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The Influences of Chloride Ion Transmission on Cracking and Chemical Corrosion Resistance of PHC Pipe Piles

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High-performance concrete (HPC) is crack sensitive. The emergence of cracks reduces the durability of concrete. In the marine environment, HPC tubular piles act on the foundation with water pressure and are more susceptible to chloride ion erosion. This paper studies the impact of the cracking performance and the cracks of different depths and widths of HPC with fly ash on chloride ion permeability. The experimental results show that the pozzolanic activity and filling effect of fly ash enable the HPC to have higher crack resistance grade. The penetration depth value of chloride ions increases with the crack width and depth. Compared with the crack width, the crack depth has a more significant effect on chloride ion permeability. The research in this paper provides the experimental foundation for the chloride ion erosion of offshore HPC tubular piles.

1. Introduction

The construction of marine infrastructure has boosted the economic development of coastal areas and construction of marine infrastructure in China will continue to grow at a high speed for some time in the future (Song and Kwon, 2009; Bentz et al., 2013). The infrastructure such as cross-sea bridges, port wharfs and undersea tunnels consumes a large amount of steel and concrete. The completed project is seriously damaged by the erosion of steel and concrete materials in the marine environment and the chloride ion erosion in the marine environment is the main cause of steel-bar corrosion. An important cause of corrosion (Zhang et al., 2011). High-performance concrete (HPC) is favored for its superior durability, but its low water-to-binder ratio and high cementitious material content make the high-performance concrete crack at an early stage. Once the cracks are formed, it will provide a channel for the erosion of harmful materials, which seriously reduces the durability of HPC (Maes et al., 2017). A large number of scholars have found that reducing the water-to-binder ratio, incorporating supplementary cementitious materials (such as fly ash, slag, silica fume, etc.), incorporating fibers and high temperature curing are all measures to reduce the early stage cracking of HPC (Ye et al., 2016; Ye et al., 2012).

The components of the offshore HPC concrete need to be added with superplasticizers and mineral admixtures to structurally reduce the resistance of HPC to seawater erosion, concrete cracking and the erosion of chloride ions on steel bars to a great extent (Guzmán et al., 2011; Sadati et al., 2015). The wide application of high-performance concrete (HPC) accelerates the development of offshore concrete tubular pile structure. HPC tubular piles mainly act on seawater foundation. Due to long-term salt erosion in seawater, HPC tubular piles are subject to early stage cracking, which accelerates the salt erosion process, reduces the concrete performance of HPC tubular piles and even causes serious engineering accidents. Therefore, it is necessary to conduct in-depth research on the cracking performance and chloride ion permeability of HPC tubular piles (Medeiros & Helene, 2008). This paper simulates the seawater environment and studies the cracking performance of HPC via the plate shrinkage test and the chloride ion permeability of HPC by RCM method.

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2. Experimental Materials and Preparation

2.1 Experimental Raw Materials

The cement selected is the 42.5 grade ordinary Portland cement clink from the Hebei Yanxin Building Materials Co., Ltd.; the Heng brand first-grade fly ash with the specific surface area of 3400cm^2/g; the main chemical components of cement and fly ash are shown in Table 1. Table 2 shows the physical properties of grade I fly ash. The fine aggregate selected is the standard medium sand. Its fineness modulus is 2.7; the apparent density is 2610kg/m^3; the loose bulk density is 1400 kg/m^3; the coarse aggregate selected is the continuously graded gravel with the particle size of 5-20mm. its apparent density is 2680 kg/m^3; the loose bulk density is 1500 kg/m^3. The water reducing agent selected is the poly carboxyl superplasticizer and the water reducing effect is up to 30%-35%.

Table 1: Chemical content of cement and fly ash /wt%

Item	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO
Cement	20.31%	4.68%	4.61%	63.47%	0.06%	0.87%
FA	58%	30%	4.3%	1.5%	3.2%	2.8%

Table 2: Physical properties of grade I fly ash

45μm sieve residue percentage/%	Water demand ratio/%	Loss on ignition	Sulfur trioxide content/%
11.6	86	4.2	1.6

2.2 Experimental Preparation and Test Methods

The HPC sample is prepared according to the mix proportion in Table 3. The dry materials are mixed in a mechanical mixer for 3 min and then water mixed with a water reducing agent and air entraining agent for 5 min (Abdelkader et al., 2010). The fresh concrete is poured into different test molds separately: the sample size for compressive strength is the test cube of 100mm*100mm*100mm; the sample size for flat plate method restraining cracking is 600mm*600mm*63mm. The mould is fixed with the bottom plate using the and each side of the mould is welded with two lines of, altogether 14, bolts with the size of Φ10mm*100mm bolts extended to the inside of the anchor in staggered arrangement; the prefabricated cracking method is adopted for the chloride ion penetration. The sample size is Φ100mm*200mm and the steel discs of 0.1, 0.2 and 0.3 mm are inserted respectively in the sample preparation with the insertion depths of 5 mm and 10 mm respectively. After curing for 21 days, it is cut into two Φ100 mm*50 mm samples with prefabricated cracks by cutter. The specific test methods are as follows:

(1) Compressive strength test: The YAW-300 pressure tester is used in the experiment to test the compressive strength of HPC cube samples at 7d, 28d, 56d and 90d. The loading speed is 0.5-0.8 MPa/s and three samples are taken for each group of strength test.

(2) Crack test: The crack width is measured by a crack visualizer.

(3) Rapid chloride ion permeation test: The chlorine ion permeation test is carried out by using the mix proportion in No. 4 group and the RCM unsteady chloride ion permeation method is selected for the chloride ion permeation test. The specific experimental procedure refers to the "Standard test method for long-term performance and durability of ordinary concrete ".

Table 3: HPC tubular pile sample mix ratio

No.	Water gel ratio	Water	Cement	Fly ash	Gravel	Sand	Water reducer
A	0.4	194	482	0	1046	697	1.4%
B	0.36	176	489	0	1046	697	1.4%
C	0.32	159	496	0	1046	697	1.4%
D	0.32	159	347	149	1046	697	1.4%
E	0.32	159	272	224	1046	697	1.2%
F	0.32	159	198	298	1046	697	1.0%

3. Analysis of Experimental Results

3.1 Analysis of Compressive Strength Results

Figure 1 shows the compressive strength value of HPC samples. Under the same mix proportion, the compressive strength of the sample increases with the curing period; the compressive strength value increases with the decrease of water-to-binder ratio. Furthermore, the incorporation of fly ash reduces the compressive strength of the sample to a certain extent. Compared with the sample with 0% of fly ash (sample C), the compressive strength value of the 7d concrete sample with 30%, 40% and 60% of fly ash decreases by 36%, 49% and 64% respectively and the figure of the 28d concrete sample is 10%, 25% and 41% respectively. The reason for this phenomenon is that the activity of fly ash is not high in the early stage. However, with the progress of cement hydration reaction, the cement hydration provides a good alkaline environment for fly ash and the fly ash serves as the supplementary cementitious material to generate secondary hydration reaction so as to increase the compressive strength at a later stage (Thomas & Bremner, 2012).

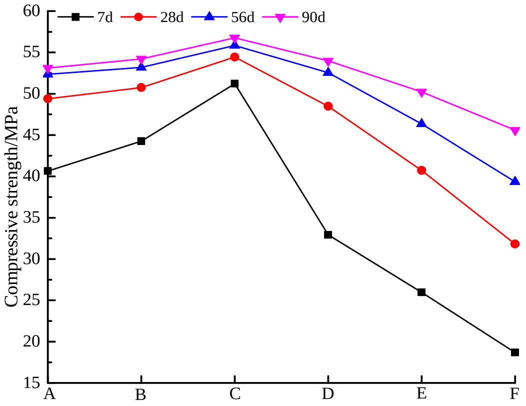


Figure 1: HPC sample compressive strength value

3.2 Cracking Analysis of HPC Samples

Table 4: Resistance level rating standard

Crack resistance grade	Evaluation criterion
First level	η≥0.70
Second level	0.55≤η<0.70
Three level	0.40≤η<0.55

Table 5: HPC concrete cracking test data

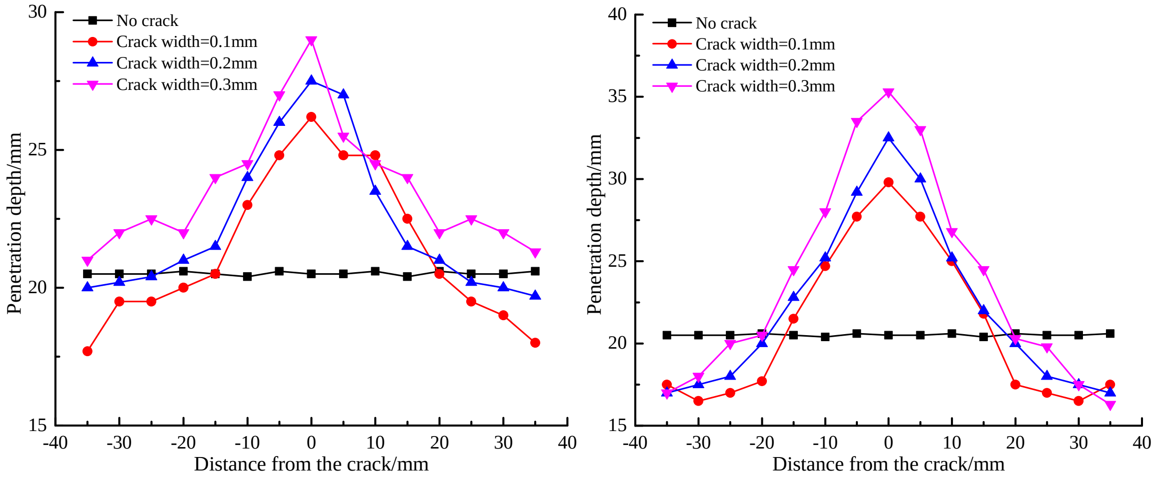
No.	ω_{max}/mm	Acr/mm^2	Cracks number	η	Crack resistance grade
A	1.32	2122	26	0.53	Third level
B	1.71	3926	26	0.12	—
C	2.10	4396	20	—	—
D	0.87	2246.5	20	0.50	Third level
E	0.69	1281.3	15	0.72	One level
F	0.73	1237.5	15	0.73	One level

The crack resistance of concrete can be evaluated by the crack resistance level (Shao & Li, 2014), as shown in Table 4. The experimental study shows that there is a continuous main crack in the sample without the fly ash has in the flat shrinkage test and some micro cracks are scattered on the main crack; while there are only some micro cracks in the sample with fly ash without continuous main crack. Table 5 shows the concrete cracking test data of each HPC. It can be clearly seen that under the same water-cement ratio, the cracking area of the sample decreases with the increase of fly ash. The concrete crack resistance grade is three, two and one when the fly ash content is 30%, 45% and 60%. The main reason for this phenomenon is that the cement content is reduced after the incorporation of fly ash, which reduces the early hydration heat, the evaporation rate of concrete moisture to a great extent and the drying shrinkage. On the other hand, the fly ash has a micro-aggregate filling effect, enabling the concrete structure to be more compact (Kariem et al., 2017, Li & Shao, 2014).

3.3 Analysis of Rapid Chloride Ion Permeability Experiment

3.3.1 Impact of crack width on chloride ion permeability

Many researchers have found that cracks have an important influence on chlorine ion permeability. The chloride ion permeability migrates into the concrete through pores and micro cracks inside the concrete. The HPC tubular pile acts on the foundation with large water pressure and the water will penetrate into the interior with the micro cracks on the HPC tubular piles, which accelerates the corrosion of steel bars and reduces the service life of HPC tubular piles. Figure 2 is a schematic diagram showing the impact of crack depth on the chloride ion permeability of HPC samples. It can be seen that when the crack depth is the same, the penetration depth of chloride ions increases with the crack width. The smaller the distance from the crack, the greater the penetration depth of chloride ions. When the crack width is 0.1 mm and 0.2 mm respectively, the penetration depth of chloride ions is smaller than that of the sample without cracks when the distance from the crack is 15-20 mm. By calculation, it can be concluded that the maximum penetration depth, the average penetration depth and the total average penetration depth in each region of chloride ions increase with the crack width when the crack width is from 0.1 mm to 0.3 mm.



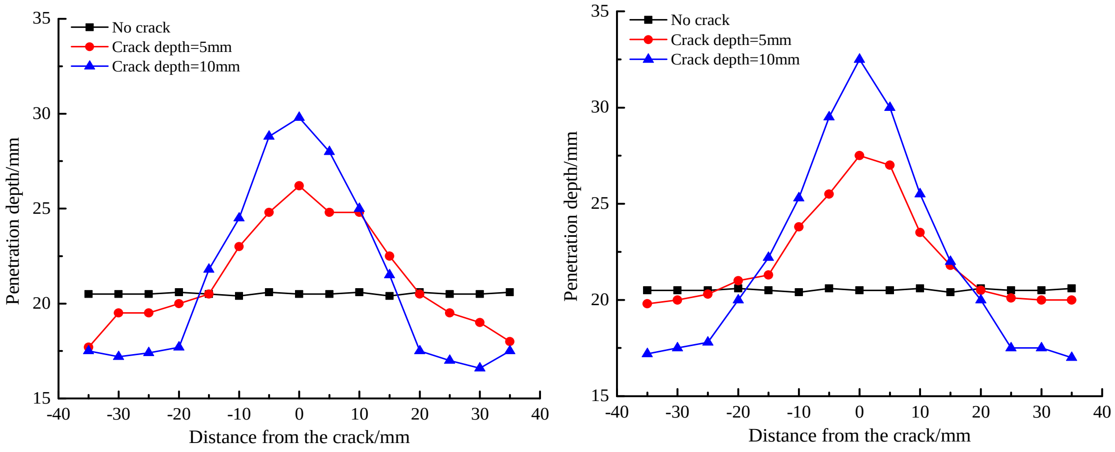
(a) Crack depth=5mm

(b) Crack depth=10mm

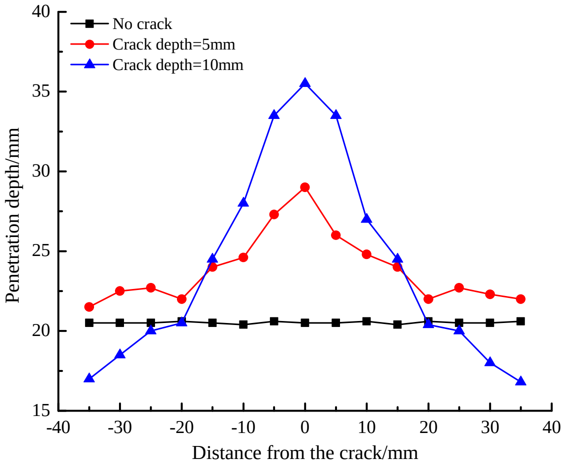
Figure 2: Crack width to the depth of chloride ion penetration of HPC specimens

3.3.1 Impact of crack depth on chloride ion permeability

When the crack width is the same, the penetration depth of chloride ions increases with the crack depth. Furthermore, there is a big difference in the penetration depth of chloride ions in different regions and the penetration depth of chloride ions 0 to 15 mm from the crack is higher than that of the sample without cracks; the penetration depth of chloride ions 20 to 35 mm from the crack is lower than that of the sample without cracks. The reason for this phenomenon is that the existence of cracks provides a channel for the transport of chloride ions. Under the action of an external electric field, most of the chloride ions tend to permeate through the channel, and thus the average penetration depth of the sample far from the crack is lower than the total average penetration depth. Figure 4 shows the relationship between the crack depth and the diffusion coefficient of chloride ions. Compared with the crack width, the impact of crack depth is more significant on the chloride ion permeability. The effect of chloride ion depth is more significant on the maximum penetration depth of chloride ions.



(a) Crack width=0.1mm *(b) Crack width=0.2mm*



(c) Crack width=0.3mm

Figure 3: Crack depth to the depth of chloride ion penetration of HPC specimens

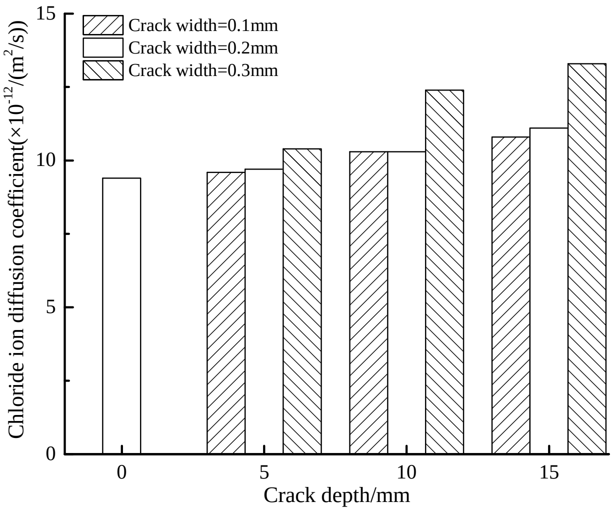


Figure 4: Relationship between crack depth and chloride ion diffusion coefficient

4. Conclusion

This paper prepares the high-performance concrete to simulate the erosion effect of seawater environment on tubular piles and studies the cracking of HPC samples and the chloride ion permeability of the sample with cracks. The specific conclusions are as follows:
(1) The compressive strength value increases with the decrease of water-to-binder ratio and the incorporation of fly ash reduces the compressive strength value of the sample to some extent. The secondary hydration reaction of fly ash increase the compressive strength value of the sample at later stage.
(2) Under the same water-cement ratio, the cracking area of the sample decreases with the increase of fly ash. The crack resistance grade of the concrete is three, two and one when the fly ash content is 30%, 45% and 60% respectively.
(3) The chloride ion permeability increases with the crack depth and crack width, but the impact of crack depth on chloride ion permeability is more significant than that of the crack width. The effect of chloride ion depth is more significant on the maximum penetration depth of chloride ions.

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