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Effect of sulfate solution on the frost resistance of concrete with and without steel fiber reinforcement

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Abstract

Properties of plain concrete (PC) and steel fiber reinforced concrete(SFRC) (with water/cement ratio of 0.44, 0.32 and 0.26) subjected to freeze–thaw cycles in 5.0% sodium sulfate solution were investigated in this paper. It was found that during the initial 300 freeze–thaw cycles, sulfate solution had little effect on the relative dynamic modulus of elasticity (E_d) of concrete. In further freeze–thaw cycling, the effect of sulfate solution on E_d was much more obvious. Both PC and SFRC specimens with w/c of 0.44 failed before 300 cycles and exhibited similar developing trends of the E_d whether freezing and thawing in sulfate solution or in fresh water. As for the concrete specimens with w/c of 0.26, the decline of E_d was more serious when freezing and thawing in sulfate solution than that in fresh water after 300 cycles. The adoption of steel fiber greatly restrained the decline of E_d and changed the failure mode of the specimen from brittle crack in midspan of PC to gradually decline of E_d up to failure under the combined action of freeze–thaw cycles and sulfate attack. Test results also demonstrated that there was an interaction effect between the action of freeze–thaw cycles and sulfate attack.

Keywords: Concrete; Fiber reinforcement; Freezing and thawing; Sulfate attack

1. Introduction

The durability of concrete involves resistance to frost, corrosion, permeation, carbonation, stress corrosion, chemical attack and so on. Generally, properties of concrete have been well understood under the separate action of these deterioration mechanisms [1–5]. However, in practice, the degradation of concrete usually is the result of combined action of mechanical stress, physical and chemical attack and can be accelerated by the combined action of several deterioration mechanisms. The conclusions obtained from separate tests are not always correct and can have insufficient reliability. Therefore, it is necessary to study the properties of the concrete subjected to the combined action of two or more deterioration mechanisms. Thus, the influence of sulfate attack on the frost resistance of plain concrete (PC) and steel fiber reinforcement concrete (SFRC) was investigated in this paper. It is possible that concrete encounters sulfate attack in cold regions.

2. Experimental procedure

2.1. Materials and mix proportions

A Chinese standard (GB175-92) 525[#] Portland cement (which has standard compressive strength of 52.5 MPa at the age of 28 days) was used. The chemical components of the cement were shown in Table 1. Natural river sand with fineness modulus of 2.36 was used. Coarse aggregate was a crushed stone with maximum diameter of 10 mm. A low-carbon steel fiber with an aspect ratio 40 was used to prepare SFRC. The mix proportions were listed in Table 2. The air

Table 1
Mineralogical composition of cement

Component	C_3S	C_2S	C_3A	C_4AF	f-CaO
Content by mass (%)	55.7	22.1	5.1	16.8	0.3

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Table 2
Composition and characteristics of concrete

Series	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Steel fiber (kg/m^3)	Air content by volume (%)	Compressive strength at 28 days (MPa)
PC-0.44	409	180	657	1169	0	2.8	56.0
PC-0.32	440	142	665	1236	0	2.7	76.2
PC-0.26	477	124	621	1262	0	2.5	89.0
SFRC-0.44	409	180	854	926	117	2.2	60.8
SFRC-0.32	440	142	816	1039	117	2.3	89.7
SFRC-0.26	477	124	749	1124	117	2.6	95.0

content of fresh mixed concrete was measured according to ASTM C 231.

2.2. Samples and testing programs

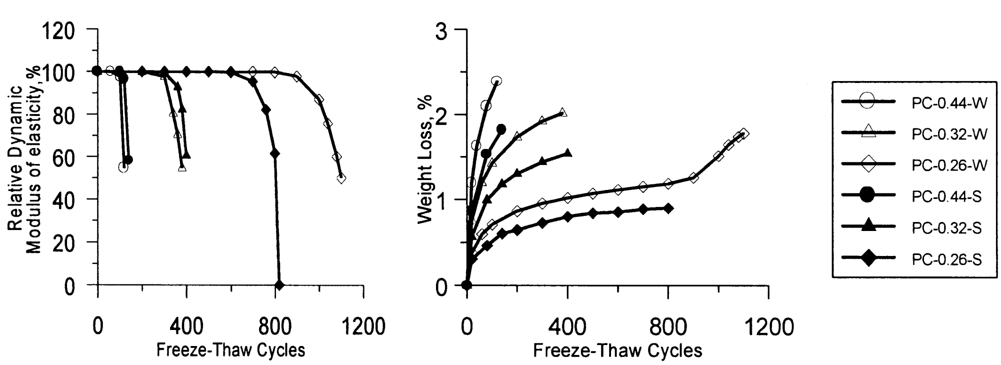
Concrete prisms with size of $40 \times 40 \times 160$ mm were cast and demolded 24 h later. Thereafter, all the specimens were cured in a condition of 20 ± 3 °C and 95% RH for 23 days. Then some of the specimens were immersed in a 5% (by mass) sodium sulfate solution and the remained in water for 4 days. Three prisms were tested for each batch. Freeze–thaw cycling test following ASTM C666A was performed at the age of 28 days. The temperature of concrete samples was controlled by a Pt sensor embedded in the center of a concrete sample. The temperature of the sample center ranged from -17.0 ± 1 to 6.0 ± 1 °C. The dynamic modulus of elasticity (E_d) and weight loss (W_l) of the specimens were measured at different freeze–thaw cycles. The dynamic modulus of elasticity was tested according to ASTM C597, and E_d was the ratio of the dynamic modulus of elasticity for a certain cycles to the initial value before subjected to freeze–thaw cycles. According to the test procedure, the specimen fails if its E_d drops to 60% or less or its loss of weight exceeds 5.0%. The ultimate number of freeze–thaw cycles up to failure (N_f) was also monitored. The corresponding properties of the samples exposed to sulfate solution were tested at the same time.

3. Results and discussions

3.1. Influence of sulfate attack on the frost resistance of concrete

Fig. 1 shows W_l and E_d of PC concrete subjected to freeze–thaw cycles in fresh water and in sodium sulfate solution. During the initial 300 freeze–thaw cycles, the drop of E_d is slower in solution than that in fresh water. However, in subsequent freeze–thaw cycles, the drop of E_d accelerated due to the sulfate attack. For PC-0.26 freezing and thawing in solution, the drop of E_d exceeds that in water at about 600 cycles. PC-0.44 and PC-0.32 failed both in solution and water prior to the drop of E_d exceeds that in water.

The experimental results showed that the weight loss of concrete subjected to freeze–thaw cycles in solution was slower than that in water as show in Fig. 1(b). This may be related to the differences in physical properties of frozen water and solution, such as freezing point, deformability or ductility. It is known that the pores in concrete are not saturated completely. If the increased volume of water or solution can be accommodated by the free space of pores in concrete, the deterioration will be moderated. The accommodation of increased volume of frozen solution by free space of pores in concrete depend in the deformability or ductility of frozen water or solution.



(a) (b)

Fig. 1. Change of E_d and W_l of PC subjected to freeze-thaw cycles.

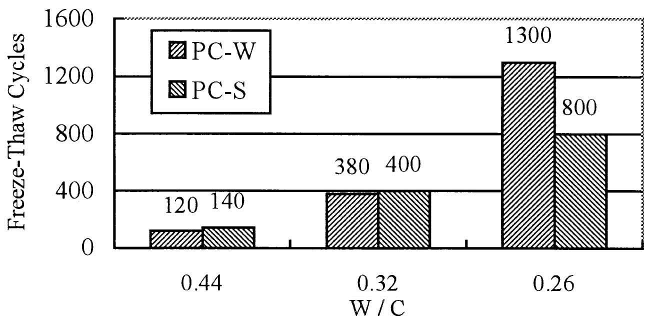


Fig. 2. Freeze-thaw cycles of concrete subjected to the combined action of two factors.

The average cycles (N_f) of freeze–thaw up to failure of three prisms for each series of concrete was shown in Fig. 2. For PC-0.44 and PC-0.32, the N_f of the concrete freezing and thawing in sulfate solution was increased than that in fresh water by 17% and 5%, respectively. For PC-0.26, however, the N_f of the concrete freezing and thawing in sulfate solution were decreased by 38% than that in fresh water.

Test results also manifested that the failure mode of the concrete was affected by sulfate attack when subjected to freeze–thaw cycles. When freezing and thawing in sulfate solution, most of the PC specimens cracked and failed after a certain number of cycles (ultimate number of freeze–thaw cycles). However, when freezing and thawing in water, the E_d of the specimens declined gradually and the specimens did not fail until the E_d reached to 60%.

3.2. Effect of steel fiber reinforcement

It was as anticipated that the adoption of steel fiber greatly restrained the degradation of concrete subjected to the deterioration mechanisms. Fig. 3 shows that the decline of E_d of SFRC occurred later than that of PC whether freezing and thawing in sulfate solution or in fresh water. The w/c had similar effect on E_d of SFRC as that of PC when subjected to various damage actions. Fig. 4 shows that the W_l of SFRC was almost the same as that of PC, which manifested that steel fiber reinforcement had little effect on the weight loss of concrete whether freezing and thawing in sulfate solution or in fresh water. Fig. 5 shows that the N_f of SFRC was increased significantly compared to PC. The adoption of steel fiber also changed the failure mode of concrete when subjected to freeze–thaw cycles and sulfate attack. During the experiment, all the specimens of SFRC were observed to have few cracks in midspan when subjected to the combined action of freeze–thaw cycles and sulfate attack.

3.3. Discussion

3.3.1. Sulfate attack

Sodium sulfate solution had both positive and negative effects on the concrete subjected to freeze–thaw cycles. The positive effect was that when concrete immersed in solution, sodium sulfate permeated into the pores and the concentration of pore solution increased, which led to the freezing point of pore solution dropped. The lower freezing point of pore solution resulted in the concrete damaged fairly moderate when subjected to freeze–thaw cycles. The negative effect was that concrete suffered from the sulfate attack. However, it took at least 45 days for sodium sulfate attack to take effect, which corresponded to more than 300 cycles of freeze–thaw. The concrete with w/c 0.44 failed before 300 cycles of freeze–thaw, therefore, for PC-0.44 subjected to freeze–thaw cycles in sodium sulfate solution, the positive effect was dominant, which led to a more moderate degradation than that of in fresh water. For PC-0.26, due to the much lower w/c, the frost resistance improved significantly and the N_f was far more than 300 cycles. After 300 freeze–thaw cycles, the sulfate attack took effect, which greatly accelerated the damage of concrete. Sulfate attack resulted in expansion and interior microcrack in concrete and led to the concrete seriously deteriorating when subjected to freeze–thaw cycles. As a result, the brittle cracking occurred in the midspan of the concrete specimen.

3.3.2. Steel fiber reinforcement

Steel fiber retarded the initiation and propagation of microcracks, thus decelerating the damage and failure of concrete during freeze–thaw cycles. In addition, the

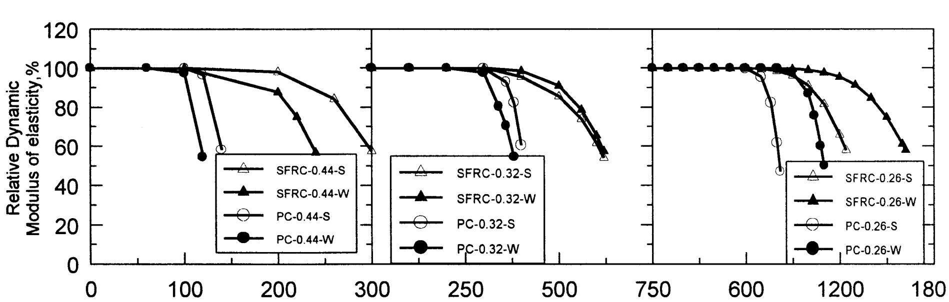


Fig. 3. Relative dynamic modulus of elasticity vs. freeze-thaw cycles.

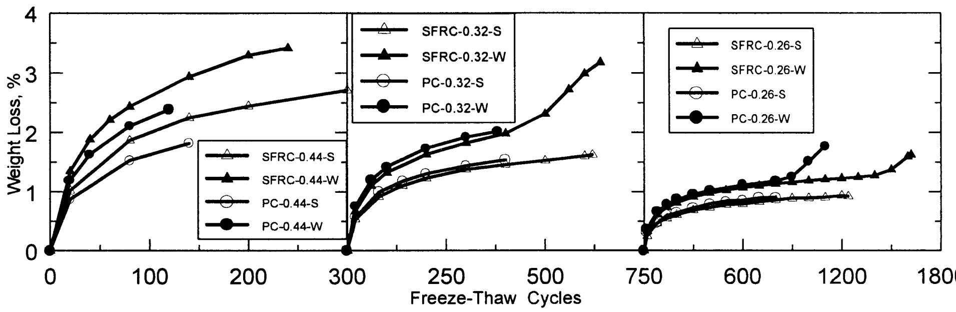


Fig. 4. Weight loss of PC an SFRC vs. freeze-thaw cycles.

improvement of failure mode of SFRC was related to the bridging effect and crack-arresting ability of the steel fiber. However, randomly scattered steel fiber had no effect on the porosity and degree of saturation of concrete and could not prevent the scaling off of the concrete surface. Therefore, the weight loss of SFRC was almost the same as that of PC.

3.3.3. Interaction effect of freeze–thaw cycles and sulfate attack

As mentioned above, the sodium sulfate solution had both positive and negative effects on the frost resistance. Sulfate attack resistance was also affected by freeze–thaw cycles negatively and positively. The negative effect was that freeze–thaw cycles resulted in the microcracks in concrete, which led to more sulfate solution available, so the sulfate attack occurred continuously. The positive effect was that the lower temperature slowed down the diffusion of the sulfate ion and led to a slower sulfate attack.

4. Conclusions

(1) The concrete with water/cement ratio of 0.44 and 0.32 exhibited a little moderate degradation when freezing and thawing in 5.0% sodium sulfate solution compared to that in fresh water.

(2) When freezing and thawing in sodium sulfate solution, the degradation of the concrete with water to cement ratio of 0.26 was more serious than that in fresh water. The decline of E_d accelerated when freezing and thawing in sodium sulfate solution.

(3) The properties of SFRC were superior to that of PC. When subjected to the combined action of freeze–thaw cycles and sulfate attack, the decline in E_d of SFRC was much slower than that of PC, and the ultimate number of freeze–thaw cycles of SFRC was greater than that of PC also.

(4) The failure mode of PC was brittle cracking in midspan when freezing and thawing in sulfate solution. In fresh water, however, the failure mode was a gradual decline of E_d up to failure. When with the reinforcement of steel fiber, the failure mode of concrete was a gradual decline of E_d up to failure whether freezing and thawing in sulfate solution or in fresh water.

(5) Freeze–thaw cycles and sulfate attack affected each other. Sulfate attack resulted in the microcracks in concrete, which led to more serious deterioration. Freeze–thaw cycles resulted in more sulfate solution be available. The lower temperature during freezing slowed down the diffusion of sulfate ion and restrained the sulfate attack.

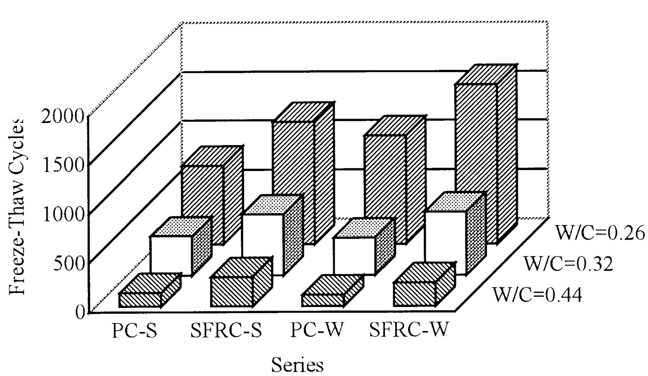


Fig. 5. Freeze-thaw cycles of concrete.

Acknowledgments

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