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Communication

Damage and damage resistance of high strength concrete under the action of load and freeze-thaw cycles

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Abstract

This paper presents the damage of concrete and its dependence on different strength grades of concrete under the simultaneous action of load and freeze-thaw cycles, and analyzes the inhibiting effect of air entrainment and steel fibers on damage. The loss of dynamic elastic modulus and the flexural strength of specimens subjected to freeze-thaw cycles were determined. Experimental results show that the damage process is accelerated and the extent of damage increased under the simultaneous action of load and freeze-thaw cycles. The lower the grade of concrete is, the greater the damage is. At a higher stress ratio, concretes suffer more serious damage. The addition of steel fiber or air entrainment or the combination of the two to concrete can improve its ability to resist damage.

Keywords: Freezing and thawing; High strength concrete; Fiber reinforcement; Damage; Double factors

1. Introduction

It has been a significant scientific and technical problem to improve the durability and to prolong the service life of concrete in the world [1–4]. For half a century, studies on the durability of concrete have been confined to the influence of a single factor. In practical engineering, however, two or more actions usually cause the worsening of properties of concrete. The damage is usually synergistic. For some engineering applications, such as highway pavements, airport pavements, bridge decks, and dams in hydraulic engineering, the damage might come from the double actions of load and freeze-thaw cycles, especially in cold northern climates [5]. In this paper, the damage process of various concretes under the simultaneous action of load and freeze-thaw cycles is demonstrated, which is of great importance for critical assessment of the durability of concrete under comprehensive conditions.

2. Materials and experiments

2.1. Materials

A Portland cement with a specific surface area of 3000 cm^2/g and a specific gravity of 3.1 g/cm^3 was used. The fineness modulus of fine aggregate was 2.6. The coarse aggregate used was a crushed stone with a maximum diameter of 10 mm. Superplasticizer was supplied by Shanghai Xinpu Chemical Factory (Shanghai, China). The Materials College of Tongji University provided the air-entraining agent. The length of steel fiber was 20 mm, and the aspect ratio was 60. The tensile strength was 750 MPa. The mixture proportions of various concretes are given in Table 1.

2.2. Experiments

The specimen sizes were $40 \times 40 \times 160$ mm for flexural test and $40 \times 40 \times 40$ mm for compressive tests. Stress ratio was 0, 0.1, 0.25, and 0.5, with respect to failure stress, respectively. In order to control the loading process so that no stress relaxation should be produced while the specimens were under freeze-thaw cycles, a special loading device was designed (Fig. 1). The force was applied by adjusting the deformation of springs. The loading and freeze-thaw cycles were simultaneously applied to specimens in an automatic freeze-thaw machine according to ASTM C666. The dy-

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Table 1
The mixture proportions of various concretes

Series of concretes	Volume fraction (%)	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Air entraining (%)	Water/cement ratio
C40							
PC	0	409	180	658	1169	0	0.45
SFRC	1.5	409	180	819	961	0	0.45
C50							
PC	0	398	151	734	1198	0	0.38
SFRC	1.5	398	151	849	1038	0	0.38
C60							
PC	0	440	142	666	1237	6.7	0.32
SFRC	1.5	440	142	817	1039	6.7	0.32
C80							
PC	0	477	124	700	1299	4.2	0.26
SFRC	1.5	477	124	787	1133	4.2	0.26

namic elastic modulus and the strength at the end of freeze-thaw cycles were determined.

3. Results and analysis

3.1. Damage regularity of ordinary concrete under the simultaneous action of load and freeze-thaw cycles

The strength grades were C40, C50, C60, and C80; their corresponding water/cement ratios were 0.45, 0.38, 0.32, and 0.26. Fig. 2*(a)* to *(d)* shows the changes of dynamic elastic modulus of different grade concretes under the simultaneous actions of load and freeze-thaw cycles at the stress ratios of 0, 0.1, 0.25, and 0.5. It can be seen that for ordinary cement concrete, strength grade, stress ratio, and freeze-thaw cycles are important factors that determine the properties of concrete under the double damage actions. At the same stress ratio, concrete of higher strength can undertake more freeze-thaw cycles, and the dynamic elastic modulus decreases more slowly with freeze-thaw cycles. Obviously, the damage caused by the double actions at high-stress ratios is the most serious. At a stress ratio of 0.5, PC80 concrete can endure only 150 cycles of freeze-thaw, which is much lower than at a stress ratio of 0.25. When compared with the test results under freeze-thaw cycles without loading, the damage extent is increased and the damage rate accelerated, also.

Table 2 shows the results of flexural strength of different grade concrete. It can be seen that for low strength concrete, the loss of flexural strength after the simultaneous actions of both load and freeze-thaw cycles is evident. For high strength concrete, however, the influence of stress ratio on flexural strength is slight.

3.2. The inhibiting effect of additions on the damage of concrete

In order to improve the ability to resist damage under the double actions, steel fiber, air entraining agent, and the combination of the two were added to the concrete. It is rec-

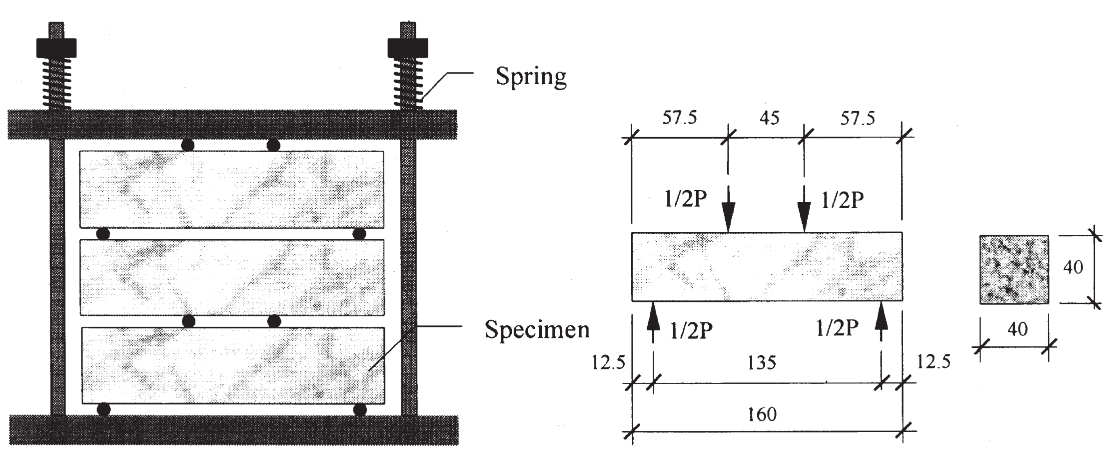

Fig. 1. Schematic description of the loading device.

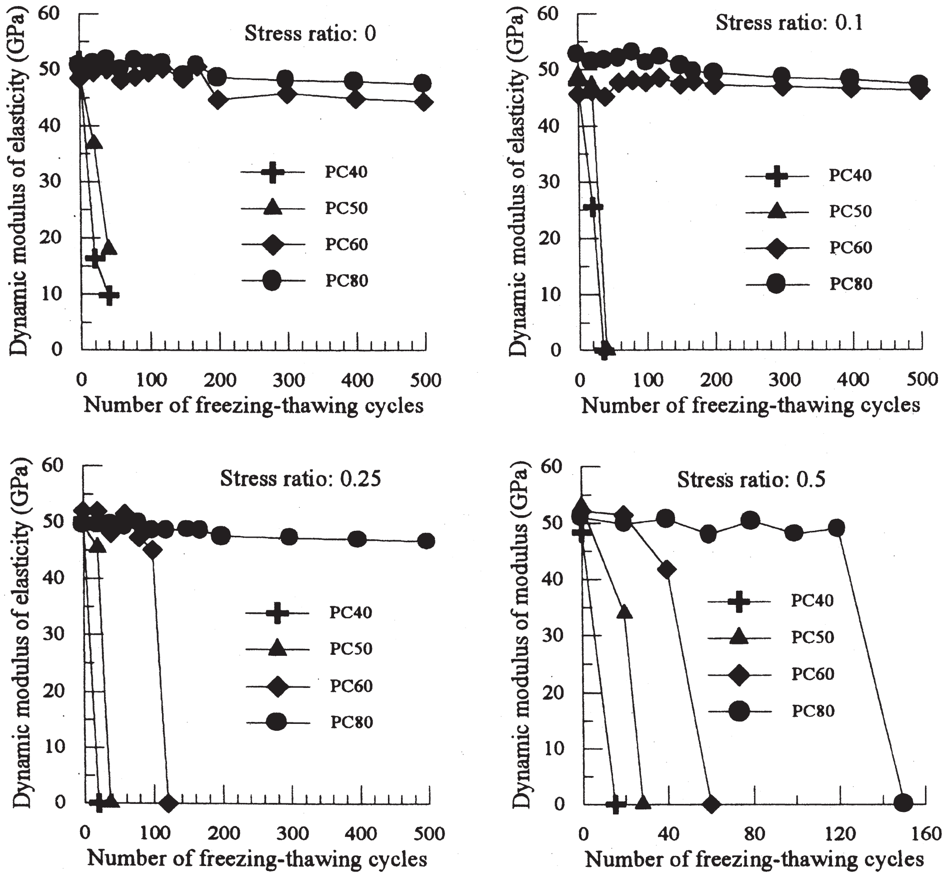

Fig. 2. The loss of dynamic modulus of elasticity of Portland cement concrete under the double actions of load and freeze-thaw cycles.

ognized that the crack-resisting effect from steel fiber and the pressure-releasing effect from air entraining can improve the properties of concrete [6–8].

The results are shown in Figs. 3 and 4. It can be seen that the ability of steel fiber-reinforced concrete (SFRC) to resist the damage of double factors is greatly improved. For the same grade concrete, SFRC can undertake more freeze-thaw cycles than ordinary concrete at the same stress ratio. At the stress ratio of 0.1, SFRC50, SFRC60, and SFRC80 can ensure 500 cycles of freeze-thaw without failure of concrete. At the stress ratio of 0.5, SFRC80 suffers little after 500 cycles of freeze-thaw.

Furthermore, the combination of steel fiber and air-entraining agent to concrete can further improve the ability to inhibit damage under the simultaneous actions of load and freeze-thaw cycles (Fig. 5). At the stress ratio of 0.25, the air-entrained steel fiber-reinforced concrete SFRC60 shows little change in dynamic elastic modulus after 500 freeze-thaw cycles. Even at the stress ratio of 0.5, the loss of dynamic elastic modulus is modest. For SFRC80 concrete, the dynamic elastic modulus remains almost unchanged. The results shows that the frost resistance of air-entrained steel fiber-reinforced concrete under different stress ratios might be enhanced further because of the crack-resisting ef-

Table 2
Flexural strength (MPa) of concrete after double damage actions

Stress ratio	0, no frost, strength	0, frost, strength (cycles)	0.1, frost, strength (cycles)	0.25, frost, strength (cycles)	0.5, frost, strength (cycles)
PC40	7.63	5.15 (20)	5.13 (20)	4.15 (20)	4.13 (20)
PC60	8.76	6.54 (20)	–	–	6.55 (60)
PC80	9.80	8.46 (500)	8.43 (500)	8.37 (500)	8.33 (500)
SFRC40	10.70	7.09 (20)	6.88 (20)	–	–
SFRC60	12.50	11.03 (500)	10.50 (500)	10.48 (500)	9.98 (500)
SFRC80	13.40	13.20 (500)	12.90 (500)	12.43 (500)	12.40 (500)

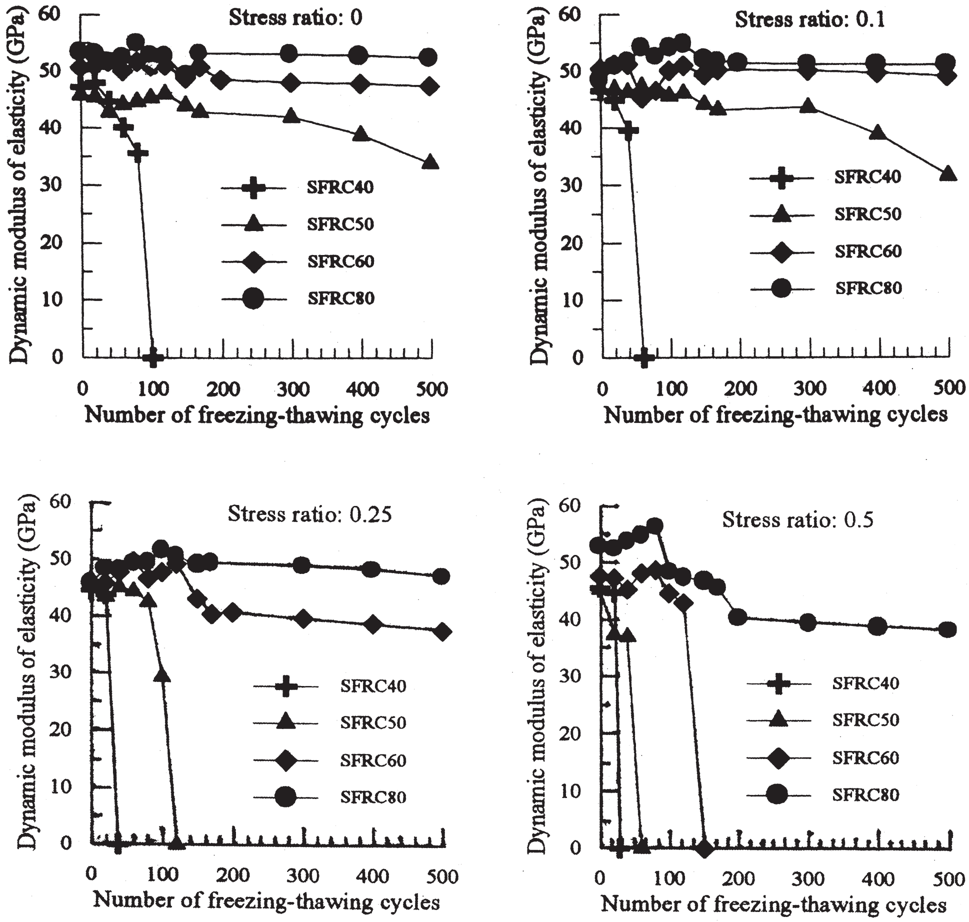

Fig. 3. The loss of dynamic modulus of elasticity of SFRC under the double actions of load and freeze-thaw cycles.

fect from steel fiber and the pressure-releasing effect from the air entrainment.

4. Discussion

From the above results, it is evident that the damage of different kinds and grades of concrete under the simultaneous actions of different stress ratios and freeze-thaw cycles is a very complex fatigue process. This process results from the double effects of factors that deteriorate the structure and resist the deterioration. The damage process depends mainly on two factors. One is the strength grade of concrete matrix. For the matrix, the improvement of the microstructure, in particular the pore size and the pore morphology, is good for resisting damage. Furthermore, the decrease of pore size might lower the freezing point. Therefore, higher strength concrete usually has a better resistance to the double actions. The other is the ability of resisting damage. The incorporation of air entraining may increase the amount of closed pores and relax the pressure during the freeze-thaw cycles. The addition of steel fiber may play a role in inhibition of the initiation and propagation of cracks. When air-entraining agent and steel fiber are incorporated into concrete, both the pressure-releasing effect and the crack-resisting effect contribute to the ability to resist deterioration due to the simultaneous actions of load and freeze-thaw cycles.

5. Conclusions

The applied stress ratio is an important factor that influences the inhibiting capacity of concrete to damage under the simultaneous action of load and freeze-thaw cycles. The higher the stress ratio is, the greater is the damage rate and extent.

The crack-growth resistance effect from steel fiber and the pressure-releasing effect from the entrained air may inhibit the damage of concrete incorporated with steel fiber or air entrainment or the combination of the two.

Under the simultaneous actions of load and freeze-thaw cycles, the damage rate and extent depend on the grade of concrete: the higher the grade is, the less the damage is.

The loading device described in the text is proved to be

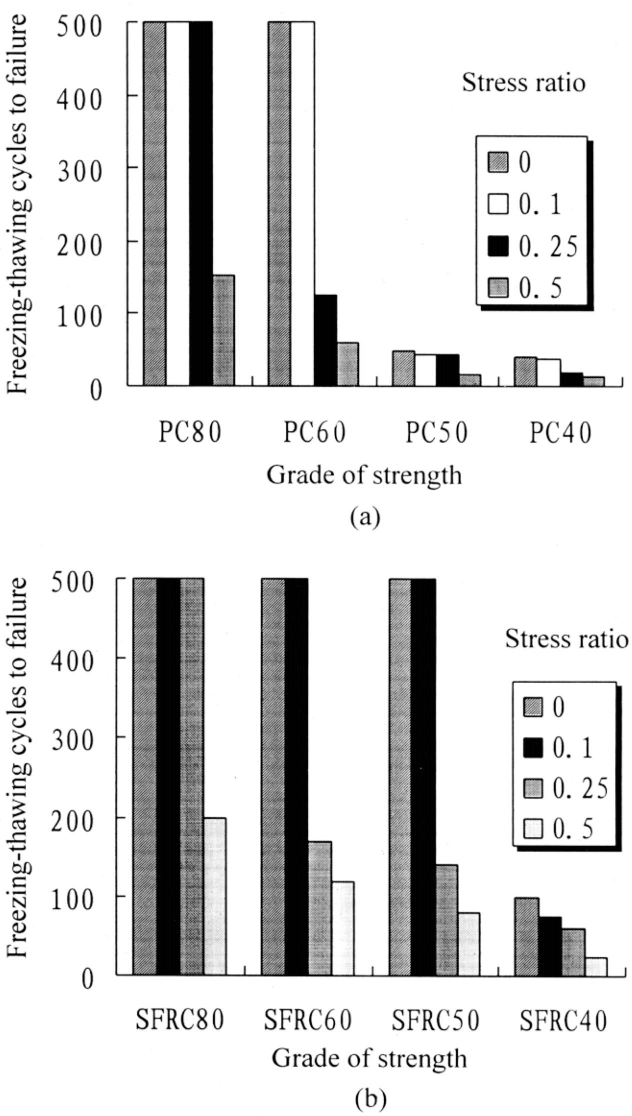

Fig. 4. Comparison of SFRC and Portland cement concrete under the double actions of load and freeze-thaw cycles.

valid for preventing the stress relaxation under freeze-thaw cycles.

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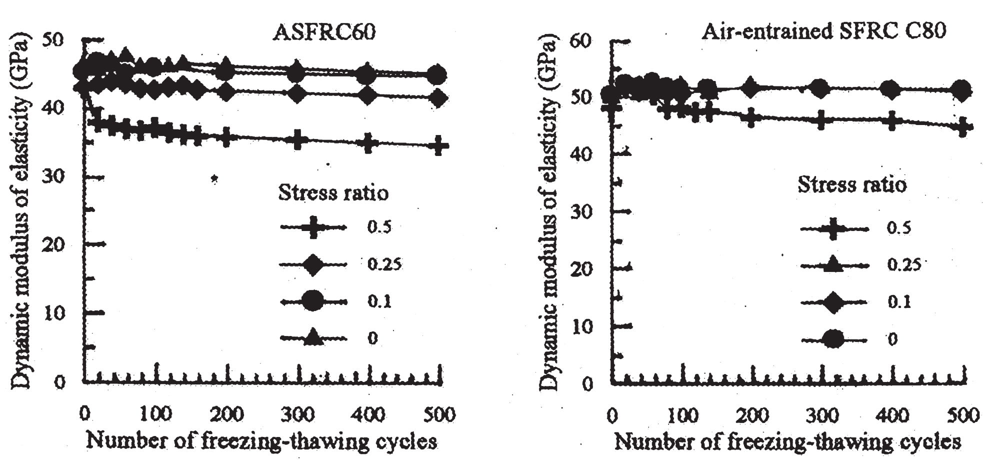

Fig. 5. The effect of the combination of steel fiber and air entrainer on the properties of concrete under the double actions of load and freeze-thaw cycles.