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Chloride diffusion in the cracked concrete

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ABSTRACT: The diffusion of chloride is affected by the cracks in the concrete materials. The influences of cracking width on the chloride diffusion coefficient and diffusion surface are discussed in this paper. The chloride diffusion coefficient of concrete varies with the cracking widths, and there exist upper and lower limitations. The effect of cracking on the chloride diffusion can be divided into three cases: 1) when the width is less than 0.03mm, its effect can be neglected due to self-healing; 2) when the width is more than 0.1mm, two-dimensional diffusion will happen in the cracking zone; 3) and when the crack width is between 0.03 and 0.1mm, chloride diffuses into concrete along and perpendicular to the crack surface simultaneously. Formula for chloride diffusion in these three cases were brought forward, and an calculation example was given according to the analysis of this article. The results of calculation agree well with the test, which can provide a reference to the design of concrete durability.

1 INTRODUCTIONS

Chloride is a very important factor which influences the durability of concrete structures in their service life. It can induce the steel corrosion and concrete cover cracking. Ingress of chloride in the concrete was studied since 1970' (Collepardi 1972, Buenfeld et al. 1987, Boddy 1999, JIN 2007). Many useful conclusions have been gotten about this. But only a few of them considered the crack's effect. However, cracking is an inevitable phenomenon for RC structures in their service life as shrinkage, thermal variation, loading effect and so on. Different maximum cracking widths were framed in the concrete code, from 0.1 mm (CEB-FIP model code 90) to 0.4 mm (ACI Committee 222).

Some researches about the crack's effect on the chloride ingress into concrete had been done by experimental and theory analysis. Kato & Uomoto (2005) proposed a model to simulate chloride ion profiles in the cracked concrete under wet and periodic drying-wetting conditions. In the model, cracked zone was treated as the exposed surface of the concrete while considering the balance of the total amount of chloride in the cracked zone and in the crack. Mohamed (2003) developed a rational finite element model to calculate the transport of chloride ions into cracked concrete by advection and diffusion under saturated or unsaturated conditions based on a realistic representation of the crack geometry. Li (2003) considered the variation of surface chloride concentration and used a new solution to Fick's second law to calculate the chloride ingress in concrete under different conditions of load-induced cracks. All these models considered the crack width's effect. The chloride content in the cracked zone increases as crack width increases.

However, many tests found that crack had no influence on the chloride ingress when crack width were below a specific value, and crack width represented similar influence on chloride penetration when crack width was bigger than another critical value. The models proposed above can not explain this phenomenon. So it is necessary to develop a new model to simulate the chloride ingress in concrete more accurately.

The crack width decreases from surface to interior for most RC structures. However, the most important part influencing the steel corrosion is the cover crack, whose width can be considered unchanged. To simplify the calculation, constant crack width will be considered in following model.

2 SIMPLIFIED MODEL

Penetration of chloride ions into porous media such as concrete takes place by two major mechanisms: diffusion and advection. Diffusion occurs under a concentration gradient, whereas advection is related to transport of substances by moving water under a pressure head. For the saturated condition, diffusion is the dominant mechanism for chloride ingress. So we only consider the diffusion of chloride ions in cracked concrete.

2.1 *Chloride diffusion coefficient in crack D_{cr}*

The total chloride diffusion flux of cracked concrete can be divided into two parts: the flux in uncracked parts and the flux in the cracked parts. Chloride ions diffuse in crack with a different coefficient D_{cr}, which is much larger than the coefficient in matrix. Many experiment researches concluded that D_{cr} varied with the crack width, and had no relationship with the materials. The regular is shown as below:

1) When surface crack width $w < w_1$ (w_1 is the lower limit which makes crack influence the chloride diffusion), the product of subsequent hydration and self-healing of cemetitious materials will jam the crack. So the crack's effect on chloride diffusion can be ignored, $D_{cr} = D_0$, which is showed in Figure 1a.

2) When $w_1 \le w \le w_2$ (w_2 is the upper limit which makes crack influence the chloride diffusion), the product of subsequent hydration can not block the crack completely, so chloride diffusion will happen in the unblocked parts, this makes D_{cr} between D_0 and D_{H_2O} (chloride diffusion coefficient in free solution at the same environment), which is showed in Figure 1b.

3) When $w>w_2$, the product of subsequent hydration can not block the crack, so D_{cr} is equal to D_{H_2O}. At this situation, as D_{H_2O} (1.25×10^{-9} m^2/s in 6% NaCl solution at 20 ℃) is much larger than D_0 (about 10^{-12}m^2/s), chloride ions will quickly diffuse into crack and reach stable, then the chloride ions in the crack will diffuse into matrix through crack surface, causes two dimensional diffusion near crack. In this case, we can assume the chloride ion concentration in crack is equal to the solution, diffusion perpendicular to crack will be considered with that from exposed surface, which is showed in Figure 1c.

The values of w_1 and w_2 get by researchers are showed in Table 1. From this table, we can determine that the upper limitation is about 100μm, the lower limitation is about 30 μm. When crack width is between w_1 and w_2, D_{cr} increases with the width increases. It is also related to temperature and humidity. Djerbi et al (2008) get the value of D_{cr} through steady–state test at 20 ± 5 ℃. In the test, cracks were got by splitting test, and chloride concentration is 0.513 mol/L. The values and regression curve are showed in Figure 2, which is:

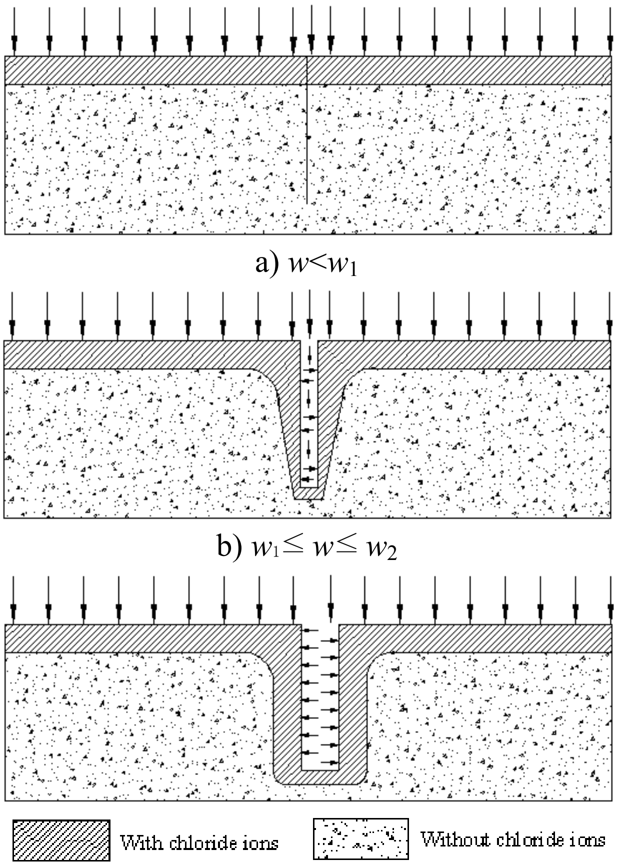
Table 1. Upper and lower limitation of cracking width influencing D_{cr}.

Sources	w_1 (μm)	w_2 (μm)	Material
Takewaka	50	100	Concrete
Ismail	30	99	Inert
Ismail	30	125	Mortar
Francois	30	-	Concrete
Kato	-	75	Concrete
Djerbi	30	80	Concrete

(Takewaka et al 2005, Ismail et al 2004, Ismail et al 2008, Francois et al 2005, Kato & Uomoto 2005, Djerbi et al 2008)

$$D_{cr}=16.9-27.4 \exp(-0.0176w) \qquad (1)$$

In the expression, the units of w and D_{cr} is μm and 10^{-10} m^2/s respectively. This expression can be used to calculate D_{cr} when w is between 30 and 100 μm under normal conditions.



c) $w>w_2$

Figure 1. Chloride diffusion in different cracking widths.

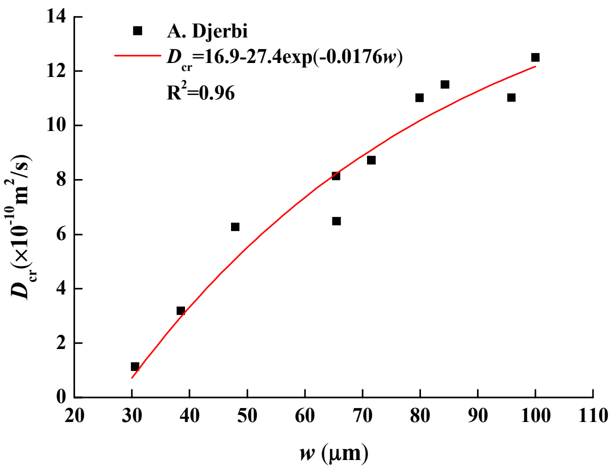


Figure 2. Values of D_{cr} when $w_1 \leqslant w \leqslant w_2$.

2.2 *Chloride diffusion in cracked concrete*

As D_{cr} is related to crack width, so the diffusion of chloride ions in cracked concrete is also influenced by crack width, a sample as Figure 3 will be used to analysis the chloride diffusion in cracked concrete. In the sample, crack width is w and depth is h, origin of coordinate is at the initial cracking point. The analysis is as below:

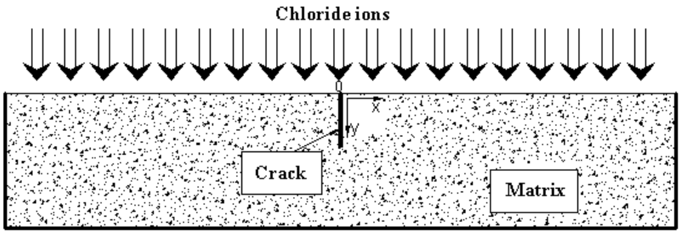


Figure 3. Calculation schematic of chloride diffusion into concrete with single crack.

1) When $w<w_1$, $D_{cr}=D_0$, crack's effect can be ignored, Fick's second law can be used to calculate the chloride diffusion in the cracked concrete. The chloride content $C(y,t)$ at the location y in a given time t is

$$C(y,t)=C_s\cdot\left[1-\mathrm{erf}\left(\frac{y}{2\sqrt{D_0 t}}\right)\right] \qquad (2)$$

where as C_s is the surface chloride ion concentration, D_0 is the apparent diffusion coefficient, erf is the error function, $\mathrm{erf}(z)=\frac{2}{\sqrt{\pi}}\int_0^z \exp(-x^2)\mathrm{d}x$.

2) When $w_1\le w\le w_2$, the crack's effect must be considered, chloride diffusion in crack can be considered as diffusion in water with a different coefficient D_{cr}, which increases with the crack width increases, the chloride ions diffused into crack can be expressed as

$$C^{cr}(y,t)=C_s\cdot\left[1-\mathrm{erf}\left(\frac{y}{2\sqrt{D_{cr}t}}\right)\right] \qquad (3)$$

This is the surface chloride concentration in crack wall. Assuming the diffusion coefficient along x and y direction is same, then the expression and boundary condition of chloride diffused into cracked concrete is:

Expression: $$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2}+D\frac{\partial^2 C}{\partial y^2} \qquad (4)$$

Boundary condition: $C(x,y,0)=C_0=0$

$$C(0,y,t)=C^{cr}(y,t)$$
$$C(x,0,t)=C_s \qquad (5)$$

As the surface chloride concentrations in exposed and crack surface are different, analytical solution about this expression can not be gotten, finite element method can be used for analysis.

3) When $w>w_2$, $D_{cr}=D_{H_2O}$, the diffusion process in crack can be ignored, and the surface chloride concentration in crack wall is equal to the concentration in exposed surface, so we can use two dimensional Fick's second law to calculate, the chloride content at location (x, y) and time t is

$$C(x,y,t)=C_s\cdot\left[1-\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\mathrm{erf}\left(\frac{y}{2\sqrt{Dt}}\right)\right] \qquad (6)$$

3 CALCULATION ANALYSIS

According to the analysis described above, a sample similar to Figure 3 will be calculated. the sample's cover depth is 30 mm, surface chloride concentration is 1 (normalized), crack depth is 30 mm (equal to the cover depth), crack width are 10, 30, 60, 90, 120 μm, and D_{cr} are 5×10^{-6}, 7.4×10^{-5}, 7.37×10^{-4}, 1.25×10^{-3} $\mathrm{mm^2/s}$ separately according to equation (1). To simplify the analysis, a finite element software will be used for calculating. The chloride concentrations are showed by mean of iso surface in Figure 4 after 1 year exposure.

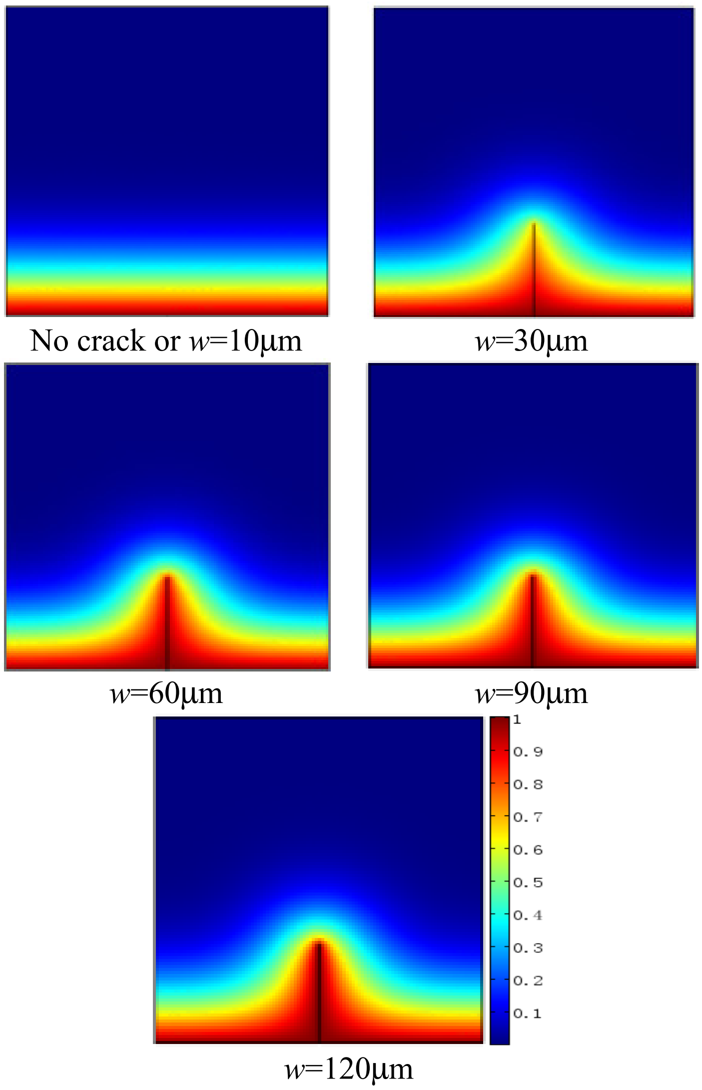
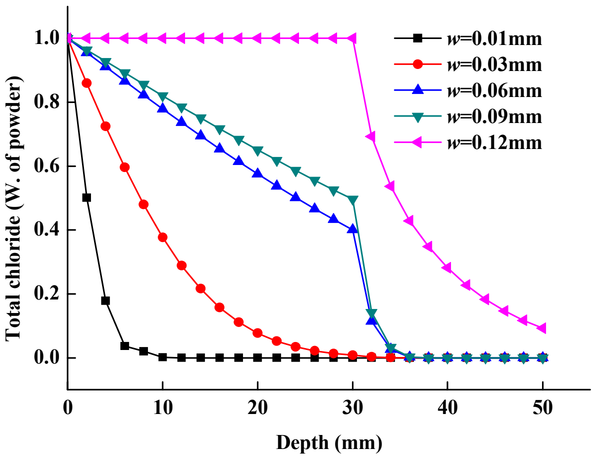


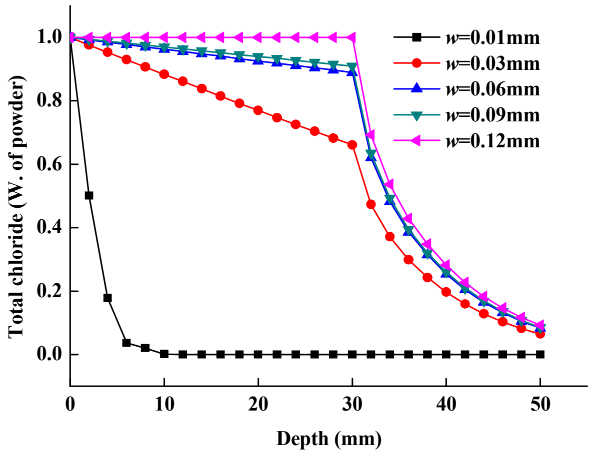
Figure 4. Chloride diffusion in cracked concrete with different crack widths (t=1 year).

3.1 *Diffusion along y direction*

The chloride concentration in crack along y direction after 10 days and 1 year exposure are showed in Figure 5. It can be noted that in short term, the influence of crack width on chloride diffusion is very significant. At same position, chloride concentration is larger for wider crack. But for long term exposure, crack width's influence is not significant.



a) t=10 days



b) t=1 year

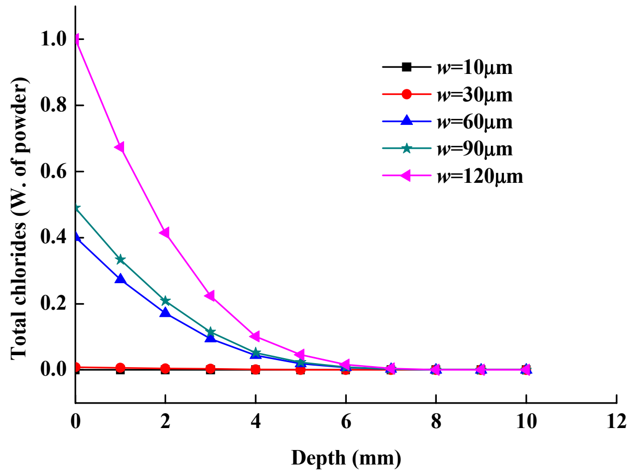
Figure 5. Chloride diffusion along y direction in different cracking widths.

3.2 *Diffusion along x direction*

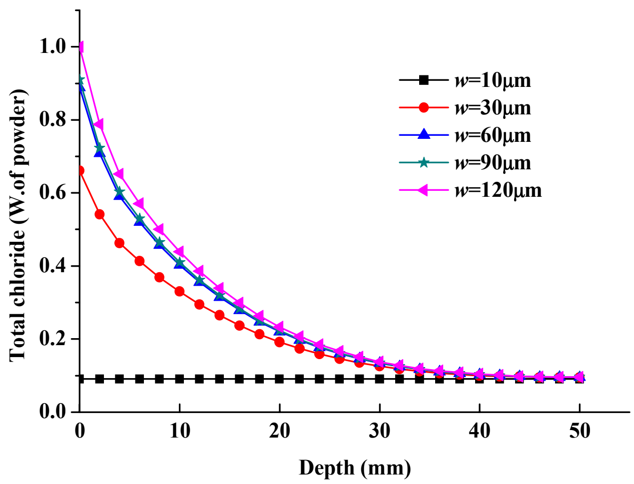
At the position of steel (about 30mm depth), the chloride concentration along x direction after 10 days and 1 year exposure are showed in Figure 6, from the figure, it can be concluded that chloride concentration increases as the width increases after 10 days exposure. The influence of crack width on chloride concentration is more significant for short term diffusion than for long term diffusion. This can be called "short-term effect".

4 TEST VERIFICATION

Test results of Ismail (2008) are used to verify the correctness of this model. In the experiment, a mechanical expansive core was used to generate cracks of constant width across the thickness of the mortar sample. Chloride penetration tests were carried out on mortars at 28 days. Specimens with crack openings ranging from 6 to 325 μm were subjected to a test designed to allow chloride diffusion along the crack path for a period of 14 days. The chloride content was 32.99 g/L, the grinding position is depth enough from the exposed surface to confirm that the chloride concentration in the grinding area used to measure the perpendicular-to-crack profiles was only affected by chloride ions entering via the crack plane and not from the exposed surface. 0.1 mol/L $AgNO_3$ was used to detect the chloride content. In the test, the chloride content of initial condition and from the exposed surface were also get, these data were used to get the surface chloride content and the apparent diffusion coefficient. Then the chloride content perpendicular to crack surface was calculated. Result of calculated and tested when crack widths were 20, 96, 125 μm were shown in Figure 7. The calculate results is in a good agreement with the test results.



a) t=10 days



b) t=1 year

Figure 6. Chloride diffusion along x direction in different cracking widths.

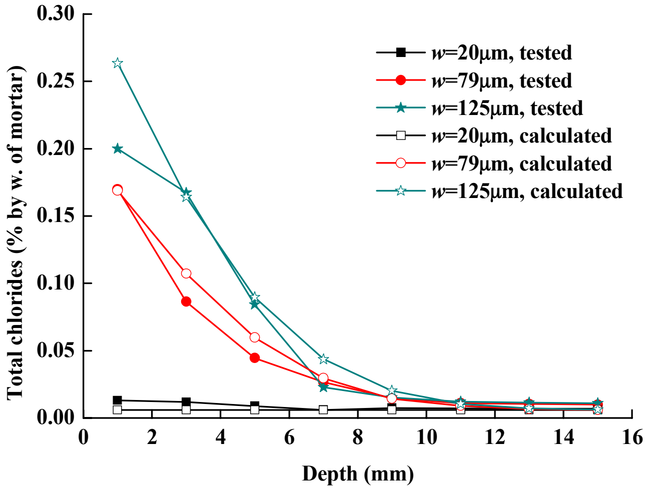


Figure 7. Perpendicular-to-crack chloride penetration profiles in cracked samples after 14 days in chloride solution.

5 PARAMETRIC ANALYSIS

In previous section, effect of crack width on chloride penetration into cracked concrete has been studied. To investigate other factors' influence (such as crack length, surface chloride concentration and diffusion coefficient in concrete) on the chloride penetration, a parametric study has been carried out to investigate the effect of cracking pattern and material properties. The unit cell shown in Figure 8 has been chosen as a representative volume element, which contains 1984 degrees of freedom and 961 triangular elements. The cell includes a crack whose width is 60 μm, the concrete and crack are saturated before chloride ingress. The chloride content in A-A section after 5 years exposure is compared. Chloride threshold for corrosion is assumed to be 1.2 kg/m^3 according to JSCE.

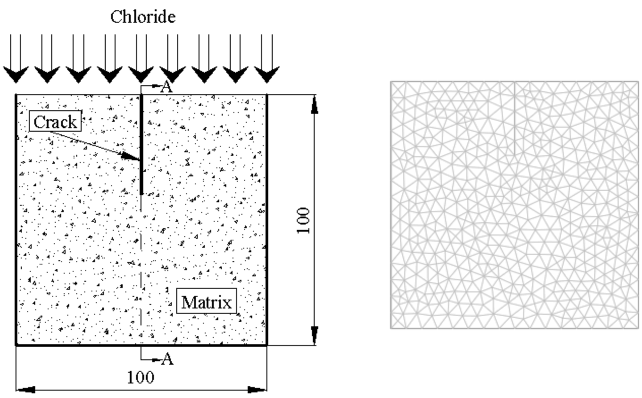


Figure 8. Cracking pattern and finite element mesh (mm).

5.1 *Crack length*

Four crack lengths have been investigated: 20, 30, 40, 50 mm. The chloride concentration at surface is assumed to be 13 kg/m^3. It can be seen from Figure 9 that chloride content in the cracked section is sensitive to crack length. Chloride content is increasing with the crack length. At the cracked plane, the chloride ion concentration is much higher than away from the crack or in the case where no crack exists. A rather sharp decrease is noticed beyond the crack tip.

5.2 *Chloride concentration at surface*

Four chloride concentrations at surface have been considered—2, 4.5, 9 and 13 kg/m^3. These concentrations correspond to the severity of the environmental condition according to the distance of site from seaside and/or nature of the exposure conditions (submerged zone, splash zone, atmospheric zone) as classified by the JSCE specifications. Figure 10 clearly shows that the chloride penetration is sensitive to surface chloride concentration.

5.3 *Chloride diffusion coefficient in concrete*

Four chloride diffusion coefficients have been considered: 1×10^{-13} m^2/s, 1×10^{-12} m^2/s, 5×10^{-12} m^2/s, 1×10^{-11} m^2/s, represent the quality of concrete. The results are shown in Figure 11. The chloride concentration is insensitive to D_0 in crack but sensitive in concrete.

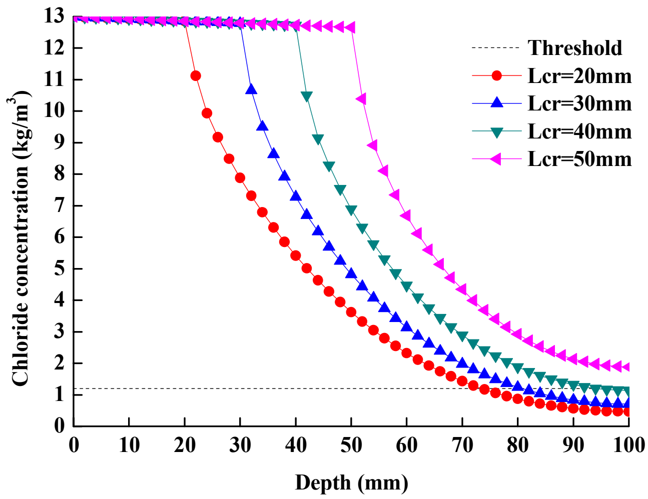


Figure 9. Effect of crack length on chloride ion ingress.

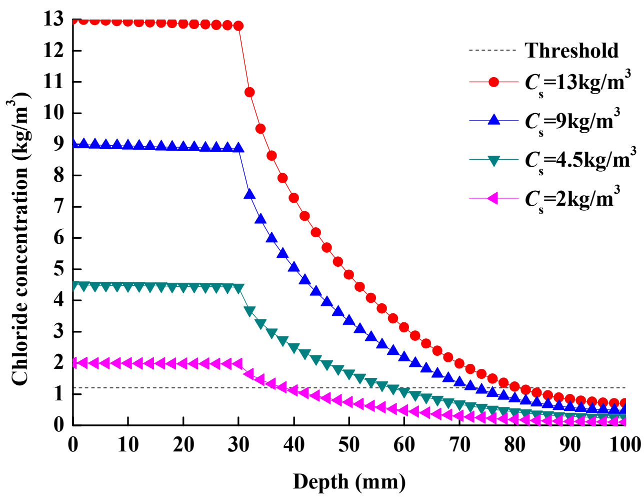


Figure 10. Effect of surface chloride concentration.

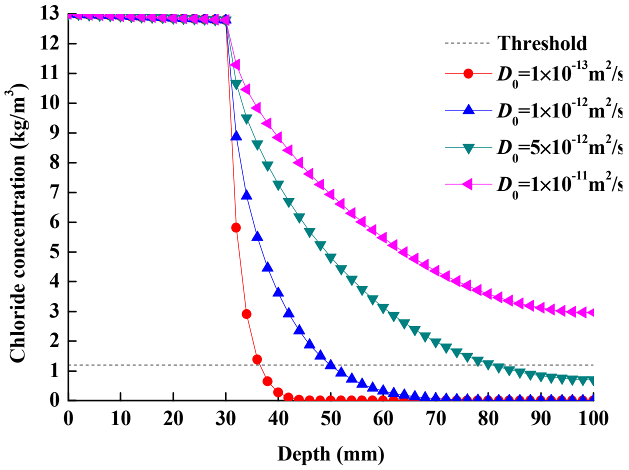


Figure 11. Effect of chloride diffusion coefficient in concrete.

5.4 *Corrosion initiation time*

The reinforcement in concrete at a depth of 30 mm will corrode at different time when the crack width varies. Figure 12 shows the corrosion initiation time in cracked plane. There is a sharp decrease for the steel to corrode when crack width is between 30 - 60 μm.

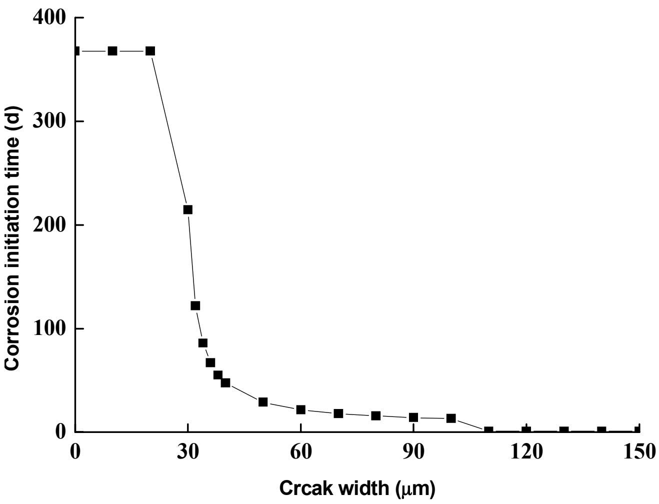


Figure 12. Steel corrosion initiation time in different crack widths.

6 CONCLUSIONS

Following conclusions can be drawn from the results of this research:

- Chloride diffusion coefficient in crack D_{cr} varies with crack width w, there exist lower w_1 and upper limitation w_2. Relationship between D_{cr} and w is: 1) when $w < w_1$, $D_{cr} = D_0$, 2) when $w_1 \leq w \leq w_2$, $D_0 < D_{cr} \leq D_{H_2O}$, D_{cr} can be expressed as D_{cr} = 16.9-27.4exp(-0.0176w), 3) when $w > w_2$, $D_{cr} = D_{H_2O}$. Test results showed that w_1 = 0.03 mm, w_2 = 0.1 mm.
- The calculate methods in different crack widths can be represented as: 1) when $w < w_1$, crack's effect can be ignored, Fick's second law can be used to calculate chloride diffusion. 2) when $w_1 \leq w \leq w_2$, chloride will diffuse through two directions: perpendicular to exposed surface and crack surface, but these two surface chloride content are different. 3) when $w > w_2$, chloride diffuse similar to 2), only the two surface chloride content are the same.
- Simulated example shows that when crack width is bigger than 30 μm, chloride content perpendicular to exposed surface and crack surface both increase with the crack width increases. Chloride content in short term exposure is sensitive to long term exposure.
- Crack width, length and surface chloride concentration represent significant impacts on the chloride penetration in crack and concrete, where as chloride diffusion coefficient in sound concrete has little influence in crack.

ACKNOWLEDGEMENTS

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