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Durability of Polypropylene Fiber Concrete Exposed to Freeze-Thaw Cycles with Deicing Salts

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***Abstract*—In cold snowy regions, buildings are usually exposed to deicing salts. The corrosion of reinforcement steel is accelerated under the environment, and results in deterioration of concrete, especially under freeze-thaw condition. Polypropylene fibers (PPF) are used to reduce concrete cracking, and it can also improve concrete's durability properties under freeze-thaw conditions with the existence of deicing salt. A total of four groups of specimens with different amounts of PPF were prepared. To observe the effects and roles of PPF on specimen's durability performance, freeze-thaw tests, microscopic observation, and chloride concentration tests were carried out. The results showed that mixing PPF into specimens improved the concrete resistance of freezing and thawing with deicing salt, chloride penetration, compared to the control volume containing 0.1% PPF.**

***Keywords*—polypropylene fiber concrete; durability; freeze-thaw damage; deicing salt; chloride concentration**

I. Introduction

Reinforced concrete structures are simultaneously exposed to chemical, mechanical, and physical attack during the service period. Each mechanism can lead to reinforced concrete structure's deterioration. In addition, the deterioration process can be accelerated considerably by the synergistic action of different attack forms. One of the major causes of concrete structure deterioration was steel corrosion induced by chloride. Chloride ions from deicing salt or sea water can induce the corrosion of the reinforcement [1]. Scaling can occur due to a number of processes: 1) exposure of highly saturated concrete to freezing and thawing [2], 2) scaling of concrete surfaces [3], 3) crystallization of salt in concrete pores that results in production of internal stress [4], and 4) expansion forces as a result of corrosion of reinforced concrete structure when a chloride-based deicing salt is used [5]. While the physical attack of deicing salts has been widely investigated, the chloride ingress into concrete has been studied less frequently.

In recent years, Fibers have gained popularity used in reinforced concrete structure, mainly to improve the resistance of concrete to dry shrinkage cracking [6]. Fiber-matrix interface characteristics are significantly important in controlling the fiber pullout and debonding process that governs the nonlinear behavior and stress-crack opening relationship of concrete [7]. Generally, sliding, pulling-out, and debonding of the fibers enhance the bridging action during both macro and micro cracking of the matrix [8]. Although resistance of concrete to dry shrinkage cracking is reduced by fiber, the fiber concrete's performance may still deteriorate due to chemical, environmental, or physical conditions [9]. Polypropylene fibers (PPF) are commercially used to control plastic shrinkage cracking of concrete at relatively low volume fractions. However, few data is existed on the deterioration due to PPF concrete's frost damage under salt conditions. To investigate the resistance of concrete to frost damage with PPF under salt conditions, concrete with different PPF amounts was experimentally studied under freeze-thaw cycles considering salt conditions.

The authors of this paper make an effort to interpret the durability of PPF concrete by investigating the relative dynamic modulus of elasticity and internal frost damage when exposed to a deicing salt environment. The chloride ingress behavior of PPF concrete was also studied to identify a suitable PPF fiber content to enhance the intrinsic frost resistance of concrete.

II. Materials and Methods

A. Raw Materials

The ordinary Portland cement with Grade 42.5 used in this study and was produced by the Shannxi Qinling Cement Plant. The crushed limestone had a diameter of 5–15 mm and was obtained from Jingyang. Jing River sand was used with a fineness modulus of 2.62. The fly ash was produced by the Wei River Power Plant. The mixing water was Xi'an tap water. Four groups of concrete samples were designed with different amounts of fiber volume. Table I shows the all samples' mixing proportions.

TABLE I. MIX PROPORTIONS OF SAMPLES

Type	*Cement* (kg/m^3)	*Stone* (kg/m^3)	*Sand* (kg/m^3)	*Fly ash* (kg/m^3)	*Fiber Volume (%)*	*Water reducer*
C1	375	1048	720	85	0	proper
C2	375	1048	720	85	0.9	
C3	375	1048	720	85	2.7	
C4	375	1048	720	85	4.5	

B. Experimental Procedures

Specimens with the dimensions of 100 mm × 100 mm × 100 mm and 100 mm × 100 mm × 400 mm were prepared in the laboratory. All specimens were cured in a standard environment with a relative humidity of 95%±5% and temperature of 20 °C±2 °C for one month and then cured under atmospheric conditions for two months.

In order to simulate actual freeze-thaw conditions with deicing salt, specimens repeated the freeze-thaw cycles of in accordance with JTJ 270-98 (MCC 1998), and the deterioration during the test was assessed. In the test, a chloride solution with 3.5% NaCl concentration was used. Each specimen's relative dynamic modulus of elasticity were measured after 240 freeze-thaw cycles.

The amount of chloride ions were measured by cubic specimens. The samples were used for drilling to generate concrete powder from various depths of the sample. The chloride content in concrete was obtained by traditional titration with silver nitrate in accordance with the standard test JTJ 270-98 of China (MCC 1998)[10] and ASTM C1218-17 (ASTM 2017)[11].

III. RESULTS

A. Change of Relative Dynamic Modulus Of Elasticity

The relative dynamic modulus of elasticity of samples are shown in Figure I after the freeze-thaw cycles in salt solution. The results in Figure I showed that, the relative dynamic modulus of elasticity degraded as the freezing-thawing increased. Specimen C4, which relative dynamic modulus of elasticity decreased to 97.9% of the initial value, had deteriorated slightly. However, specimen C1's relative dynamic modulus of elasticity had severely deteriorated, which decreased to 93.85% of the initial value. All curves have three phases, the initial phase slope was relatively steep, and the second curve exhibited a steady and gradual slope, and the curve slope was steep finally. The results showed that, the resistance of concrete to freeze-thaw cycles was improved by adding PPF significantly. The incorporation of fiber reduced the specimen damage and also inhibited the extension of micro-cracks.

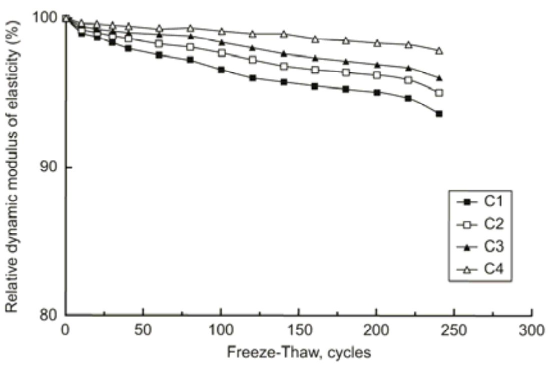
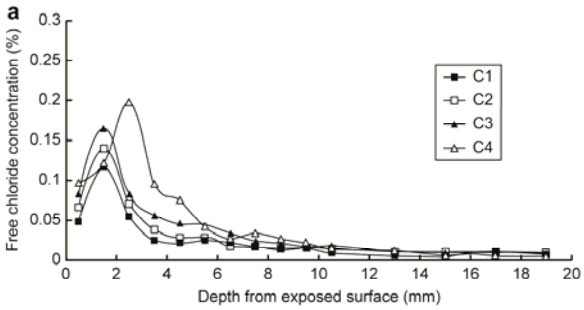


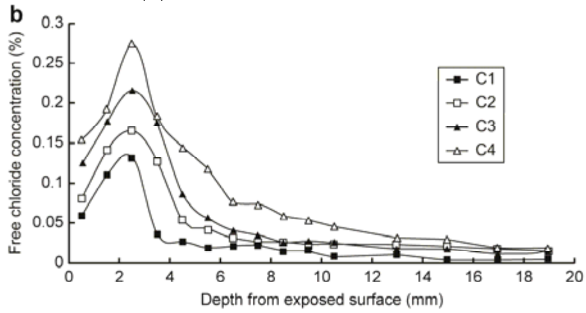
FIGURE I. RELATIVE DYNAMIC MODULUS OF ELASTICITY CHANGES WITH NUMBER OF FREEZE-THAW CYCLES

B. Chloride Profile of PPF Concrete

After the 50th and 100th cycles, the specimens' chloride concentrations are measured, which are plotted in Figure II. All curves have a similar trend. There is a chloride ion enrichment region between a depth of 1 and 4 mm from the surface of the specimens. As freeze-thaw cycles and fiber volume increase, the chloride ion concentration tended to increase. In specimen C2, the highest chloride content deposit at 1.5 mm from the surface; similarly, it is 2.5 mm for C4, where the chloride ion changed violently near the peak. It is believed that the moisture induce the chloride migration under the freezing and thawing, which can be interpreted in two phases. First, during the freeze phase, water is removed from the mesopores in the cement paste by the ice crystals in the air void; therefore, the pore's higher salt concentration is induced by liquid's transportation. Second, the surrounding mesopores will be refilled by liquid melt from ice during the thaw phase; the liquid induced the chloride migration to the surrounding pore. The chloride profile was contributed by two phases.



(A) 50TH FREEZE-THAW CYCLE



(B) 100TH FREEZE-THAW CYCLE

FIGURE II. CHLORIDE PROFILES FOR SPECIMENS

C. Micro-structure Observation

Figure III shows the micro-structure inside the specimens before freezing and thawing. In Figure III, except in the case of C2, with the increase in the PPF content, the micro-structure becomes loose. In Figure IV, more micro-cracks appear inside the specimens. After 100 freeze-thaw cycles, specimen C2 has distinct dense compared to the other specimens, while excessive fibers inhibited the extent of micro-cracks. Because of the diffusion of salt solution during freeze-thaw cycles, many NaCl crystals form inside specimens.

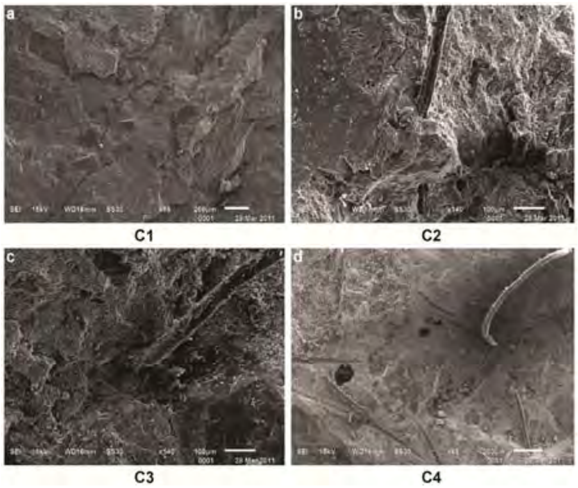


FIGURE III. SCANNING ELECTRON MICROSCOPE (SEM) PHOTOGRAPHS OF SPECIMENS WITHOUT FREEZE-THAW CYCLES

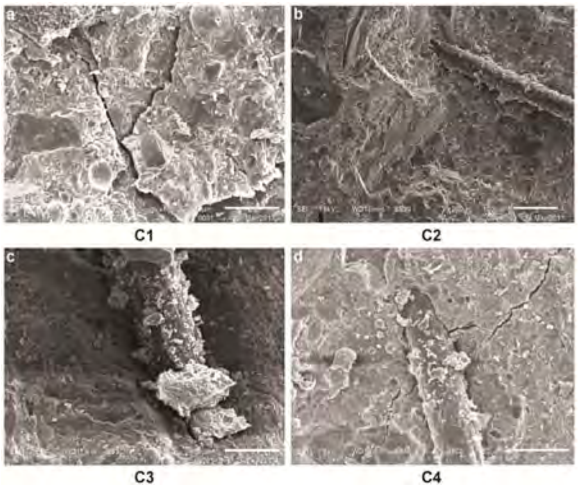


FIGURE IV. SEM PHOTOGRAPHS OF SPECIMENS AFTER THE 100TH FREEZE-THAW CYCLE

D. *Chloride Diffusion Coefficient*

Ion diffusion coefficient is an important index to reflect the resistance of concrete to chlorine salt and is also an important parameter to express the ability of chlorine ion migration in concrete.

According to the second law of Fick,

$$C_{x,t} = C_0 + \left(C_s - C_0\right)\left(1 - erf\,\frac{x}{2\sqrt{D_{cl}t}}\right) \quad (1)$$

where is the chloride content at a depth x and exposure time t, is the initial chloride concentration within concrete, is the surface chloride concentration within the concrete, and erf(x) denotes the error function.

According to the measured result of free chloride ion concentration and equation (1), MATLAB is used for curve fitting, and the chlorine ion diffusion coefficient D_{cl} is obtained. The results are presented in Table II.

This section considers the chloride diffusion coefficient D_{cl} of specimens after freezing and thawing with deicing salt. Table 4 presents the diffusion coefficient of the chloride ion in the samples of different groups. Both the number of cycles and fiber content affect the D_{cl} of specimens. The results show a similar trend for all concrete mixtures that the chloride ion diffusion coefficient of each specimen decreases with the increase of freeze-thaw cycles with deicing salt. For example, D_{cl} of ordinary concrete C1 after 100 freeze-thaw cycles is 77% of D_{cl} of C1 without freeze-thaw cycles. The chloride ion diffusion coefficient of fiber content of 0.5% C4 reduces to 6.82×10^{-12} mm^2/s, which is 76% of D_{cl} of C4 without freeze-thaw cycles.

The fiber content effect on the diffusion coefficient of the chloride ion is significant. Specimen C4 with 0.5% fiber content showed a high D_{cl} value and poor chloride migration resistance after 100 freeze-thaw cycles, which is 6.09 times that of specimen C2 with 0.1% fiber content.

Several mechanisms have been proposed to explain the damage in deicing conditions. In this study, the results showed that the salt transmits with the hydraulic pressure, which will be rich on the surface of the specimens. When the saline solution is frozen, the ice does not incorporate any of the dissociated salt ions in the crystal lattice [12], but the salt is attached to the surface of the ice. Therefore, the D_{cl} of the specimen decreases with the freeze-thaw cycles. The specimen with proper fiber content is the densest system, so specimen C1 has the lowest value after the freeze-thaw cycles with deicing salt.

TABLE II. CHLORIDE DIFFUSION COEFFICIENT/($\times10^{12}MM^2/S$)

Number of Freeze-Thaw Cycles	*C1*	*C2*	*C3*	*C4*
0	5.14	4.95	6.89	8.94
50	4.06	2.17	6.46	7.49
100	3.98	1.12	5.14	6.82

IV. CONCLUSIONS

The investigation of the durability of concrete with PPF under freeze-thaw cycles with deicing salts leads to the following conclusions.

Using PPF as a cement strengthening material in concrete, the incorporation of 0.5% by volume, enhanced concrete's resistance under freeze-thaw cycles with deicing salt solution. The loss rate of the dynamic modulus of elasticity and the scaled mass decreased with the increase in PPF content. With the fiber content increased from 0 to 0.5%, the loss rate of the dynamic modulus of elasticity reduced from 93.58% to 97.9%, and the loss ratio of mass decreased from 98.1% to 98.96%.

The chloride concentrations of specimens tend to increase with freezing-thawing cycles and the PPF volume. The moisture's transportation induce migration of chloride with freezing-thawing cycles. There is a Cl^- enrichment region between a depth of 1 and 4 mm from the surface of specimens and the chloride ion changed violently near the peak.

The pore volume's increment of the capillaries is caused by the excessive utilization of PPF, which improved the content of chloride and water. However, the suitable proportion of PPF increased the resistance to chloride penetration of concrete probably, considering that the high PPF content increase the pore volume.

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