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Effect of chloride salt, freeze–thaw cycling and externally applied load on the performance of the concrete

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Abstract

The effect of sodium chloride solution, freeze–thaw cycling and externally applied load on the performance of concrete was experimentally investigated. The results show that the concrete specimens subjected to freeze–thaw cycling scaled more severely in chloride salt solution than those in water, and weight losses of the specimens tested in chloride salt solution were twice as much as those tested in water. However, dynamic modulus of elasticity of the concrete specimens decreased more slowly in chloride salt solution than in water due to the decline in the freezing point of the chloride salt solution compared with water. It is also shown that the performance deterioration in the concrete subjected to multidamaging processes was significantly accelerated. The larger the stress ratios, the fewer freeze–thaw cycles the concrete could bear. When steel fiber is incorporated, performance degradation in the steel fiber-reinforced concrete exposed to the multidamaging processes could be considerably retarded.

Keywords: Degradation; Chloride salt; Freeze–thaw cycling; Externally applied load; Steel fiber

1. Introduction

The evaluation of durability and service life for concrete structures is quite important and complicated, and it has been discussed in previous papers [1–5]. Performance deterioration caused by a monodamaging process, such as freeze–thaw cycling, is not consistent with the real conditions to which concrete structures are actually exposed. It has been found that the deterioration of concrete could be accelerated when subjected to dual-damaging processes, e.g., simultaneously subjected to both external loading and freeze–thaw cycling [6,7]. Moreover, deterioration of concrete becomes more severe when subjected to multidamaging processes, e.g., simultaneously exposed to external load, freeze–thaw cycling, chloride or sulphate attack and so on. In this paper, the concrete with different strength levels when exposed to mono-, dual- and multidamaging processes was investigated, and the improvement from steel fiber to resist against the performance degradation in concrete was discussed as well.

2. Materials and test methods

2.1. Materials

The 525# R(II) Portland cement, river sand with fineness modulus 2.36, coarse aggregate of crushed basalt stone with maximum size of 10 mm, XP-II superplasticizer, steel fibers with length of 20 mm and aspect ratio of 40, respectively, were used in the test. The proportions of the various concrete mixes with three strength levels are given in Table 1.

2.2. Test methods

Tests of concrete specimens (40×40×160 mm) subjected to freeze–thaw cycling or to externally applied load in water or in a NaCl solution (3.5% by weight) were carried out in accordance with ASTM C666A. The beam specimens were subject to third point bending, and the stress ratios, i.e., the ratios of externally applied flexural load to the ultimate

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Table 1
Proportions of the concrete mixes

Series	w/c	V_f (%)	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)
C40NPC	0.44	0	409	180	658	1169
C60NPC	0.32	0	440	142	666	1237
C80NPC	0.26	0	477	124	622	1262
C40SFRC	0.44	1.5	409	180	658	1169
C60SFRC	0.32	1.5	440	142	666	1237
C80SFRC	0.26	1.5	477	124	622	1262

flexural load capacity, were controlled by specially designed loading frames [7]. The losses of both the dynamic modulus of elasticity and the weight in the concrete specimens were measured and recorded. Three specimens were tested for each concrete mix.

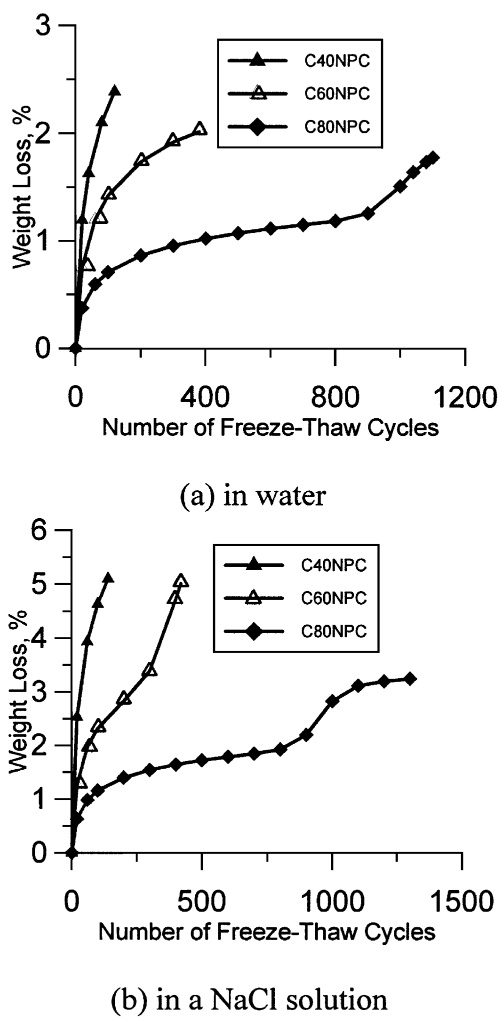

Fig. 1. Weight losses in concrete subjected to freeze–thaw cycling in water or in a NaCl solution.

3. Results and discussion

3.1. Effect of NaCl solution on the frost resistance of the concrete

There is much difference in frost resistance of the concrete specimens between that tested in fresh water and in the chloride solution. Concrete with good frost resistance often scaled severely in a NaCl solution when subjected to freeze–thaw cycling, the weight losses of concrete specimens reaching failure threshold earlier in a NaCl solution than in water. Fig. 1a and b gives the weight losses of the plain concrete (C40NPC, C60NPC and C80NPC) subjected to freeze–thaw cycling in water or in a NaCl solution. Fig. 1a shows the weight losses decreased and the ultimate freeze–thaw cycles increased for the concrete with higher strength levels. Fig. 1b refers to the results of the freeze–thaw cycling in a NaCl solution. It should be noted that the concrete mixes (C40NPC, C60NPC) with higher water-to-cement ratios could not bear more than 500 freeze–thaw cycles and failed with their weight losses exceeding 5%.

Weight losses were mainly caused by the surface scaling of the concrete specimens. It has been found that in actual

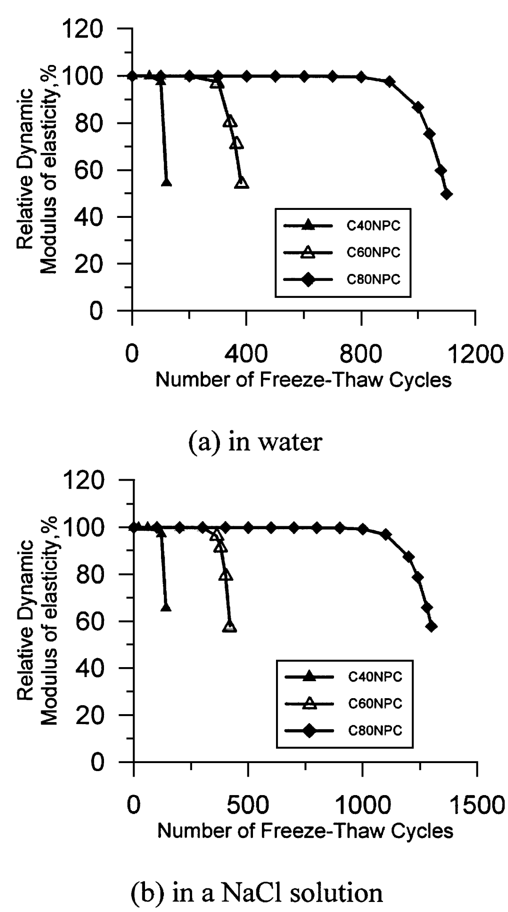

Fig. 2. Changes in the relative dynamic modulus of elasticity of concrete subjected to freeze–thaw cycling in water or in a NaCl solution.

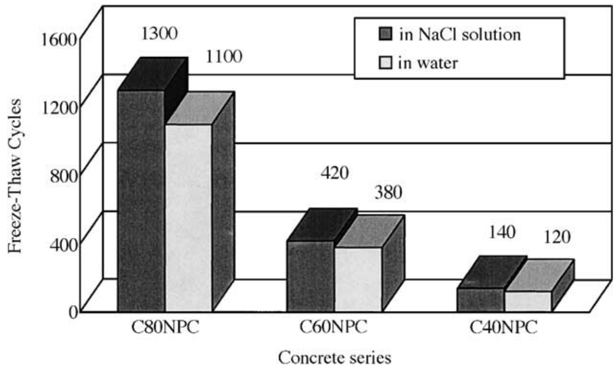

Fig. 3. Freeze–thaw cycles of the concrete at failure in water or in a NaCl solution.

environment, concrete surfaces scale markedly due to exposure to freeze–thaw cycling or to deicing salt. The rates of freeze–thaw cycling in these tests were much higher than those in actual environment; thus, the scaling observed in the tests was more severe. The maximum scaling depth in the specimens was over 5 mm. Besides, the weight losses of the specimens in a NaCl solution were about twice as large as those in water.

Changes in the dynamic modulus of elasticity of the concrete specimens when exposed to freeze–thaw cycling in water or in a NaCl solution are given in Fig. 2. The relative dynamic modulus of elasticity is the ratio of the dynamic modulus of elasticity measured at certain freeze–thaw cycles to that measured before the freeze–thaw cycling. Although severe scaling occurred in the surfaces of the concrete tested in a NaCl solution, the losses of dynamic modulus of elasticity were fewer in a NaCl solution than in water. NaCl lowers freezing point of water, e.g., the freezing point of a 3.5% NaCl solution is −2.03 °C [8,9]. Moreover, the smaller the capillary pores in concrete, the lower the freezing point of the solution in those pores. The lower freezing point is beneficial to the improvement in the frost resistance of the concrete. As shown in Fig. 3, the numbers of freeze–thaw cycles at failure in a NaCl solution were roughly 20% higher than those in fresh water.

3.2. Effect of externally applied load on the frost resistance of the concrete

Fig. 4 shows the relative dynamic modulus of elasticity of the concrete subjected to different stress ratios (0, 0.1, 0.25, 0.5) at different freeze–thaw cycles. The control specimens were those cured in 20±5 °C, RH >90%, exposed neither to freeze–thaw cycling nor to externally applied flexural load. It denotes that externally applied load accelerated the degradation process of the concrete subjected to freeze–thaw cycling. The larger the stress ratios, the faster the relative dynamic modulus of elasticity dropped and the fewer cycles at failure. Without external load, i.e., the stress

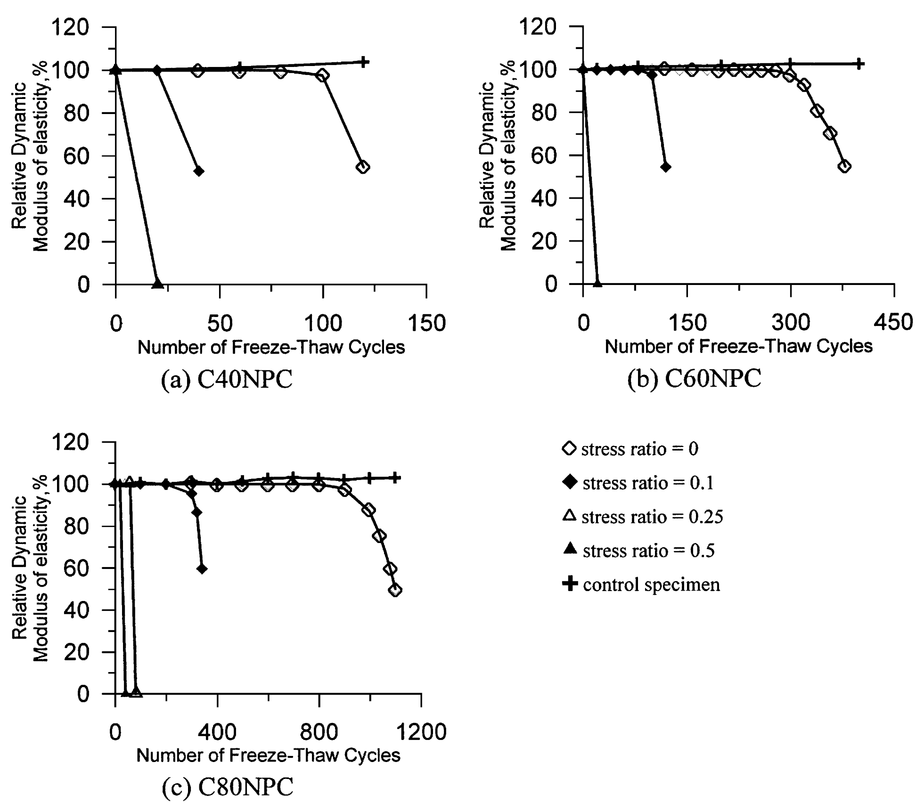

Fig. 4. Effect of stress ratios on the relative dynamic modulus of elasticity of concrete subjected to freeze–thaw cycling.

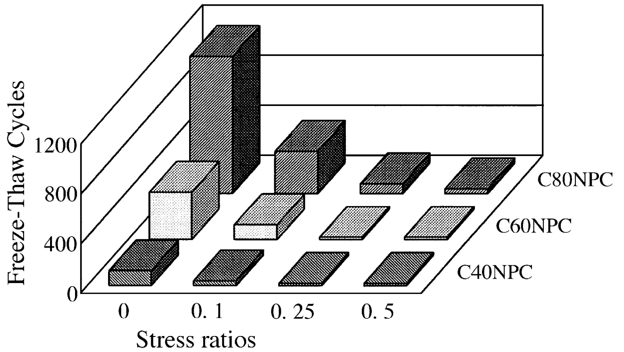

Fig. 5. Freeze–thaw cycles of concrete at failure under externally applied load.

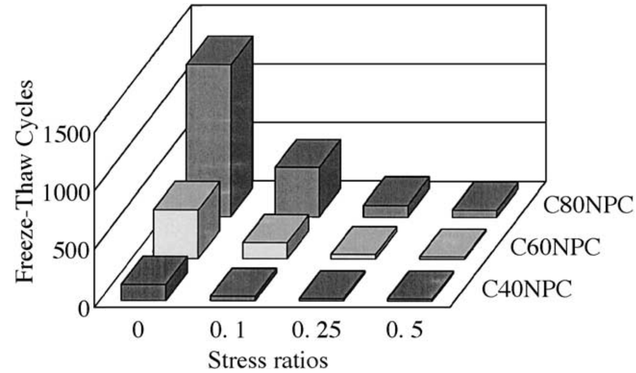

Fig. 7. Freeze–thaw cycles of concrete at failure when subjected to multidamaging processes.

ratio was zero, the relative dynamic modulus of elasticity did not decrease even at 2000 cycles. With stress ratio 0.5, C80NPC failed in a brittle manner after 40 cycles, the relative dynamic modulus of elasticity dropping down to zero. It is noticeable that stress ratios had little effect on the weight losses of the concrete subjected to the freeze–thaw cycling. The reason was that the external load merely accelerated initiation and propagation of cracking, increasing the amount and the size of cracks, but not the scaling of the concrete surfaces.

As shown in Fig. 5, external applied load had evident influence on the maximum freeze–thaw cycles. When stress ratio was 0.5, all the concrete failed between 20 and 40 cycles; when stress ratio was 0.25, the higher the strength of the concrete, the larger the freeze–thaw cycles at failure and the stronger the frost resistance of the concrete.

3.3. Performance deterioration of the concrete subjected to the multidamaging processes

As shown in Fig. 6, the relative dynamic modulus of elasticity was evidently affected by externally applied load when the concrete was subjected to the multidamaging processes, i.e., subjected simultaneously to the external

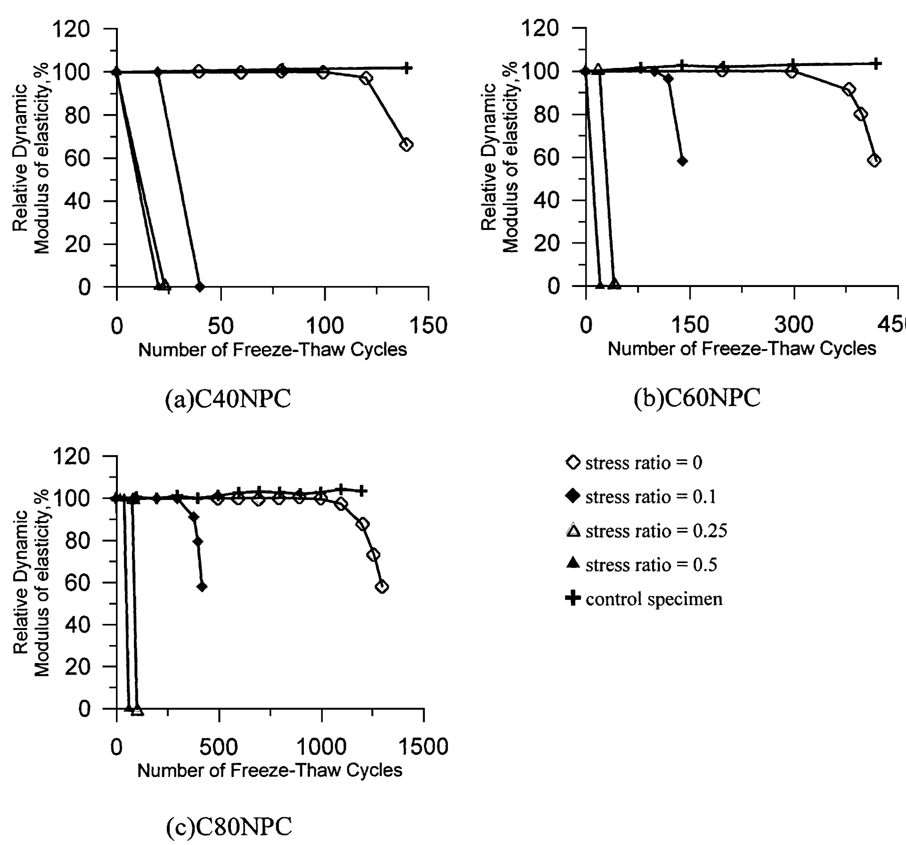

Fig. 6. Relative dynamic modulus of elasticity of concrete subjected to multidamaging processes.

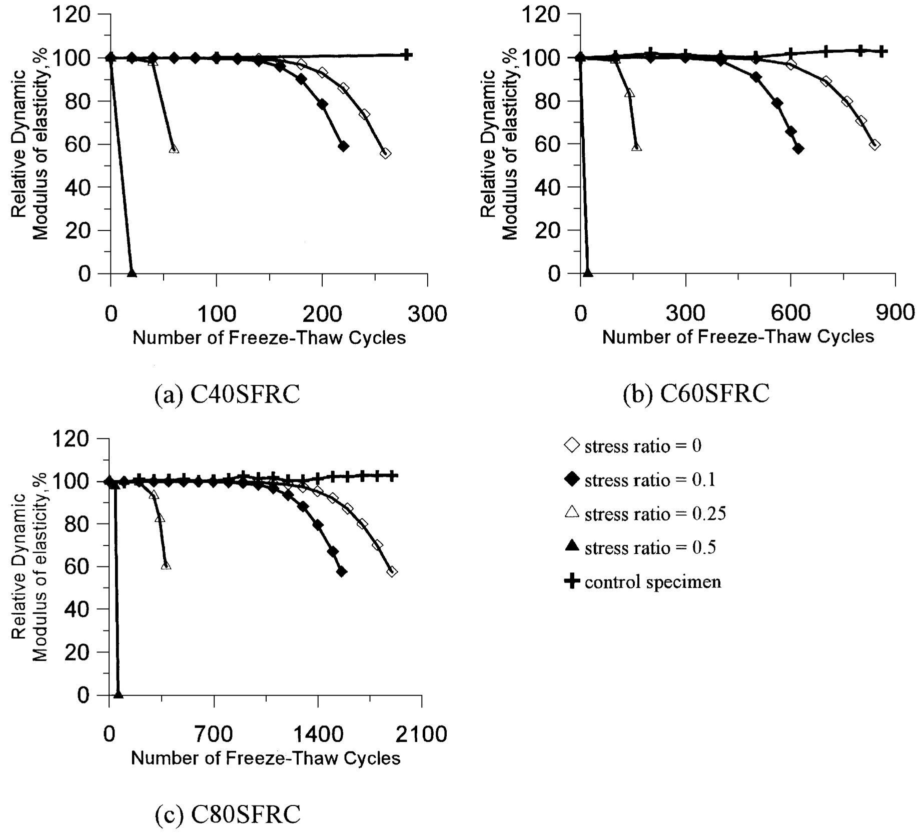

Fig. 8. Effect of steel fiber on the relative dynamic modulus of elasticity of concrete subjected to multidamaging processes.

load, freeze–thaw cycling and chloride attacks. When the stress ratio was equal to 0.25 or 0.5, the concrete exhibited a quite brittle failure, the relative dynamic modulus of elasticity dropping down to zero. When the stress ratio was 0.1 or 0, the concrete specimens could bear much more freeze–thaw cycles.

Due to decline in the freezing point of the chloride salt solution, the losses in the relative dynamic modulus of elasticity when the concrete was subjected to the multidamaging processes were fewer than those when the concrete was simultaneously subjected to external load and freeze–thaw cycling in water, i.e., dual-damaging processes. The difference in the losses of the relative dynamic modulus of elasticity decreased when the concrete was subjected to higher stress ratios. The freeze–thaw cycles at failure when the concrete was exposed to the multidamaging processes are shown in Fig. 7. When the stress ratios increased, the ultimate freeze–thaw cycles were considerably reduced, and the difference in the freeze–thaw cycles between the concrete with different strength levels was reduced as well.

In a word, for the concrete exposed to the multidamaging processes, external loading could accelerate the losses of the dynamic modulus of elasticity, and NaCl solution could speed up the weight losses. Therefore, performance deterioration in the concrete subjected to multidamaging processes was much more severe than that under mono- or dual-damaging processes. For example, when the concrete were subjected to the multidamaging processes (stress ratio 0.25), the maximum freeze–thaw cycles at failure for C40NPC, C60NPC and C80NPC were about 10% of those when the concrete were merely subjected to freeze–thaw cycling in water.

Changes in the relative dynamic modulus of elasticity of the steel fiber-reinforced concrete subjected to the multidamaging processes are given in Fig. 8. When the stress ratios were 0.1 and 0.25, the relative dynamic modulus of elasticity of the plain concrete decreased sharply below 60% of the original values, while the relative dynamic modulus of elasticity of the SFRC remained 60% of the original, even though visible cracks appeared in the concrete surfaces. However, for the plain concrete, the dynamic modulus of elasticity reached failure threshold as soon as cracks appeared in the concrete surfaces. Thus, the steel fiber-improving strength, toughness and cracking resistance of concrete could limit and retard the deterioration in concrete when subjected to the multidamaging processes.

4. Conclusions

Severe surface scaling occurred when the plain concrete was subjected to freeze–thaw cycling in a 3.5% NaCl solution, in which the weight losses of the concrete were larger than those in water. Due to the decline of the freezing point of the salt solution, the ultimate freeze–thaw cycles of the concrete in a NaCl solution were about 20% higher than those of the concrete exposed to the freeze–thaw cycling in water, while the losses in the dynamic modulus of elasticity of the former were fewer than those of the latter. Externally applied flexural loading accelerated the performance deterioration of the concrete when subjected to freeze–thaw cycling. The higher the stress ratios, the faster the dynamic modulus of elasticity dropped. However, the externally applied load had little influence on the weight losses of the concrete. There was much difference in the failure mode between that subjected to monodamaging process and that subjected to dual-damaging processes. When the stress ratios were high, brittle failure at early cycling occurred. When the plain concrete was subjected to the multidamaging processes, the dynamic modulus of elasticity dropped sharply and the weight losses increased, severe scaling occurring in the concrete surfaces. Steel fiber could retard the performance deterioration of the concrete and improve the resistance against multidamaging under severe conditions.

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