series of time incrementing steps, i.e., $\Delta t=0.01$ h, 0.001 h, 0.0001 h and 0.00001 h are selected to find their effect on the chloride diffusion speed along the crack pathway. Figure 6 shows the calculated results under this series of time steps. It can be seen that when the time increments are smaller than 0.0001 h, the chloride profiles will become very close. Thus, in the following analysis, the time increment will be set as 0.0001 h in order to reduce computing time but to obtain a relatively sufficient precision.

As pointed out by Ismail *et al.* (2004), the rate of chloride penetration perpendicular to crack walls is not restricted by the liquid-phase diffusion of chloride along the crack path. As well known, the diffusion coefficient of chloride ions in free bulk water is about $2.032 \times 10^{-9} \text{ m}^2/\text{s}$ ($7.315 \text{ mm}^2/\text{h}$) at 25°C (Oh and Jang 2004). Therefore, firstly the diffusion coefficient of chloride in cracks larger than $60 \mu\text{m}$ is arbitrarily taken this value. Based on these conditions, the total chloride penetration profiles from the exposed surface obtained both from test and

numerical analysis are shown in Fig. 7. The chloride profiles from the freely exposed surface (top surface) of numerical result by the model in Fig. 5 are taken along a vertical line which is about 15 mm away from the crack to guarantee a one-dimensional diffusion. The profiles predicted by the numerical model are in close agreement with test results, which indicates that the diffusion coefficient of bulk brick is acceptably reasonable.

As the first step of cracking effect analysis, the nominal diffusion coefficient of chlorides through cracks, D_{cr} , will be taken the value in free water to compare with test results. However, as depicted in Fig. 8, the profiles of perpendicular-to-crack penetration obtained from test and numerical analysis deviate each other to a large degree. The location of the chloride penetration profile in the numerical analysis is about 25 mm deep from the exposed surface. This value is regarded as the average depth of the grinding areas as shown in Fig. 4. It suggests that, in the analysis when the chloride diffusion coefficient along crack (width $w_{cr} > 60 \mu\text{m}$) is assumed to be the value in bulk water, the diffusion rate of chlorides perpendicular to crack wall surface is much slower than that obtained by test method. Such a result can be understood that chlorides transport faster through crack than that in free water during the test process. This phenomenon implies that the process of chloride moving along cracks may involve more than one transport mechanisms but not only diffusion. Therefore, determining the real value of D_{cr} becomes a crucial task in order to accurately predict chloride profiles in cracked building materials.

3.2 Determination of D_{cr} at different crack widths

In this paper, D_{cr} denotes the nominal chloride diffusion coefficient through a single crack because as stated above, chloride moving into a crack is not a typical diffusion process. The value of D_{cr} will be obtained in this paper by the trial and error method so as to approach the test results. As indicated previously, D_{cr} is dependent on the crack width. Thereafter, higher values of D_{cr} will be given for larger cracks. Figure 9 shows the comparisons between calculated profiles of chlorides perpendicular to the crack wall at the depth of 25mm for different w_{cr} and experimental data. At the depth of 25 mm, there are only chlorides penetrating horizontally (one dimension) to reach this location because the maximum diffusion depth of chlorides from top surface is less than 10mm (see Fig. 7). It can be observed that when the crack width is larger than a threshold, e.g., about $60 \mu\text{m}$, D_{cr} is independent of the crack width and may be given a big value as $10000 \text{ mm}^2/\text{h}$. Although an obvious decrease of the value of D_{cr} can be noted when the crack width is less than $60 \mu\text{m}$, the relationship between D_{cr} and the crack width is not clearly accordant. This may be attributed to the limited test data. As a result, currently it is not possible to accurately estimate the value of D_{cr} depending on the crack width when the opening is less than a threshold. Therefore, a unique value of D_{cr} for crack width below $60 \mu\text{m}$ is

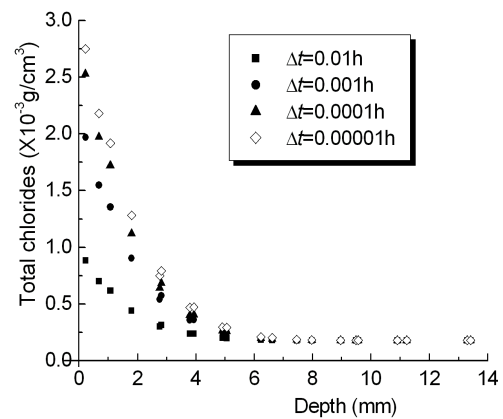


Fig. 6 Effect of time increment on chloride profiles perpendicular to the crack wall ($D_{cr}=10000 \text{ mm}^2/\text{h}$, $T=10 \text{ h}$).

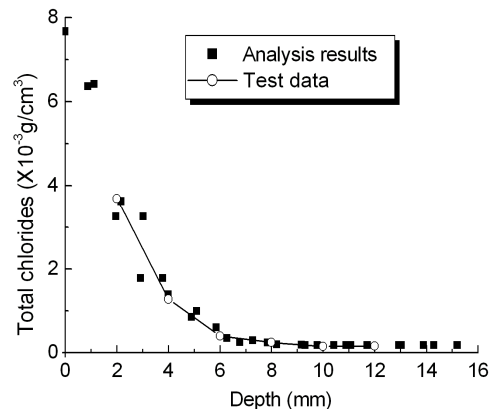


Fig. 7 Profiles of the sample from the exposed surface.

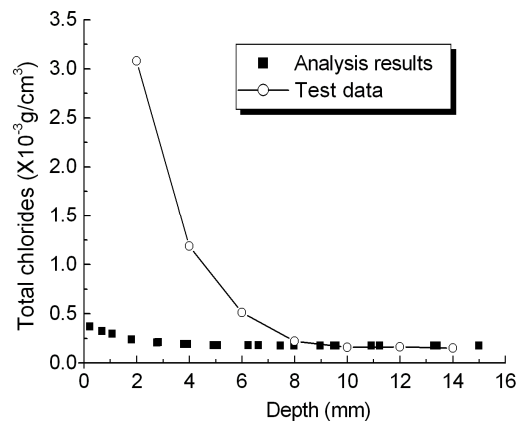


Fig. 8 Profiles perpendicular to crack wall surface.

determined based on the three values of D_{cr} obtained at $53 \mu\text{m}$, $34 \mu\text{m}$ and $21 \mu\text{m}$, respectively, i.e., 3000 , 1500 , $4500 \text{ mm}^2/\text{h}$. Their mean value is $3000 \text{ mm}^2/\text{h}$.

4. Chloride diffusion in cracked concrete

4.1 Diffusion of uncracked concrete

Based on the test results (Rodriguez and Hooton 2003),

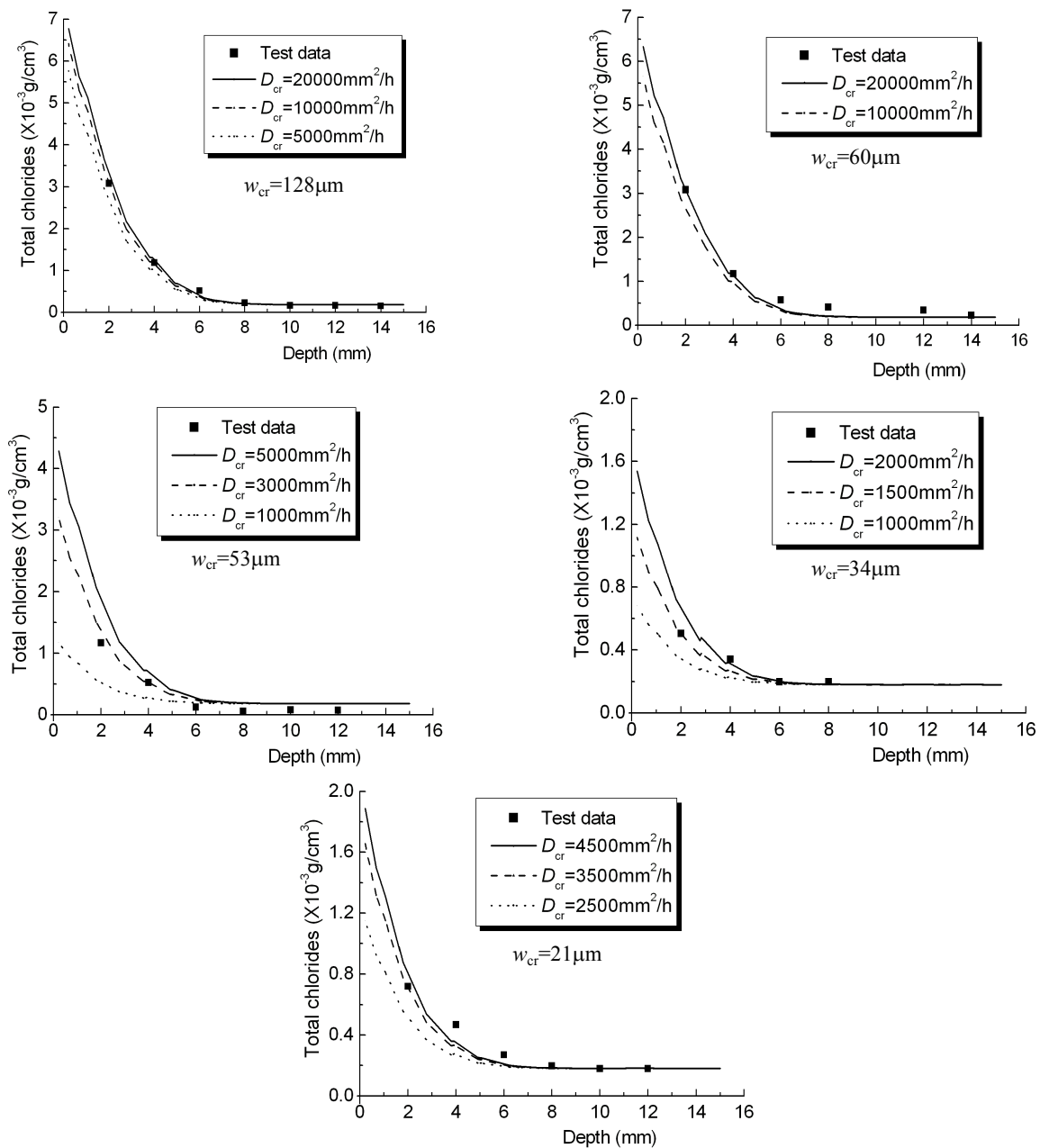


Fig. 9 Profiles perpendicular to crack surface with different D_{cr} at different w_{cr} .

the average values of diffusion coefficient and chloride surface concentration for uncracked concrete have been respectively estimated as $3.11 \times 10^{-2} \text{ mm}^2/\text{h}$ and 0.77% by weight of concrete (0.185 g/cm^3). The numerical simulation specimen has the similar coarse aggregate contents (about 40% volume fraction). The exposed time is 40 days. The numerical model for uncracked concrete specimen is given in **Fig. 10** with 537 Voronoi elements and 5674 lattice network elements (for sake of clearness, the lattice elements are not depicted).

Figure 11 shows the schematic comparison of depth of chloride penetration between test observation and computing result. The black curve in **Fig. 11a)** and white curve in **Fig. 11b)** indicate the penetration front of chlo-

rides by experimental method and numerical simulation respectively. It is clearly found that the effect of aggregate inclusions can be successfully expressed by the numerical simulation since it gives a similar chloride penetration profile with the test observation. The coarse aggregates, especially those with relatively larger size can, to some extent, restraint the ingress rate of chlorides due to their lower permeability. On the other hand, the presence of porous and connected ITZ, which is a very thin boundary layer around the aggregate with higher porosity than mortars, will contribute to facilitating the movement of chlorides. The effect of ITZ usually plays a stronger role than that of the aggregates. This opposite impacting mechanism can be used to explain the statistic

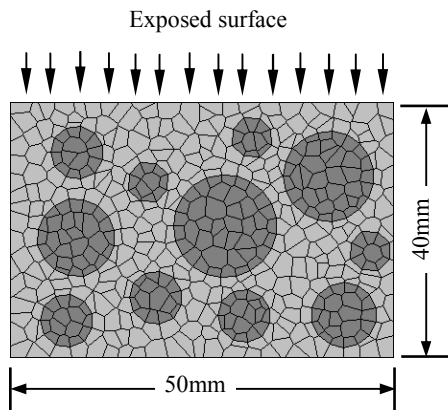


Fig. 10 Numerical model of the uncracked concrete.

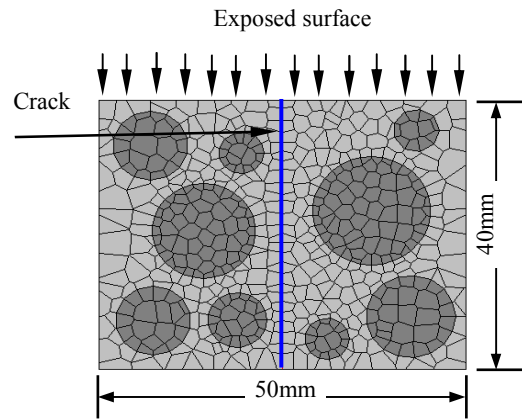
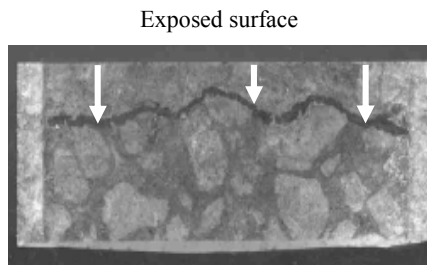
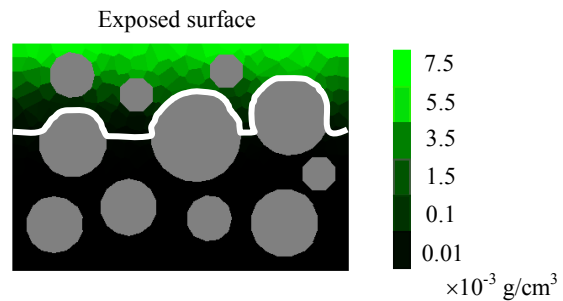


Fig. 12 Element meshing result of the concrete specimen.



a) Photo scan of the test specimen (Rodriguez and Hooton 2003)



b) Numerical analysis results

Fig. 11 Depth of chloride penetration in uncracked concrete specimens.

finding that concrete usually has higher diffusion coefficient than that of mortar (Wang *et al.* 2008).

4.2 Chloride diffusion in cracked concrete

In Rodriguez and Hooton (2003), a transecting, parallel-wall crack with approximately constant width was induced in the sample by means of splitting tensile method. The characteristic (crack shape and surface feature) of the crack is supposed to be similar as that created by Ismail *et al.* (2004). But in Rodriguez and Hooton (2003), the range of crack width is from 80 μm to 680 μm . In the present study, with purpose of verifying the magnitude of D_{cr} obtained above, one case in their test with crack width of 90 μm is selected and the D_{cr} is set as 10000 mm^2/h ($2.8 \times 10^{-6} \text{ m}^2/\text{s}$) based on the above analysis. The specimen after being numerically meshed is shown in Fig. 12 by arranging the crack in the middle of the sample. The exposed time is same as that of the uncracked specimen, i.e. 40 days.

Both the chloride diffusion along depth of the specimen and vertical to the crack wall surface are considered and compared to investigate whether the chloride diffusion is dependent on the crack or not. The chloride profiles on these two directions are presented in Fig. 13 and schematically shown in Fig. 14. Specimen in Fig. 14a) represents two different penetration processes separated by the crack. The left hand part of the cracked sample

was sealed on the top surface and only exposed to lateral diffusion of chlorides from the surface of crack into concrete, which can be treated as a one-dimensional process. However the profiles for right half sample, particularly its top part was the result of a two-dimensional diffusion since its exposed surface was not sealed. The profiles along depth of the specimen and vertical to the crack surface are taken from locations about 15 mm away from the crack and 25mm depth from the exposed surface respectively in order to reduce the influence of two-dimensional diffusion. It can be seen from Fig. 13 that the two chloride profiles are quite close to each other, leading to the conclusion that the lateral diffusion of chlorides from the crack surface into the bulk concrete is uniform along the crack pathway. This conclusion agrees well with the test results that the transecting, parallel-wall cracks with width larger than the critical value behave like free concrete surfaces exposed to chloride solution because the diffusion coefficients of concrete measured along the perpendicular direction to crack surface are similar to those of uncracked concrete (Rodriguez and Hooton, 2003). In addition, the chloride profile obtained by Ishida *et al.* (2009) for a cracked concrete by modeling analysis is shown in Fig. 14 too, which has the quite similar tendency with this paper's finding although their model was based on a smeared crack concept but not a discrete element method. In Ishida *et*

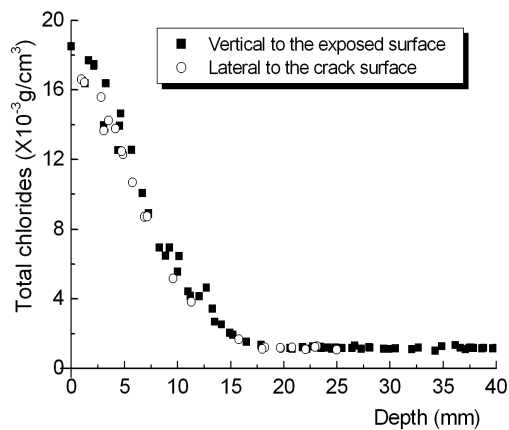


Fig. 13 Chloride profiles along depth of the specimen and vertical to the crack surface.

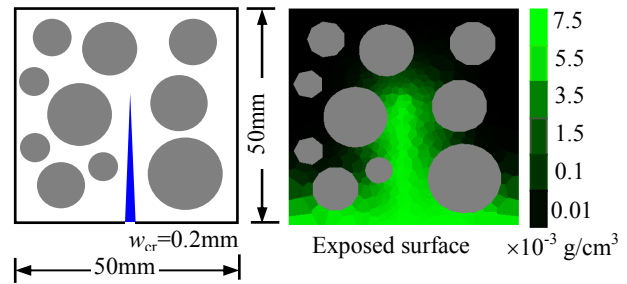
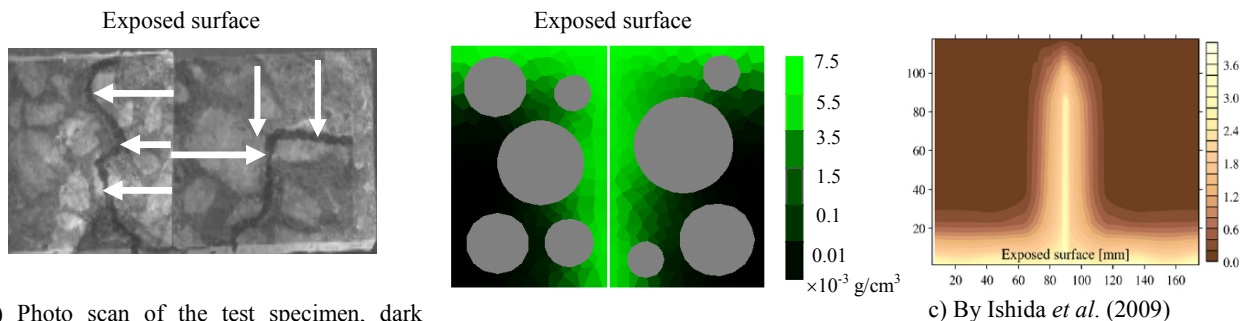


Fig. 15 Chloride penetration in cracked concrete with single tapered crack.



a) Photo scan of the test specimen, dark curves meaning the diffusion depth (Rodriguez and Hooton 2003)

b) Numerical analysis results

c) By Ishida *et al.* (2009)

Fig. 14 Chloride penetration in cracked concrete with single parallel-wall crack.

al.'s numerical model, the effect of cracking is realized by converting the crack width to the void porosity of a cracked element. Therefore, it can be concluded that when crack width is greater than the critical value, the nominal diffusion coefficient in it, D_{cr} , must be given a much high value (e.g., 10000 mm²/h).

4.3 Tapered crack on chloride diffusion

A specimen with a tapered crack in the middle section is shown in Fig. 15. The maximum crack width at the exposed surface is 0.2 mm and the crack length is 30 mm. Because the crack opening varies along crack direction from the exposed surface ($w_{cr}=0.2$ mm) to the end point ($w_{cr}=0$ mm), a width-dependent chloride diffusion coefficient D_{cr} is given following such law: $w_{cr} \leq 60$ μ m, $D_{cr}=3000$ mm²/h; $w_{cr} > 60$ μ m, $D_{cr}=10000$ mm²/h. It is obvious that tapered crack can also greatly accelerate the penetration speed of chlorides. Of course, the method proposed in this paper can also be easily applied to the more common case of multiple cracks. For more accurate prediction, therefore, it is necessary to consider the effects of crack width variation and crack spacing in the prediction of durability and service life of concrete structures.

5. Conclusions

Cracks play an important role in the transport properties of concrete because they can offer additional flow channels and allow more aggressive ions to penetrate. With help of the available experiment findings from literatures, this paper proposes a numerical method to quantify the diffusion coefficient of chloride through cracks with a relatively wide width range. The following conclusions can be drawn:

- 1) By analysis and comparison with experimental results, it is observed that when the crack opening width is larger than a critical value, the diffusion coefficient of chloride through cracks, D_{cr} , is independent of the crack width and has been determined as 10000 mm²/h. This value is much larger than that in free bulk water. Such a phenomena may be attributed to the additional transport mechanism for chlorides moving through crack spaces, e.g. convection current due to the small temperature gradient and/or small hydraulic pressure gradient.
- 2) When the crack width is less than the critical value, D_{cr} is numerically determined in a range from 1500 mm²/h to 4500 mm²/h. Because no consistent dependence of D_{cr} on crack width is observed, the av-

erage value of $3000 \text{ mm}^2/\text{h}$ is temporarily obtained. It should be pointed out here that D_{cr} may vary with the crack width when less than the critical value. As more knowledge is acquired on the influence of crack width on D_{cr} , the quantitative relationship between D_{cr} and crack width can be established.

- 3) The chloride penetration profiles in a cracked concrete specimen predicted by the proposed model exhibit good agreement with test results.

Acknowledgements

This study was supported by the Open Research Fund Program of State Key Laboratory of Hydrosience and Engineering (sklhse-2011-C-03), the Fundamental Research Funds for the Central Universities (No. DUT11LK38) and Open Foundation of State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (2011490801). The supports of Center for Concrete Core, Korea to the Yonsei University of Korea and the Asia-Africa Science and Technology Strategic Cooperation Promotion Program by the Special Coordination Funds for Promoting Science and Technology of Japan are also acknowledged.

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