The Investigation of Crack widths for the Effect of Cracks on Chloride Penetration of Concrete

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Abstract

Chloride penetration into concrete is a hot issue of concern all over the world, notwithstanding, very few attempts have been conducted to explore the effect of cracks on choride penetration. Cracks provoke to lose a main function of watertightness of concrete and lead to reduce the service life of concrete. For this reason, it is necessary to define a critical crack width to prevent a quick chloride penetration through crack.

In this study, experiment is focused on establishing a critical crack width in terms of chloride penetration. Concrete specimens with different crack widths / crack lengths have been subjected to rapid chloride migration testing. In a side of analytical solution, a simple approach to quantify the chloride diffusion coefficient of only crack zone excluding sound concrete was proposed. The result clearly showed a critical crack width of 0.03 mm.

Based on the experimental results, a phenomenological model was proposed to explain the meaning of critical crack width in practical engineering. In this model, cracked concrete zone was divided into three zones. These zones corresponded to a wide crack, a zone with micro-cracks and an uncracked zone.

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1. Introduction

Over the past few decades, a considerable number of studies on the durability of concrete have been carried out extensively. A lot of improvements have been achieved especially in both measuring techniques as well as modeling of ionic flows. However, the majority of these researches have been performed on sound uncracked concrete, although most of in-situ concrete structures have more or less micro-cracks. It is only recently that the attention has shifted towards the influence of cracks and crack width on the penetration of chloride into concrete. Although micro-cracks may not degrade the structural integrity immediately, they can affect the long-term durability performance of concrete structures by permitting penetration of aggressive substances into concrete easily. Accordingly the penetration of chlorides into concrete through the cracks can make a significant harmful effect on corrosion.

The objective of this study is to define a critical crack width. The critical crack width in this study is designed for a threshold crack width, which contributes to the first variation of chloride diffusion coefficient in responsive to the existence of cracks. A simple solution is formulated to realize the quantifiable parameter, chloride diffusion coefficient for only cracked zone excluding sound concrete. From the examination on the trend of chloride diffusion coefficient of only cracked zone for various crack widths, a critical crack width is founded out. Crack widths smaller than this critical crack width are considered not to have a significant influence on the rate of chloride transport inwards, while chloride penetration does proceed faster above this critical crack width. Based on achievement mentioned above, a schematic phenomenological model is proposed in an engineering framework.

2. Chloride Diffusion Coefficient for Only Crack Zone

Most of literatures of this topic had dealt with chloride penetration through cracks in terms of diffusion. The researches had been devoted to obtain experimentally the chloride diffusion coefficient of total cracked concrete including crack zone. However, since cracked concrete should be divided into two zones; crack zone and sound zone, the chloride diffusion coefficient of crack zone and sound zone should be estimated separately. This means chloride

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diffusion coefficient should be estimated each zone. Since there is no literature that tried to calculate a chloride diffusion coefficient of only crack zone excluding sound concrete, this study focuses on establishing new approach, which can express effectively the rate of penetration of only crack zone.

In principal, it is difficult to describe the chloride diffusivity of only cracked zone. However, it is possible to depict the permeability coefficient of multi-phase medium by Darcy's law. If crack zone and uncracked zone are considered as the first phase and the second phase respectively, total cracked concrete becomes a two-phase medium. If the permeability coefficient can be converted into the diffusion coefficient in this two-phase medium, it can be materialized to formulate the diffusion coefficient of cracked zone excluding sound zone.

As the procedure mentioned above, a good point to start is to define the diffusion coefficient and the permeability coefficient. The flow of liquids, gases and ions in concrete should be interrelated to some extent in terms of pore structure system of concrete. If concrete is idealized as consisting of a bundle of straight pore tubes, the general relationship between the permeability coefficient and the diffusion coefficient can be derived. Provided that Hagen-Poiseuille's law is valid also in small pores, the permeability of a single straight pore with radius in medium is given by eq. (q) and the diffusion coefficient is also given by eq. (2).

$$K = \frac{\pi \cdot r_{K(e)}^4}{A} \qquad (1)$$

$$D = D_o \cdot a_{D(e)} = D_o \frac{\pi \cdot r_{D(e)}^2}{A} \qquad (2)$$

where, $r_{K(e)}$: effective radius for permeability coefficient K, A : cross area of medium, D_o : diffusion coefficient in pure bulk fluid, $a_{D(e)}$: area fraction of effective pores $r_{D(e)}$. If it is assumed that effective radius for chloride diffusion coefficient D, $r_{D(e)}$, equals effective radius for permeability coefficient K, $r_{K(e)}$, the theoretical relationship can be derived as Eq. (3).

$$K = \frac{A}{8\pi D_o^2} D^2 \approx C \cdot D^n \qquad (3)$$

$$K_T \cdot i_T = K_I \cdot i_I + K_{II} \cdot i_{II} \qquad (4)$$

where, K_I: permeability coefficient of medium I, K_{II} : permeability coefficient of medium II, i_I: pressure gradient of medium I, i_{II}: pressure gradient of medium II. Parameter n depends on the aggressive substance and equals 3/2 on condition that permeant and diffusant involved are water and an ion, respectively.

By Darcy's law, the permeation of this two-phase medium can be described. Inserting Eq.(3) in to Eq. (4), diffusion equation of two-phase medium is yielded as :

$$\frac{H_T}{D_T^{3/2}} = \frac{H_I}{D_I^{3/2}} + \frac{H_{II}}{D_{II}^{3/2}} \qquad (5)$$

If medium I, medium II and medium I + II are regarded as a crack zone, a sound zone (uncracked zone), and a total cracked concrete, respectively, a theoretical expression for chloride diffusion coefficient of only crack zone I excluding crack zone II can be derived as:

$$D_{cr} = \sqrt[3]{\left(\frac{\frac{d_{cr}}{1}}{\frac{d_T}{\sqrt[3]{D_T^2}} - \frac{d_{ucr}}{\sqrt[3]{D_{ucr}^2}}} \right)^2} \qquad (6)$$

where, d_{cr} : crack depth, d_T : total chloride penetration of total cracked concrete, d_{ucr} : chloride penetration of uncracked concrete, D_{cr} : chloride diffusion coefficient of only crack zone, D_{ucr} : chloride diffusion coefficient of uncracked concrete, D_T : chloride diffusion coefficient of total cracked concrete.

Now we can quantifiably estimate an average flow rate through cracks in concrete by Eq.(6). This is based on an assumption that the relationship between the permeability coefficient and the diffusion coefficient is still effective in cracked concrete as well.

3. Experiment

One concrete mixture was produced, as marked in Table 1. Concrete was cast into 150 × 150 × 150 mm cube molds and then they were exposed to air atmosphere at relative humidity of 65% and temperature of 20 °C for 26 days after

2 days of moist curing at temperature of 20 °C. The concrete specimens were cored with a coring machine of Φ 100 mm and skin was eliminated. After notch of size 5 × 5 mm and length 100 mm were created at the surface of concrete, two steel plates were attached in these specimens.

Table 1. Mixing Proportion of Concrete

28days strength (MPa)	Air (%)	Slump (mm)	G_{max} (mm)	w/c	Unit weight (kg/m^3)			
					Water	Cement	Sand	Gravel
28.5	4.5 ± 1.5	150 ± 10	16	0.50	185	370	720	1021

LVDT was attached on the both sides of the concrete specimens to control CMOD. For fabricating artificial cracks, tensile stress was subjected to these two steel plates by the loading machine, 8872 series of INSTRON. Targeted crack widths were around 0.05 mm, 0.10 mm, 0.15 mm, and 0.20 mm. After cracks were generated in concrete specimens, notches were eliminated. The dimensions of cracked concrete specimens then were a diameter of 100 mm and a thickness of 50 mm. Three cracked concrete specimens per intended crack width were prepared.

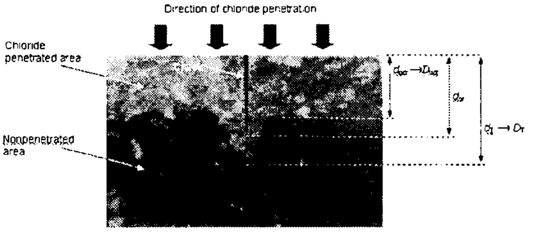

Fig. 1 Chloride diffusion coefficients with carious zones

In order to remove air from concrete, the specimens were put in the vacuum chamber for three hours. The specimens were then fully impregnated by epoxy. After a day, the specimens were cut into a thickness of 3 mm. Following the crack, the crack width and crack depth of the section were investigated by using optical microscope DM RXP manufactured by LEICA Co. Ltd. As for the RCMT, the chloride penetration distances for each depth of cover were averaged from two split faces of each sample, and for two replicate slices per condition in accordance with NordTest NT-Build 492. The chloride diffusion coefficient of concrete was calculated at three zones: total cracked concrete including sound zone, cracked zone excluding crack, and sound zone, as shown in Fig. 1. Inserting the chloride penetration depth d_T at total cracked zone and d_{ucr} at uncracked zone, chloride diffusion coefficient D_T and D_{ucr} could be obtained, respectively. To obtain the chloride diffusion coefficient D_{cr} of only cracked zone excluding crack zone, crack depth d_{cr}, which equaled a thickness of the first phase, was inputted into Eq. (6).

4. Results and Discussion

Targeted crack widths were intended to be 0.05 mm, 0.10 mm, 0.15 mm and 0.20 mm, however, effective crack widths were significantly smaller than the targeted crack widths. Since the concrete specimens for RCMT must have a thickness of 50 mm, it is impossible to fabricate cracked concrete specimens with a crack depth of 50 mm over. For this reason, the maximum crack width was intended as much as possible within the scope of limited crack depth of 50 mm. Cracks were created from a minimum width of 0.012 mm to a maximum width of 0.117 mm.

Figure 2 presents total chloride diffusion coefficient of total cracked concrete including cracked zone for various ratios of crack width to crack depth (W_{cr} / d_{cr}). As expected, the chloride diffusion coefficient tends to grow with higher W_{cr} / d_{cr}. However, this figure doesn't deserve draw the notice for the accurate relationship satisfactorily.

Figure 3 shows total chloride diffusion coefficient of concrete including crack zone for various crack widths. This result shows a more accurate correlation than previous relation with W_{cr} / d_{cr}.

Figure 4 presents relative chloride diffusion coefficient (D_T / D_{ucr}) between cracked concrete and uncracked concrete for various crack widths. There is an agreement on that chloride diffusion coefficient has a rising trend from crack width of 0.03 mm. Trend to satisfactory extent is still not appeared to define critical crack width.

Figure 5 shows the chloride diffusion coefficient of only cracked zone, which is obtained by the way suggested in this study. Somewhat surprisingly, the increase in diffusion coefficient of crack zone is very well correlated with the evolution of microcracking. Two important examinations should be pointed out here. First, the chloride diffusion coefficient of only crack zone is a constant within the crack width of 0.03 mm. Experimental result shows clearly, however, that crack width greater than about 0.03 mm appears to have effect on chloride diffusion. In other words, chloride diffusion coefficient is responsive to 0.03 mm of crack width, which can be sufficiently regarded as a critical crack width. Second, the chloride diffusion coefficient is directly proportional to crack width above 0.03 mm. This trend shows linear function. When we observe this accurate trend, it can be implied that proposed Eq. (6) could be a meaningful solution to calculate chloride diffusion coefficient for only cracked zone.

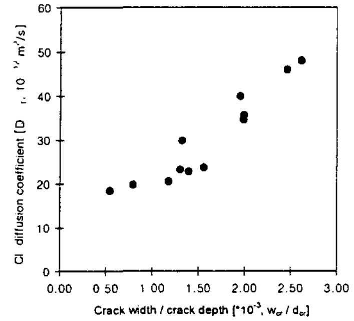

Figure 2 Total chloride diffusion coefficient vs. Crack width / depth

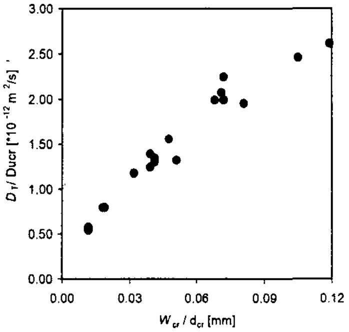

Figure 3 Total chloride diffusion coefficient

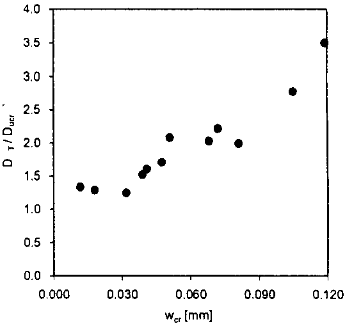

Figure 4 Relative chloride diffusion coefficient

As shown in Figure 6, crack depth d_{cr} is compared with total chloride penetration depth d_T of total cracked concrete. The chloride penetration depths d_{ucr} of uncracked zone are much bigger than remained depths ($d_T - d_{cr}$) which are subtracted crack depth d_{cr} from the total penetration depth d_T of total cracked concrete. This implies that chloride ions couldn't penetrate up to the ending point of crack depths simultaneously as soon as cracks are created, contrary to our expectations. The mostly likely reason for this is that cracks gradually become a narrow path for chloride penetration, going from the surface inwards. This rate of penetration is getting slower and slower going from the surface inwards. Another likely reason would be related to geometrical properties of cracks such as unconnectivity and tortuosity. There are primary cracks at the surface of concrete, however, micro-cracks at internal concrete is not connected to each other. Broadly speaking, this remained depth seems to be inversely proportional to crack width. Accordingly it can be also inferred that chloride ions can penetrate through crack promptly to some distance as soon as a wide cracks create. A more prescriptive approach based on the microscopic investigation of crack in terms of chloride penetration is required to determine this depth as a function of crack width.

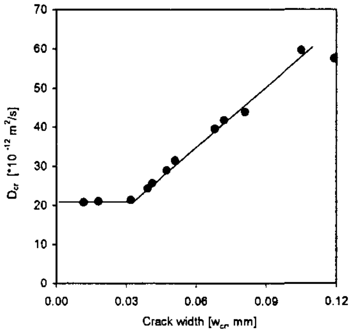

Figure 5 Chloride diffusion coefficient of cracked zone

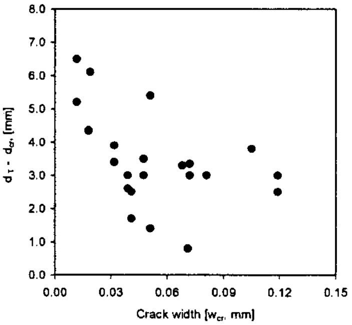

Figure 6 Comparison of chloride penetration depth and crack depth

5. Conclusions

Concrete can be considered as a tight material, as long as the crack width is smaller than 0.03 mm. 0.03 mm of critical crack width looks like very stern criterion. However, this critical crack width should not be underestimated if we consider that transition zone with an average thickness of 0.02 mm has a high chloride diffusivity of about 2.83 times in comparison with cement paste. In the meantime, it is difficult to make out clearly the mechanism of mass transportation through crack as diffusion, even if the crack is very small scale. Because the main driving force on chloride penetration through cracks can be influenced by a fluid viscosity or potential energy. Nevertheless, proposed solution for the chloride diffusion coefficient of only crack zone is expected to be an effective mean for idealization of the penetration behavior simply.

References

[1] NT Build 492, Concrete, Mortar and Cement-Based Repair Materials: Chloride Migration Coefficient from Non-Steady-State Migration Experiment

[2] JSCE (1999). Materials for Revision of JSCE, Standard Specification for Design and Construction of Concrete Structures [Construction], Concrete Library 99.