# INVESTIGATION OF THE CHLORIDE ION PENETRATION OF HIGH-PERFORMANCE POLYPROPYLENE FIBER REINFORCED LIGHTWEIGHT AGGREGATE CONCRETE

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***In this work, to decrease the chloride ion penetration of high-performance polypropylene fiber reinforced lightweight aggregate concrete (HPPLWAC), mineral admixtures were added into concrete mixtures in two forms. One was added in powder form and the other was using the mineral admixture paste to prewet the lightweight aggregates. The mineral admixtures including fly ash, slag, silica fume added in the separate or composite mixed forms. The scanning electron microscope (SEM) was used to observe the microstructures of concrete to reveal the improvement mechanism of permeability. The results showed that the separate mineral admixtures could decrease the chloride ion penetration of HPPLWAC. When 10% silica fume was added, the chloride ion diffusion coefficient of HPPLWAC decreased by 71.1% compared to the reference group and obtained the best resistance to chloride ion penetration compared to other groups. Composite mixed mineral admixtures could effectively improve the resistance to chloride ion penetration of HPPLWAC. The optimal resistance to chloride ion penetration was obtained when adding 20% slag and 10% silica fume into the reference group and its chloride ion diffusion coefficient decreases by 73.2% compared to the reference group. The lightweight aggregates prewetted by using mineral admixture paste could improve the chloride ion penetration of HPPLWAC, and the slag paste had the best effect. Using DPS to prewet lightweight aggregates had more significantly effect on improving the resistance to chloride ion permeability of HPPLWAC than lightweight aggregates prewetted by using mineral admixture.***

***Keywords:*** *high-performance polypropylene fiber; lightweight aggregate; chloride ion penetration; prewetting; microstructure*

## 1. Introduction

The resistance to chloride ion permeability is one of the most important indexes to evaluate the durability of concrete. Improving the resistance to chloride ion penetration has a great significance to enhance the durability of concrete. Compared to ordinary concrete, lightweight aggregate concrete (LWAC) has the characteristics of light weight and excellent durability [1,2]. Previous study has shown that the resistance to chloride ion penetration of LWAC increased with the age of concrete [3].

The concrete cover can effectively prevent the erosion medium invading into the concrete. However, chloride ions can easily permeate into the concrete structure through the interlocking pore of lightweight aggregate (LWA). It limits the application of LWAC in marine environment [4]. It has been found that the bridging effect of fibers can delay the formation of concrete cracks and reduce the width of crack [5-7], and thus improved the chloride penetration resistance of concrete. Besides, lowing the water to binder ratio could slightly decrease the permeability of concrete [8]. The traditional method to improve the resistance of ordinary concrete to chloride ion penetration is using mineral admixtures to partial replace cement [9]. Adding mineral materials into concrete can improve the workability and mechanical properties of concrete [10]. The pozzolanic and micro-aggregate effects of mineral materials can significantly decrease the porosity and thus improve the durability of concrete [11-13]. Composite mixed mineral admixtures can produce superposition effect and improve the permeability of concrete [14]. The literature of [15-17] showed that the prewetted LWAs could promote the hydration of cementitious materials and reduce the possibility of cracking, and thus decrease the chloride ion penetration.

Even though the study on chloride ion permeability of concrete has been relatively mature, the study on the resistance to chloride ion permeability of HPPLWAC is relatively limited. The aim of this work is to find a method for improving the resistance to chloride ion penetration of HPPLWAC. Three mineral admixtures including fly ash (FA), slag (S) and silica fume (SF) were added into the HPPLWAC in the separate and/or composite mixed forms. Mineral admixture pastes and DPS were used to prewet lightweight aggregates, respectively.

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**Table1**

Properties of lightweight coarse aggregate

| Bulk density (kg/m$^3$) | Apparent density (kg/m$^3$) | Cylinder compressive strength (MPa) | Water absorption in 1h (%) |
|---|---|---|---|
| 750 | 1410 | 5.0 | 16.0 |

**Table2**

Properties of HPP fiber

| Length (mm) | Diameter (mm) | Density (g/cm$^3$) | Tensile strength (MPa) | Elastic modulus (MPa) | Elongation (%) |
|---|---|---|---|---|---|
| 30 | 0.9 | 0.95 | 543 | 9 884 | 15±2 |

**Table 3**

Performance parameters of fly ash and slag

| Mineral admixture | +45μm (%) | Water requirement ratio (%) | LOI (%) | Activity index (%) | |
|---|---|---|---|---|---|
| | | | | 3d | 28d |
| Fly ash | 7.2 | 92 | 2.3 | 65 | 101 |
| Slag | 6.5 | - | 1.2 | 75 | 107 |

**Table 4**

Performance parameters of silica fume

| Bulk density (kg/m$^3$) | Average grain diameter (μm) | Specific surface area (m$^2$/g) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ |
|---|---|---|---|---|---|
| 1 600-1 700 | 0.1-0.3 | 20-28 | ≥98% | ≤0.7% | ≤0.6% |

**Table 5**

Mixture proportion (kg/m$^3$)

| Water | Cement | Sand | Aggregate | Fiber |
|---|---|---|---|---|
| 190 | 430 | 780 | 608 | 9 |

## 2.Experimental program

### *2.1. Materials*

P·O 42.5R ordinary Portland cement was used in this study. Fly ash ceramsite with a particle size of 5-20 mm and a spherical shape was used as lightweight coarse aggregate. The properties of coarse aggregate are given in Table 1. River sand with a mud content less than 3%, a bulk density of 1 550 kg/m$^3$ was used as fine aggregate.

The high-performance polypropylene (HPP) fiber was used as reinforcement material with the properties listed in Table 2. The performance parameters of mineral admixtures including fly ash, slag, and silica fume are shown in Table 3 and Table 4, respectively. DPS with a PH of 11.2 and a density of 1.08 g/cm³ was used to prewet lightweight aggregates. The water reducer with a water reducing ratio of 20% was used to adjust the workability of concrete mixtures. In this study, the mixture proportion of reference concrete with a strength grade of LC30 was designed, with listed in Table 5.

### *2.2. Experimental method*

The RCM method specified in GB/T 50082-2009 (similar to NT build 492) was used to determine the chloride ion penetration of HPPLWAC. The cylinder specimens with a diameter of 100 mm and a height of 150 mm were cast in Figure 1 and de-mode after 24h. Then these specimens were cured in the standard curing room for 7d. After that, the test specimens were sawed into three specimens with a diameter of 100 mm and a height of 50 mm to perform the chloride ion penetration test with the device shown in Figure 2.

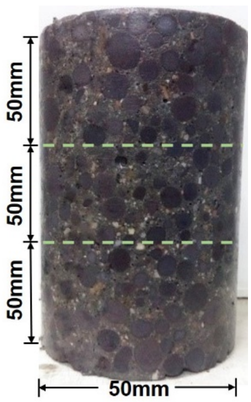


Fig.1 -Specimens size.

The diffusion coefficient of chloride ion was determined by the following equation.

$$D_{RCM} = \frac{0.0239 \times (273+T)L}{(U-2)t}\left(X_d - 0.0238\sqrt{\frac{(273+T)LX_d}{U-2}}\right)$$

Fig.2 - Device of chloride ion penetration.

where, $D_{RCM}$ is the chloride ion diffusion coefficient (×$10^{-12}$ $m^2/s$); $U$ is the absolute value of the applied voltage (V); $T$ is the average temperatures of the initial and final of the anode solution (℃); $L$ is the height of specimen (mm); $X_d$ is the average penetration depth of chloride ions (mm); t is the duration time of the test (h).

## 3. Results and discussion

### *3.1. Separate mineral admixtures*

Figure 3 shows the diffusion coefficient with separate mineral admixtures used to replace cement in HPPLWAC.

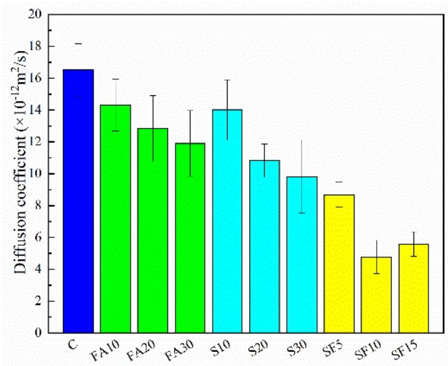


Fig.3 - Diffusion coefficient of separate mineral admixtures.

According to Figure 3, mineral admixture could effectively reduce the chloride ion diffusion coefficient of HPPLWAC. It indicated that adding proper mineral admixture could improve the resistance to chloride ion permeability of HPPLWAC. Specimen with single SF added had the minimum chloride diffusion coefficient compared with other specimens. The chloride diffusion coefficient of HPPLWAC decreased with the increase of the FA and S content. When FA and S content of 30 kg/$m^3$ was used to substitute the cement, the diffusion coefficient of HPPLWAC decreased by 27.9% and 40.5%, respectively.

The diffusion coefficient of HPPLWAC decreased firstly and then increased with the increase of SF content. When 10% SF was added into concrete, the diffusion coefficient of HPPLWAC reduced by 71.1%. As it is well known, the resistance to chloride ion permeability of concrete is mainly related to the aggregate type, mortar properties and interfacial transition zone (ITZ) of aggregate-paste and fiber-paste. The pozzolanic effect of mineral admixtures promoted the formation of C-S-H gel and reduced the $Ca(OH)_2$ content, leading to the improvement of pore structure and ITZs. Besides, the prewetted LWAs provided sufficient water for the pozzolanic reaction of mineral admixture. Besides, SF has a smaller particle size and larger specific surface area than FA and S. It could effectively fill the pores among hydration products and cement particles, increasing the compactness of concrete. Due to the pozzolanic and micro-aggregate effects of mineral materials, the concrete matrix became compactness and thus decreased the diffusion coefficient of HPPLWAC.

### *3.2. Composite mineral admixtures*

Compared to single mineral admixtures, composite mixed mineral admixtures could produce a superposition effect and effectively improve the permeability of concrete. In this section, the influence of composite mixed mineral admixtures on the diffusion coefficient of HPPLWAC was studied. In this study, nine composite mineral admixtures were selected to replace cement with the diffusion coefficient of HPPLWACs shown in Figure 4.

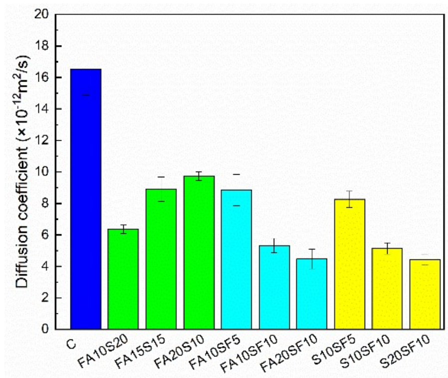


Fig.4 - Diffusion coefficient of composite mixed mineral admixtures.

According to Figure 4, composite mineral admixtures could decrease the diffusion coefficient of HPPLWAC. The anti-chloride ion performance of HPPLWAC with added composite mineral admixture were all superior than that of HPPLWAC with added single mineral admixture for the same replace content. The specimen of S20SF10 obtained the minimum diffusion coefficient with the permeability coefficient reduced by 73.2% mainly due to the superposition effect of composite mineral admixtures. The pozzolanic reactivity and reaction rate of SF was higher than that of FA and S, which was conducive to the formation of C-S-H. Besides, the CaO in S could promote dissolution of aluminum and silica phases in FA and promote the formation of C-S-H and AFt on the surface of FA particles. The increased aluminum and silicon concentration in phase could promote the hydration of S and SF[18-19].

### *3.3. Aggregate prewetted with mineral admixture paste and DPS*

The chloride ion could penetrate into LWAs easily through the connected pores. Based on this reason, mineral admixture pastes and DPS were used to prewet LWAs. The test results are shown in Figure 5.

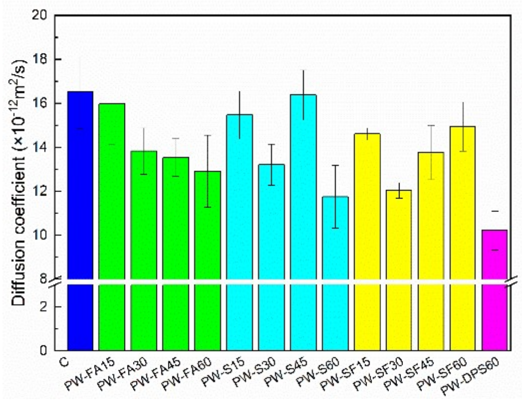


Fig.5 - Diffusion coefficient of HPPLWAC with aggregate pre-wetted by mineral admixture paste and DPS.

According to Figure 5, the mineral admixture pastes and DPS had a positive effect on the resistance to chloride ion permeability of HPPLWAC. The HPPLWAC with the LWAs prewetted by using S paste obtained the minimum chloride diffusivity. Due to the permeation of mineral admixture paste, the products of mineral admixtures' pozzolanic reaction filled some pores on the surface of LWAs. Besides, some mineral admixtures paste was easily adhered to the surface of LWAs and the late pozzolanic reaction of mineral admixture paste were beneficial for improving the compactness of ITZ between LWA and paste. The above two reasons could effectively improve the resistance to chloride ion permeability of HPPLWAC. It could also be found that the diffusion coefficient of chloride ion decreased with the increase of prewetting time of FA paste and S paste. However, this coefficient decreased firstly and then increased with the increase of the prewetted time of SF paste. The increased trend was might because the continuous water absorption of LWAs with the increase of the prewetting time led to increasing the water-to-binder ratio of ITZ between LWA and paste decreasing the compactness of this ITZ.

The aggregate prewetted by DPS had the most optimal effect on improving the resistance to chloride permeability of HPPLWACs. Compared to other groups, the permeability coefficient of HPPLWACs with LWAs prewetted by DPS was reduced by 38.16%. The reason was that DPS could react with $Ca(OH)_2$ and CaO in concrete as a kind of deep permeable sealing material. A silica gel film was produced when DPS entered the pores of LWAs, increasing the compactness of concrete matrix.

## 4. Microstructure

The performance of materials was mainly depended on the internal structure of materials. In this study, the hydration products and the ITZ between aggregate and paste were observed by SEM.

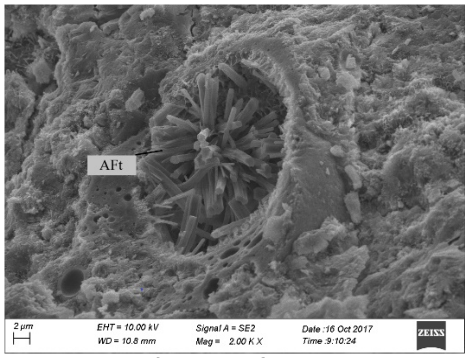


Fig.6 - Microstructure of HPPLWAC with added FA.

Figure 6 shows the microstructure of HPPLWAC with added FA at 56d. The main hydration products were hydrated calcium silicate gel (C-S-H), calcium hydroxide (CH), and ettringite (AFt). The pozzolanic reaction of FA consumed CH, and formed C-S-H. The formed C-S-H could increase the compactness of concrete matrix and reduced the intrusion paths of chloride ion.

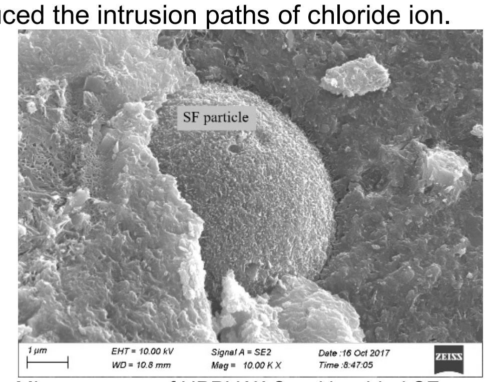


Fig.7 - Microstructure of HPPLWACs with added SF.

Figure 7 exhibits the microstructure of HPPLWACs with added SF at 56d. It could be seen that the voids of not hydrated cement particles and hydrated products could be effectively filled by SF particles. Besides, the pozzolanic reaction of mineral admixtures increased the compactness of concrete matrix. The above two reasons could explain that adding proper mineral admixtures could increase the resistance to chloride permeability of HPPLWACs.

Figure 8 shows the microstructure of ITZ between LWA and paste added SF as mineral admixture at 56d. It could be seen that the above ITZ was filled with a large number of hydration products. The superior effect of resistance to chloride permeability for HPPLWACs with added mineral admixture paste than added mineral admixture powder could be explained by the

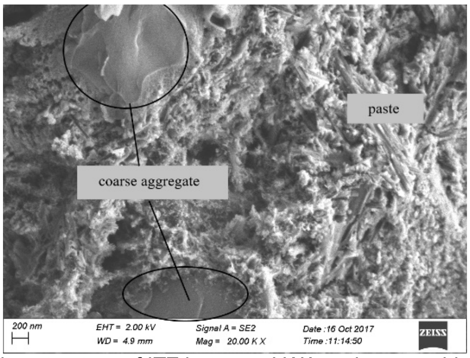


Fig.8 - Microstructure of ITZ between LWA and paste added SF as mineral admixture.

following reasons. For LWAs prewetted by mineral admixture paste, a lot of SF particles were adsorbed into the connected voids of LWAs. Then the SF particles would produce pozzolanic reaction with the cement paste. The products of pozzolanic reaction could filled the connected void and restrain the intrusion of chloride ion. Besides, pozzolanic and micro-aggregate effects of mineral materials could compact the micro-structure of concrete matrix.

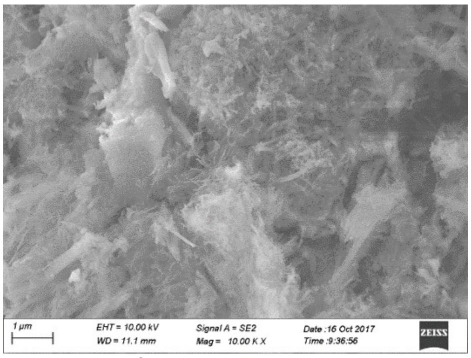


Fig.9 - Microstructure of ITZ between paste and LWAs prewetted using DPS.

Figure 9 shows the microstructure of ITZ between paste and LWAs prewetted using DPS at 56d. It could be seen that the above ITZ were filled with a large amount of hydration products and the ITZ became very compact. The thin crystalline film formed due to the crystallization of DPS would expand in the presence of water and shrinks when the water was absent.

Since the chloride ion in concrete mainly depended on the medium of water, the expanded crystalline film could effectively obstruct the transmission channel of chloride ion on LWAs. Hence, it could improve the resistance to chloride ion erosion of HPPLWACs.

## 5.Conclusion

According to the test results of this study, the following conclusions could be drawn:

(1) The mineral admixture could significantly effect on increasing the resistance to chloride ion permeability of HPPLWAC no matter in the separate form or in composite mixed form. For the separate form, SF10 obtained the most optimal effect. For the composite mixed form, FA20SF10 had the minimum chloride diffusivity.

(2) The aggregates pre-wetted by using mineral admixture paste could improve the resistance to chloride ion permeability of HPPLWAC. The LWAs prewetted by using S paste had the best effect on improving the resistance to chloride ion penetration than LWAs prewetted by using FA paste and SF paste.

(3) Compared with the LWAs prewetted by using mineral admixture paste, DPS could significantly improve the chloride penetration resistance of HPPLWAC.

(4) The LWAs prewetted by using mineral admixtures could improve the ITZ between LWAs and paste. Among three different mineral admixture paste, SF paste obtained the best effect.

(5) The LWAs prewetted by using DPS could improve the compactness of concrete matrix and had the superior improvement effect of resistance to chloride permeability than mineral admixture paste.

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