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Chloride Diffusion Investigation under Different Magnitudes of Hydrostatic Pressure for Pre-Cracked Concrete

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Abstract: The service life of the reinforced concrete structure in the marine environment can be impaired significantly due to chloride-induced corrosion. However, how the chloride diffusion in pre-cracked concrete structures is affected by the hydrostatic pressure magnitude is poorly understood. This study experimentally examined the effect of hydrostatic pressure on the chloride diffusion in pre-cracked concrete. Cracks with five different widths, *i.e.*, 20 μm, 40 μm, 60 μm, 80 μm, and 100 μm, were manually created using a splitting tensile apparatus respectively. The chloride diffusion in the concrete with a certain crack was then studied under four different hydrostatic pressures of 0 MPa, 0.1 MPa, 0.3 MPa, and 0.5 MPa. Experimental results show that the chloride diffusion in concrete with a crack greatly relies on both the hydrostatic pressure and the crack width. The chloride concentration increases as the hydrostatic pressure grows, particularly for the wider cracks with width ranging from 60 μm to 100 μm. Surprisingly, the hydrostatic pressure has a negligible effect on the chloride distribution in the concrete with a crack width no larger than 40 μm. Both the chloride diffusion coefficient and the surface chloride concentration of concrete increased gradually as the hydrostatic pressure increased. The experimental findings enrich our understanding of the behavior of pre-cracked concrete when exposed to chloride-induced corrosion at different depths of marine environments.

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1. Introduction

The performance of reinforced concrete structures built and served in marine environments are often degraded due to chloride-induced corrosion. Chloride ion penetration into concrete depends on a number of variables, such as chloride ion concentration, concrete's microstructures and properties, and the magnitude of hydrostatic pressure [1–3]. On the one hand, concrete structures are unavoidably cracked due to internal deformation and external loadings during service life. The presence of cracks in the concrete accelerates the corrosion process of the steel reinforcement. On the other hand, water pressure affects substantially the chloride penetration process into concrete with cracks whose hydraulic properties are heavily stress dependent. Therefore, understanding the behaviour of chloride diffusion in concrete with cracks under various hydrostatic pressure is critical to assess and predict the long-term durability of marine engineering concrete structures, particularly for those in the deep-sea environments [4,5].

The effect of cracks on the chloride penetration of concrete has attracted numerous investigations recently [6–15]. Aldea et al. [14] reported that the chloride permeability increased with increased crack widths and the water permeability was much more sensitive than that of chlorides. Olga and Hooton [16] however reported that chloride diffusion was independent of both crack width and crack wall roughness. François et al. [17] reported that the chloride diffusion perpendicular to the crack walls with wide cracks (width ≥205 μm) was similar to that of the surface. For the cracks ran through the specimens, the diffusion coefficient in the crack in steady-state conditions was assumed to equal

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the diffusion coefficient in free solution [7,8]. Therefore, it is apparent that cracks in concrete greatly affect the durability of reinforced concrete structures with some inconsistent findings in previous literature. Liu et al. [18–21] studied the migration mechanism of chloride in cracked concrete by numerical simulation, which provided a new idea for the durability design of concrete. In theory, stability of deep-sea concrete-made engineering infrastructures is closely associated with the concrete durability under a high hydrostatic pressure environment. However, the effect of hydrostatic pressure on the penetration of chloride in cracked concrete has been rarely explored.

This paper reports experimental studies on chloride diffusion in the pre-cracked concrete under different degrees of hydrostatic pressure. The crack of a desired width in the concrete specimen was manually created using a controlled splitting tensile apparatus and maintained during the chloride penetration process in cracked concrete. The average crack width varied from 20 μm to about 100 μm. Moreover, the effect of hydrostatic pressure on the diffusion coefficient values of the cracked concrete was examined.

2. Experimental study

2.1. Sample preparation

Figure 1 illustrates the experimental configuration for exploring the chloride transport into the cracked concrete samples under various magnitudes of hydrostatic pressure. An air pressure machine was employed to apply four different hydrostatic pressures of 0MPa, 0.1MPa, 0.3MPa and 0.5MPa on the cracked concrete, and the highest hydrostatic pressure simulated the marine environment in depth up to 50m. The concrete specimen exhibited a ring profile with an inner radius of 50 mm, outer radius of 200 mm, and height of 80 mm (Figure 1b). The concrete mixture consisted of cement, water, sand, aggregates, and water reduction agent in the ratio of 1:0.38:1.56:2.66:0.012, which complied with the Chinese Standard, JGJ55-2000 [22]. The cement type was P.II 52.5, with an apparent density of 3150 kg/m^3. The aggregate size ranged from 5 mm to 20 mm with continuous grading, and its apparent density was 2630 kg/m^3. The apparent density of sand was 2.64 g/cm^3 with a water proportion of 3.7%. The type of the water reducing agent was HP4000A with a water reduction ratio of 27.5%. The uniaxial compressive strength of the concrete was 50.5 MPa and 59.1 MPa after 14 and 28 days curing, respectively. The tensile strength of the concrete was respectively 5.36 MPa and 6.87 MPa after 14 and 28 days. Twenty concrete samples were prepared from a single batch for the concrete mixtures after 14 and 28 days curing, respectively. The concrete mixtures were cast in steel molds and compacted using a mechanical vibrator.

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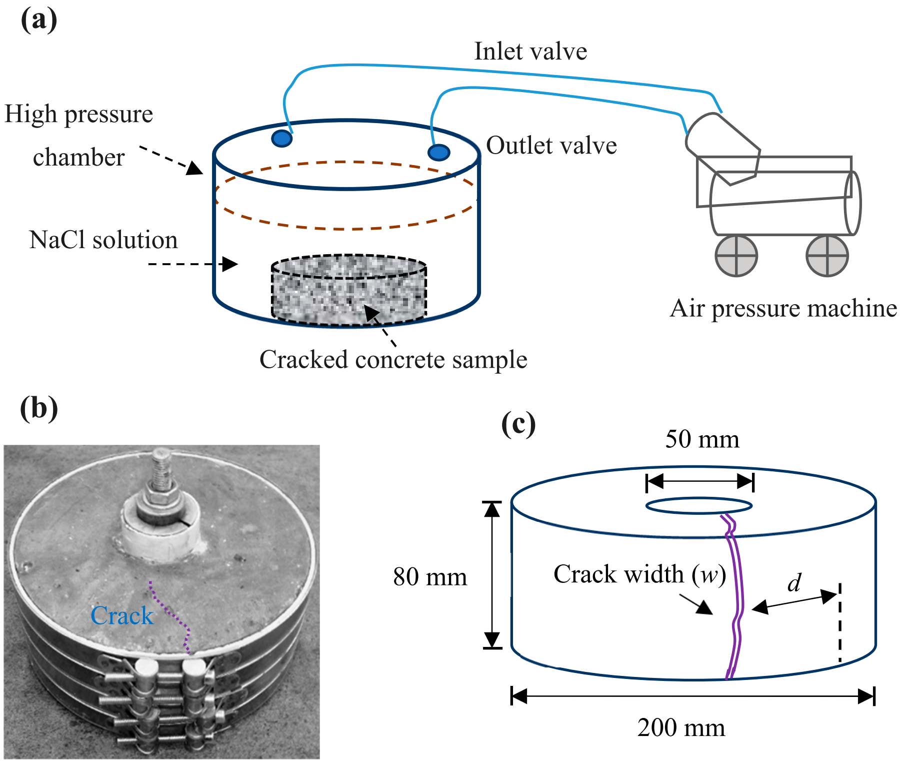

Figure 1. Experimental configuration: (a) illustration of chloride penetration test on the cracked concrete under different degrees of hydrostatic pressure, (b) concrete samples with a crack of a specified width (w), and (c) geometry of the crack concrete sample, and d is the penetration depth.

2.2. Sample pre-cracking

Cracks with five different widths of 20μm, 40μm, 60μm, 80μm and 100μm in the ring concrete sample was created by a controlled splitting tensile apparatus. A crack width gauge, DJCK-2 Type, was used to measure the crack width. After cutting, the lateral surfaces of ring concrete sample were sealed with two epoxy resin coats to ensure chloride flow through the ring concrete crack in the radial direction (Figure 1c).

3. Results and analysis

3.1. Chloride concentration quantification

The chloride concentration in concrete is estimated through the Volhard method. The powdered concrete samples normal to the crack surface are used to extract acid-soluble chloride contents [23], as shown in Figure 1c. The chloride diffusion is calculated by fitting the experimentally-measured curves. The penetration of chloride into concrete is assumed one-dimensional in a semi-infinite medium complying with Fick's second law of pure diffusion [24]:

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

Solve Eq. (1):

$$C(x,t) = C_0 + (C_s - C_0)\left[1 - erf\left(\frac{x}{2\sqrt{D_a t}}\right)\right] \tag{2}$$

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where $C(x,t)$ is the chloride concentration at distance x from the exposed surface, C_s is the surface chloride concentration, D_a is the apparent chloride diffusion coefficient, t is the exposure time, and erf is the error function [24]. The values of D_a and C_s are determined from fitting the measured chloride profile.

3.2. Effect of crack width on chloride diffusion

Figure 2 shows the chloride concentration of the ring concrete sample with different crack width under varying magnitudes of hydrostatic pressure. As the hydrostatic pressure grows from 0 to 0.5 MPa, remarkable difference in chloride concentration (C) occurs between the crack width increases from 20 μm to 40 μm and that from 60 μm to 100 μm. The chloride concentration (C) (0.025% to 0.041%) for the crack width of 20 μm to 40 μm is substantially lower than that of 60 μm to100 μm (0.19% to 0.36%), particularly for those close to the crack. The discrepancy decreases as the penetration depth (d) from the crack increases. That is to say, the crack width affects remarkably the chloride transport in concrete and the influence degree decreases with the increasing penetration depth. The effect of the crack width is less pronounced when the width is around 20 μm to 40 μm. Similarly, minor difference is found between that of crack width of around 60 μm to 100 μm. Therefore, a critical crack width exists beyond which the chloride transportation in concrete is dramatically influenced. The results are consistent with the studies reported in the literature [6,12,25].

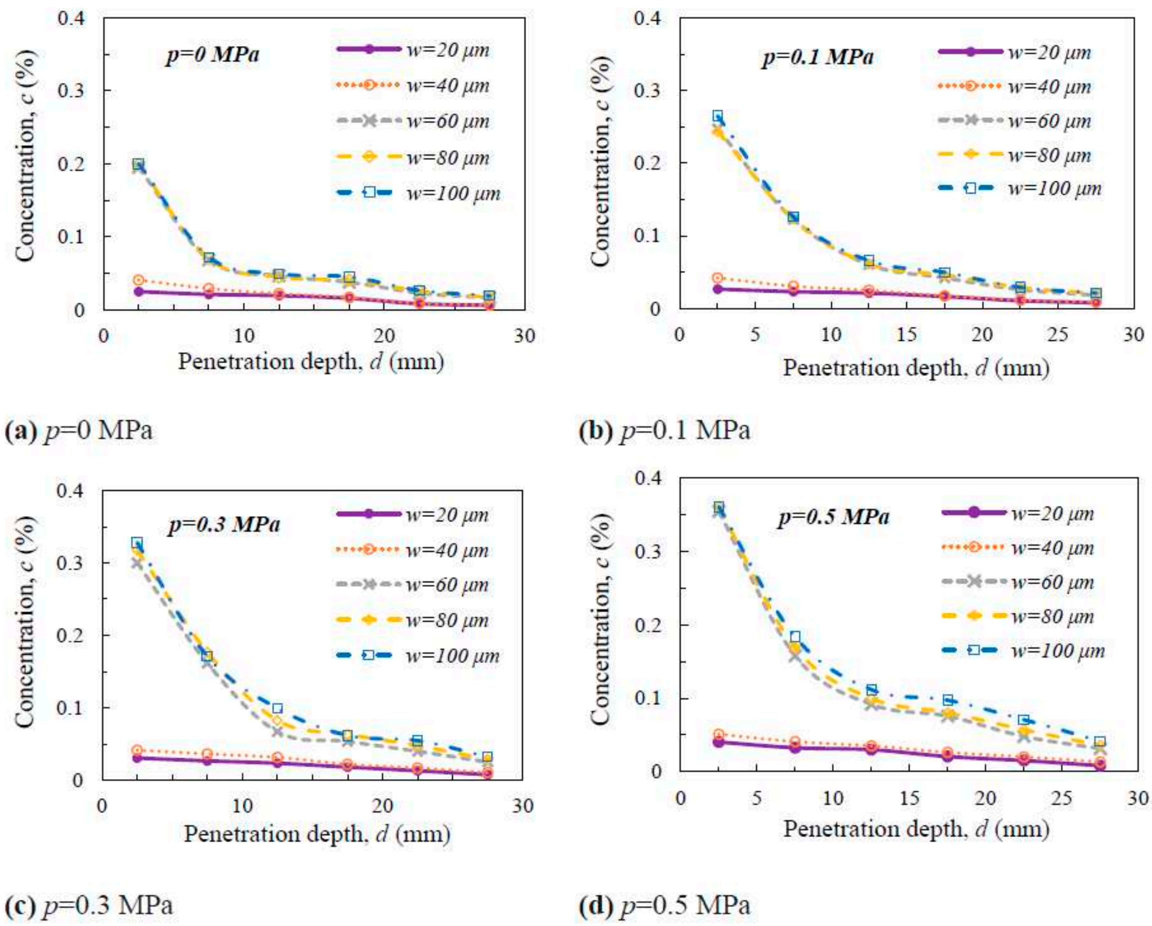

Figure 2. Chloride concentration of the cracked concrete with different crack width (w) under various magnitudes of hydrostatic pressure (p).

3.3. Effect of hydrostatic pressure on chloride diffusion

Figure 3 shows the effect of hydrostatic pressure on the chloride transport in concrete with different crack width. Appreciable difference can be found between the chloride concentration of crack width from 20 μm to 40 μm and that of crack width from 60 μm to 100 μm. The hydrostatic

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pressure slightly affects the chloride transport in the concrete with crack width from 20 μm to 40 μm, whereas the chloride concentration in concrete with crack width from 60 μm to 100 μm is strongly affected. The chloride concentration increases as the hydrostatic pressure increase, particularly for the region near the crack. The slope of the curves for the crack width from 20 μm to 40 μm is around 0.01 to 0.03 and increases to around 0.03 to 0.3 for the crack width from 60 μm to 100 μm. The slope approaches the maximum value of 0.3 at the depth of 2.5 cm. The hydrostatic pressure has dramatically effect on the chloride transport in concrete with the crack width from 60 μm to 100 μm. The relationship between chloride concentration and the hydrostatic pressure is linear:

$$C = C_0 + bp \tag{3}$$

where C is the chloride concentration in concrete, C_0 is the chloride concentration without hydrostatic pressure, b is the curve slope, and p is the hydrostatic pressure. Table 1 shows the correlation parameters of the linear relationship

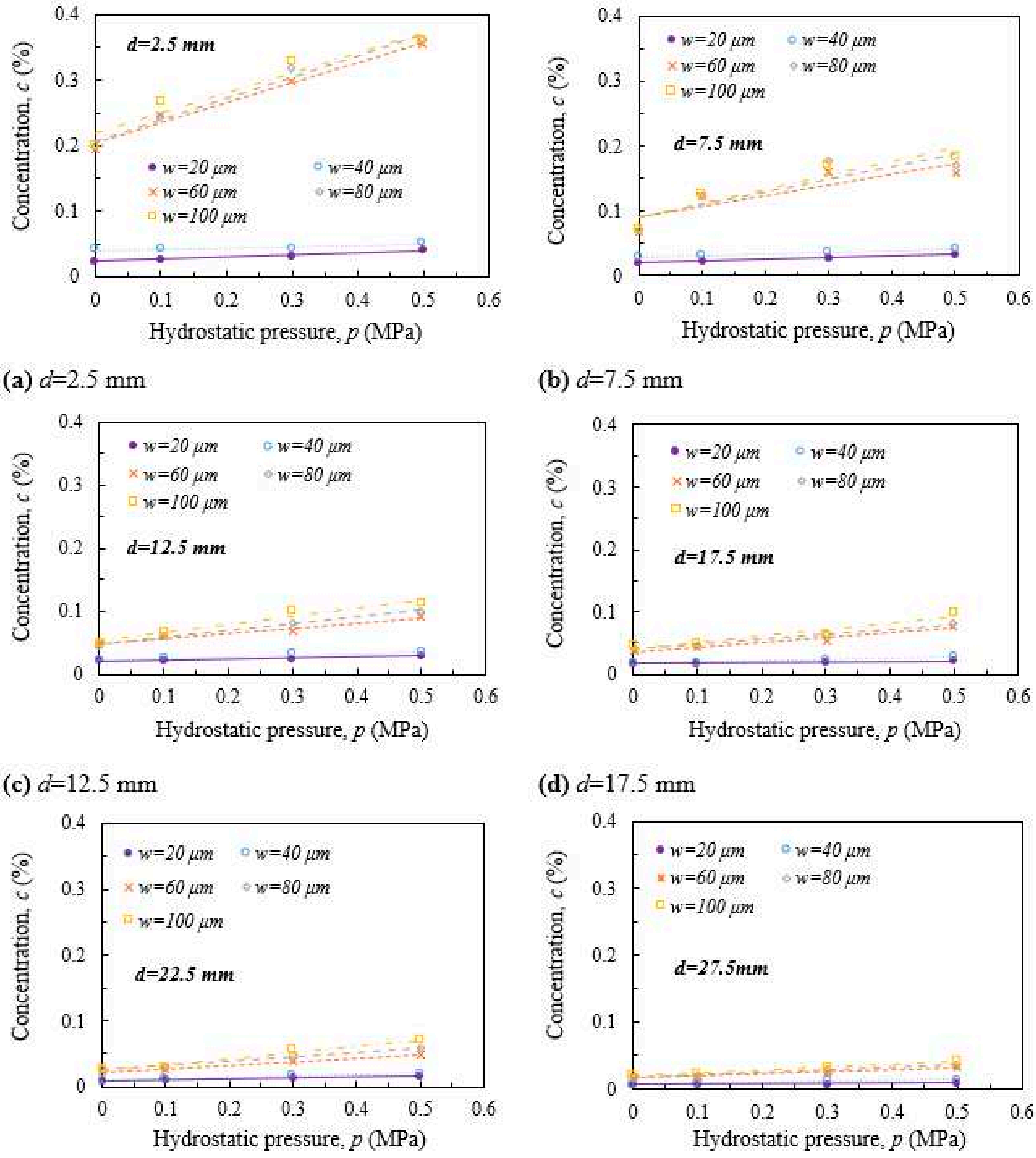


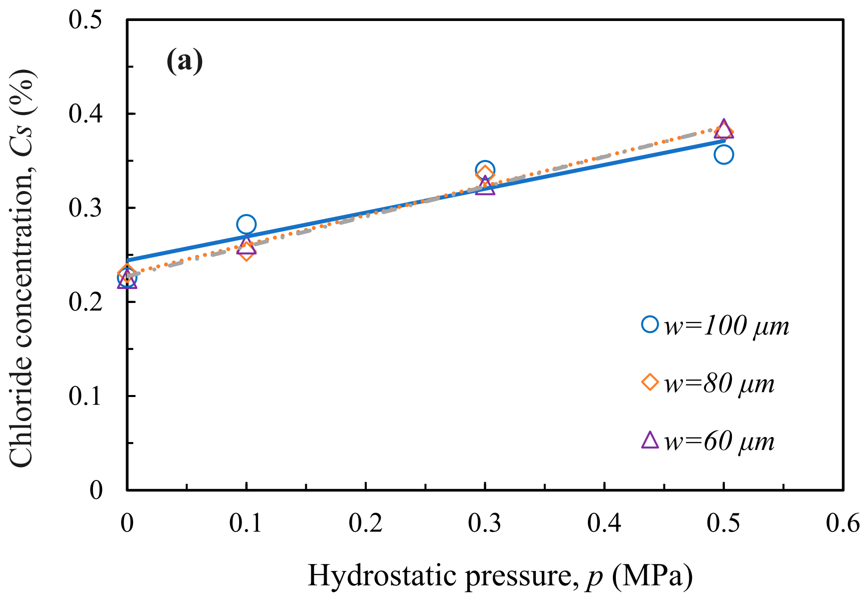
Figure 3. Effect hydrostatic pressure (p) on chloride distribution in concrete with different crack width (w). d is the penertation depth.

Table 1. The parameters for correlating with Eq.(3).

Penetration depth, *d*(mm)	Crack width, *w* (μm)									
	20 μm		40 μm		60 μm		80 μm		100 μm	
	C_0	*b*	C_0	*b*	C_0	*b*	C_0	*b*	C_0	*b*
2.5	0.02	0.04	0.04	0.02	0.21	0.31	0.21	0.32	0.22	0.31
7.5	0.02	0.02	0.03	0.02	0.09	0.17	0.09	0.19	0.09	0.21
12.5	0.02	0.02	0.02	0.03	0.05	0.09	0.05	0.11	0.05	0.13
17.5	0.02	0.1	0.01	0.02	0.04	0.07	0.04	0.08	0.04	0.10
22.5	0.01	0.01	0.01	0.02	0.02	0.05	0.03	0.07	0.02	0.09
27.5	0.01	0.003	0.01	0.01	0.02	0.03	0.02	0.04	0.02	0.05

3.4. Diffusion coefficient

Figure 4a and Figure 4b show the calculated apparent chloride diffusion coefficient D_a and the corresponding surface chloride concentration C_s based on Eq. (2), respectively. The chloride concentration (C_s) for the crack width from 60 μm to 100 μm increases linearly with increasing hydrostatic pressure. The value of C_s at *p*=0 MPa equals 0.22 and reaches 0.38 at *p*=0.5 MPa. The effect of hydrostatic pressure on the chloride diffusion into concrete is probably due to the increase of the surface chloride concentration (C_s) in the cracks given the same chloride concentration in solution, which shows the similar trend to that illustrated in Figure 3. Similarly, the chloride diffusion coefficient (D_a) initially increases over the increase in hydrostatic pressure, and keeps constant when the hydrostatic pressure exceeds 0.3 MPa, particularly for the crack width ranging from 60 μm to 80 μm. For the crack width of 100 μm, D_a increases as the hydrostatic pressure rises from 0 to 0.5 MPa. This suggests that the crack width promotes chloride diffusion under high hydrostatic pressure when the value exceeds 0.1 MPa. Both the calculated apparent chloride diffusion coefficient (D_a) and the surface chloride concentration (C_s) are influenced dramatically by the hydrostatic pressure which results in the trend of chloride diffusion as the hydrostatic pressure varies.



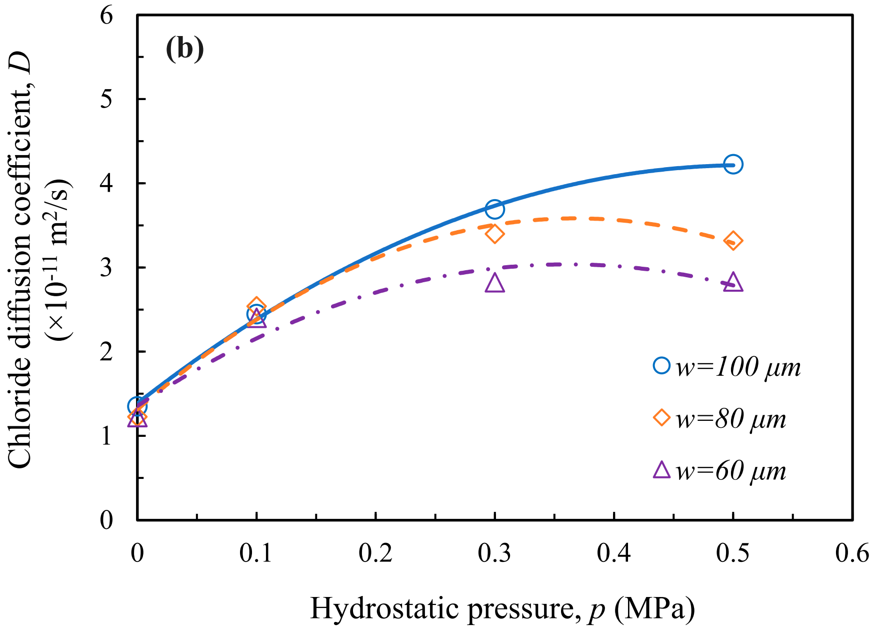


Figure 4. Effect of hydrostatic pressure (*p*) on (a) chloride concentration at the concrete surface, and (b) chloride diffusion coefficent of concrete with different crack width (*w*).

4. Conclusions

This study showed that hydrostatic pressure affected the chloride diffusion in the pre-cracked concrete with different crack widths. The effect of hydrostatic pressure should be considered when estimating the chloride diffusion in cracked concrete and thus the chloride-induced corrosion, by which the service time of the corresponding concrete structure can be accurately predicted, and effective protective actions could be taken. The main conclusions of the study are listed below.

(1) Under the hydrostatic pressure from 0 MPa to 0.5 MPa, chloride concentration in the concrete increased as the crack width increased. The chloride concentration in the concrete exhibited similar trends for the crack width range from 60 μm to 100 μm and for the crack of width from 20 μm to 40 μm, respectively. A critical crack width seemingly exists beyond which the effect of hydrostatic pressure on the chloride diffusion in concrete was significantly enhanced.

(2) For the concrete sample with a crack of width from 20 μm to 100 μm, chloride concentration increased linearly as the hydrostatic pressure ascended, particularly for the crack width ranging from 60 μm to 100 μm. Moreover, the increase of crack width enhances the effect of hydrostatic pressure on chloride diffusion, so the slope of the chloride concentration-hydrostatic pressure curve increased slightly with the increase in the crack width.

(3) The calculated chloride diffusion coefficient and the surface chloride concentration of the cracked samples increased with increasing crack width and hydrostatic pressure.

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