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Experimental study of strength and deformation of plain concrete under biaxial compression after freezing and thawing cycles

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Abstract

This study attempts to generate information about the strength and deformation behavior of plain concrete under biaxial compression after 0, 25, 50 and 75 cycles of freezing and thawing. Concrete cubes were tested under biaxial compressive stresses. Five principal compression stress ratios and four different cycles of freeze–thaw were the main variables. Static compressive strengths, stress–strain relationships and failure modes were examined. Failure modes of specimens are also described. The experimental results showed that the biaxial compressive strength of plain concrete decreased as the freeze–thaw cycles were repeated. The influence of freeze–thaw cycles and the stress ratio on the biaxial strength, the strain corresponding to peak stress and the elastic modulus after freeze–thaw cycles was also analyzed. The formula of the biaxial compressive strength in principal stress space is proposed.

Keywords: Concrete; Freezing and thawing cycles; Mechanical properties; Biaxial compressive strength; Stress–strain relationship

1. Introduction

As more and more concrete structures are being built in deeper seas and harsher environments, the demand for durable concrete has increased. Durability [1–3] is a key function for materials which are used in severe environments, and heightened durability of concrete is necessary as it is one of the most non-homogenous and demanding engineering materials used by mankind. It has been a significant scientific and technical problem to improve the durability and to prolong the service life of concrete. Used commonly for dams, hydraulic structures and offshore structures, there is now an increasing need for concrete to be used for the storage of very cold substances. In cold environments, freezing and thawing can be harmful for a porous brittle material such as concrete when it is subjected to lower temperatures. Plain concrete subjected to repeated cycles of freezing and thawing may deteriorate rapidly and failure of the material may take the form of:

– loss of strength: the water in the capillary pores of cement paste expands upon freezing. If the required volume is greater than the space available, the excess water is driven off by the pressure of expansion. The magnitude of this hydraulic pressure depends on the permeability of the cement paste, the degree of saturation, the distance to the nearest unfilled void and the rate of freezing. If the pressure exceeds the tensile strength of the paste at any point, it will cause local cracking. In repeated cycles of freezing and thawing in a wet environment, water will enter the cracks during the thawing portion of the cycle only to freeze again later, and there will be progressive deterioration with each freeze–thaw cycle. So the strength decreased with freeze–thaw cycles,
– crumbling: the surface will scale off due to the expansion caused when water freezes to ice,
– or some combination of the two.

Hence, the freezing and thawing action can be looked upon as a very complex fatigue crack propagation process.

Forster et al. [4] stated that freezing and thawing results differ depending on the original aggregate type. Recycled concrete containing freeze–thaw susceptible coarse aggregate performed better as aggregate in concrete than concrete containing that stone as new coarse aggregate. Mulheron and O'Mahony

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[5] reported that the durability of lean concrete made using recycled aggregates, appeared to be better than or similar to an equivalent control concrete made with natural gravel when subjected to freezing and thawing conditions. Sun et al. [6] investigated damage and damage resistance of high strength concrete under the action of flexural load and freeze–thaw cycles. Jacobsen et al. [7] investigated the effect of internal cracking on ice formation for high strength concrete. Marzouk and Jiang [8] investigated the tension properties of high strength concrete after freezing and thawing cycles. Soroushian and Nagi [9] reported that the durability of lightweight carbon fiber reinforced cement composites after different cycles of freeze–thaw.

The wide use of computers and the finite element method in the design and analysis of concrete structures makes it necessary to establish the strength criterion and the constitutive relationships [10,11] of concrete to get useful and valid results. The strength and deformation of plain concrete subjected to freezing and thawing cycles under biaxial compressive stress conditions need to be investigated, but these types of studies haven't been reported. This is most likely due to the following reasons:

1. The influence of freezing and thawing cycles on plain concrete under the static uniaxial compressive strength is still unclear;
2. The testing equipment needed to perform biaxial tests is not as readily available as are uniaxial testing machines;
3. The biaxial compressive strength of concrete depends considerably on test technology, such as the method to reduce the friction between the steel platen of the machine and the surface of the concrete specimen, etc.

2. Experimental procedures

2.1. Materials and mix proportions

The cementitious materials used for this investigation are Chinese standard (GB175-99) #32.5 Portland cement [12]. Coarse aggregates were crushed stone (diameter ranging from 5 mm to 20 mm) and fine aggregates were natural river sand (fineness modulus of 2.6). The water–cement ratio for the mixture of concrete was 0.50. These ingredients were mixed for about 1 min, and then the water was added slowly over a period of 1 min. Finally, the ingredients were mixed for about 2–3 min [13]. The air content of the specimen was 1.7% after mixing. Table 1 shows the mix proportions by weight of the mixture.

2.2. Samples and testing programs

Concrete specimens were 100 mm cubes and 100 mm × 100 mm × 400 mm prisms cast in steel molds and compacted by a vibrating table. The cubes were used to measure the strength and strain, and the prisms were used to measure the weight loss and the relative dynamic modulus of elasticity (RDME). RDME is the ratio of the dynamic modulus of elasticity value measured after a number of freeze–thaw cycles to the initial value before being subjected to freeze–thaw cycles. All specimens were removed from the molds 24 h after casting and then cured in a normal condition of 20 ± 3 °C and 95% RH (relative humidity) for 23 days according to "The test method of long-term and durability on ordinary concrete" GBJ82-85[14].

Table 1
Mix proportions and major parameters of concrete

Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Compressive strength at 28 days(f_c/MPa)	Tensional strength at 28 days (f_t/MPa)
383	663	1154	193	34.2	3.14

A portion of the specimens were then immersed in water for 4 days before being exposed to the freezing and thawing cycles; these specimens were put to the freeze–thaw apparatus, and were used to measured the strength, strain, weight loss and RDME after 25, 50, 75 freezing and thawing cycles respectively. The other specimens were cured in a normal condition up to 28 days; these specimens were used to measured the strength and strain prior to the freezing and thawing cycles. The maximum loading force was always applied to the surfaces that were perpendicular to the cast surfaces.

In this paper, the freeze–thaw cycling test was performed according to GBJ82-85. The temperature of the concrete samples was controlled by a Pt sensor embedded in the center of a concrete. In a single cycle, the temperature of the specimens cools from 6 °C to −15 °C and then warms to 6 °C all within approximately 2.5–3 h. The specimen is insufficient to resist freezing–thawing if its RDME drops to 60%, its loss of weight exceeds 5.0% before the 300th cycle. The RDME is measured about every 25 freeze–thaw cycles. This test is similar to the ASTM C 666,"Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing." [15] in which rectangular prisms of concrete are either frozen and thawed in water (procedure A) or frozen in air and thawed in water (procedure B). The temperature of the specimens cools from 4.4 to −17.8 °C and then warms to 4.4 °C all within 2 to 5 h in a single cycle, damage to the specimens is assessed by observation and measurement of the dynamic modulus of elasticity about every 30 freeze–thaw cycles according to the ASTM C 666 procedure A.

The freeze–thaw tests were performed in a freeze–thaw apparatus. The mechanical tests were conducted in a triaxial testing machine [16] (designed by the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology) that is capable of developing three independent compressive or tensile forces. Three layers of butter and three layers of plastic membrane were used as friction-reducing pads to measure the biaxial compressive strength. A minimum of three specimens were tested for each batch. The tests were performed under constant stress ratios ($\alpha = \sigma_2/\sigma_3 = 0.0$ (uniaxial compression), 0.25, 0.50, 0.75 and 1.0). The three principal stresses and the three principal strains are expressed as $\sigma_3 \geq \sigma_2 \geq \sigma_1$, $\varepsilon_3 \geq \varepsilon_2 \geq \varepsilon_1$ (compression denoted as positive). The loads and deformations in the two principal directions under biaxial compression were monitored and recorded after 0, 25, 50 and 75 cycles of freeze–thaw respectively.

3. Results and discussions

3.1. Experimental results

The tensile strength, the RDME and the weight loss of plain concrete after different cycles of freezing and thawing are given in Table 2. The detailed information on the tensile strength, the RDME and the weight loss has been reported earlier [17].

The experimental results of plain concrete under biaxial compression are listed in Table 3. The loading speed was 20 MPa/min in the direction of σ_3. The compressive stresses σ_2 andσ_3 were calculated by dividing the compressive loads by the area of loading (0.01 m^2).

3.2. Failure modes

The loading direction is shown in Fig. 1(a).

The failure modes of the concrete specimens under biaxial compressive loading subjected to the action of freezing and thawing cycles are shown in Fig. 1(b) and (c).

The experimental study in this paper has shown that providing a small confinement stress along the minor principal stress σ_2 direction changed the failure modes. Unlike the column-type fragments observed under uniaxial compression for plain concrete subjected to the freezing and thawing cycles, it were shear-type and parallel plate-type failure under biaxial compression, as shown in Fig. 1(b) and (c). Although the modes of failure under uniaxial and biaxial loading were different, the splitting tensile strain along the unload plane(s) was the cause of failure for both. This finding on the failure modes obtained for plain concrete under biaxial compression conditions is in agreement with a previous study [10].

It was obvious that the influence of freezing and thawing cycles on plain concrete did not change the tensile splitting mode from occurring. But there was a great change in the failure modes for plain concrete after freeze–thaw cycles under different stress ratios. The tensile strain will be caused in the direction of σ_1 because of the action of σ_3 and σ_2, and the crack forms when the strain was larger than the ultimate tensile strain of the specimen. It can also be seen that the shear-type failure (the angle of the crack with the direction of free surface is about 20°–30°) was formed on the surface of σ_2 when the lateral stress ratio was $\alpha \leq 0.50$, while the parallel plate-type fragments (about 2–4 layers) are formed on the surface of σ_3. When a stress ratio is equal to 0.75 and 1.0, the parallel plate-type fragments are formed on the surfaces of σ_2 and σ_3. Furthermore, the number of cracks became larger as the stress ratio was increased. There was no connection between the direction of the cracking and stress ratio. It was noticed that the cracks on the loaded surface have a random direction because of the influence of coarse aggregates. This differs from the conclusions of Zhenhai where there were no evident differences of the failure modes of the specimens under different stress ratios [11].

Table 2
The RDME, the weight loss and tensile strength of concrete after different cycles of freezing and thawing

Number of freeze–thaw cycles (N)	0	25	50	75	100
RDME (%)	100	85	82	72	62
Weight loss (%)	0	−0.08	−0.11	0.23	1.2
Tensile strength (MPa)	3.14	1.32	1.15	0.98	0.79

Table 3
The biaxial compressive strength and performance index of plain concrete under various stress ratios after different cycles of freezing and thawing

Stress, strain, the elastic modulus	Number of freezing and thawing cycles	Stress ratio($\alpha=\sigma_2/\sigma_3$)				
		0.00	0.25	0.50	0.75	1.00
σ_3 (MPa)	0	34.20	43.01	45.49	42.50	40.70
	25	30.01	40.20	41.56	40.21	38.65
	50	24.10	32.26	36.84	35.29	33.15
	75	21.67	31.33	35.28	34.96	31.85
ε_3 (10^{-2})	0	0.2401	0.3402	0.2910	0.2640	0.2869
	25	0.2802	0.3901	0.3405	0.3203	0.3315
	50	0.3801	0.5305	0.4802	0.4203	0.4122
	75	0.4498	0.6305	0.5506	0.5015	0.4867
E_d (10^4MPa)	0	3.001	3.120	3.342	3.625	3.640
	25	2.700	2.811	3.008	3.263	3.321
	50	1.850	1.920	1.981	2.130	2.240
	75	1.250	1.360	1.480	1.560	1.610
σ_2 (MPa)	0	0	10.75	22.75	31.88	40.70
	25	0	10.05	20.78	30.16	38.65
	50	0	8.07	18.42	26.47	33.15
	75	0	7.83	17.64	26.22	31.85

3.3. Strength characteristic

Fig. 2(a) demonstrates the influence of freezing and thawing cycles on the principal stress σ_3. It can be seen from Fig. 2(a) and Table 3 that the principal stress σ_3 decreases as the freezing and thawing cycles are repeated. The drop of strength is slower under biaxial compression than that under uniaxial compression as freeze–thaw cycles were increased. After 50 cycles of freezing and thawing, the strength under uniaxial compression decreased to 70.5% of that prior to the freezing and thawing cycles; When the stress ratio was equal to 0.5, the strength decreased to 81.0% of initial strength prior to the freezing and thawing cycles.

Fig. 2(b) shows the influence of stress ratio on the principal stress σ_3. It can be seen that the biaxial ultimate strength is greater than the uniaxial strength for the same number cycles of freeze–thaw at all stress ratios. The strength increase is dependent on the biaxial stress ratio for the same cycles of freeze–thaw. In addition, the influence of stress ratio on the principal stress σ_3 becomes larger as freeze–thaw cycles are repeated. For example, the strength under biaxial compression with the different stress ratios varied from 1.19 to 1.33 of the uniaxial strength prior to freeze–thaw cycles. However, after 50 cycles of freezing and thawing, it varied from 1.34 to 1.53 times the uniaxial strength at different stress ratios. The maximum strength σ_3 under biaxial compression with the stress ratio of 0.5 was about 1.33 of the uniaxial strength prior to the freeze–thaw cycles; while after 75 cycles of freezing and thawing, the maximum strength σ_3 under the stress ratio of 0.5 was about 1.63 of the uniaxial strength. Fig. 2(c) gives the relationship between the increments of biaxial compressive strength over

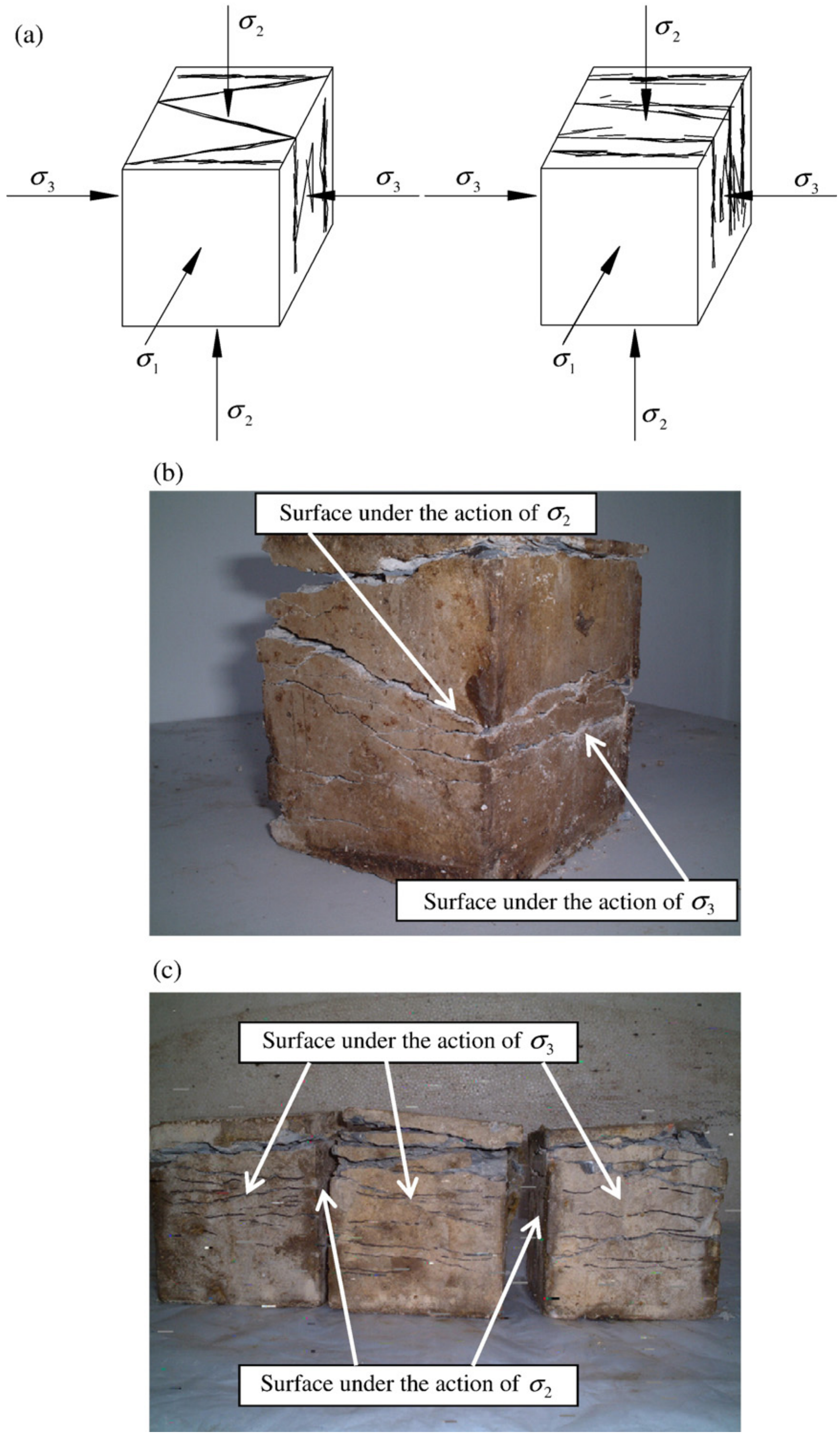

Fig. 1. Failure modes of plain concrete under biaxial compression after freezing and thawing cycles, (a) loading direction, (b) stress ratio $\alpha=\sigma_2/\sigma_3=0.50$, (c) stress ratio $\alpha=\sigma_2/\sigma_3=0.75$.

uniaxial strength after different cycles of freeze–thaw, f_c^d is the uniaxial strength after different cycles of freeze–thaw.

Kupfer [18], Traina and Mansour [19] and Koya [20] performed biaxial concrete-strength tests. The results of the biaxial compressive strength tests of Kupfer and Helmut were about 1.18 to 1.27 times uniaxial compressive strength, when 200 mm × 200 mm × 50 mm plate specimens with brush-bearing platens as a friction-reducing pads were used. The test results of Koya were about 1.25 to 1.40 times the uniaxial compressive strength when the maximum loading force was parallel with the direction of the cast, when testing 100 mm cubes with two resin sheets and silicon grease; the results of Mills and Zimmerman [21], using 57.4 mm cubes with two resin sheets and axle grease, were about 1.275 to 1.568 times the uniaxial compressive strength.

The Chinese Water Conservation and Hydroelectric Academy [22] has investigated multiaxial concrete strength using

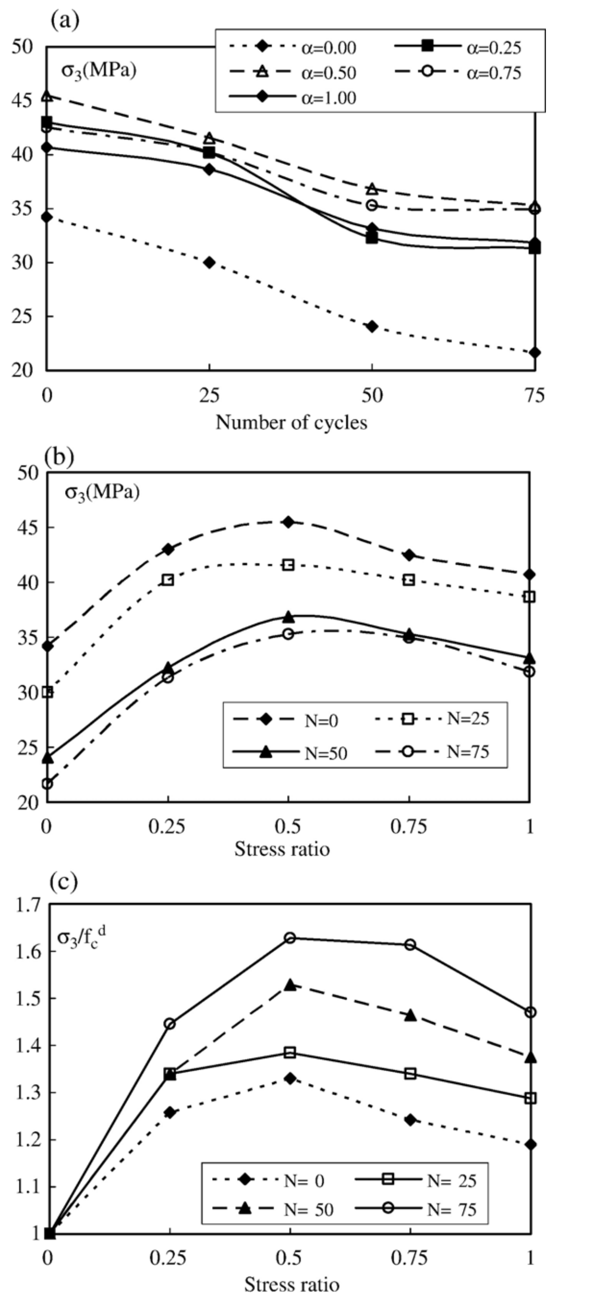

Fig. 2. (a) Influence of freezing and thawing cycles on the principal stress σ_3, (b) influence of stress ratios on the principal stress σ_3, (c) increment of biaxial compressive strength over uniaxial compressive strength after different cycles of freeze–thaw.

130 mm × 130 mm × 60 mm plate specimens. The test results were from 1.38 to 1.69 times the uniaxial strength when using resin sheets greased with MoS. Furthermore, the biaxial compression strength varies from 1.52 to 1.67 times the uniaxial strength with different stress ratios when the hollow cylinder was used as a specimen.

Comparing the test results in this paper to those of other authors showed that some of the ratios of the biaxial to uniaxial compressive strength was different. This disagreement can be attributed to: (1) the loading system effect, (2) the rate of the loading, (3) the specimen size and shape, (4) the friction-reducing material and different test methods. Even with the same material, the results of the biaxial strength of the joint program still show scatter because of the differences in casting and curing. In addition, the biaxial compressive strength scatters in a certain range even with the same loading system, rate of the loading, specimen size and shape, friction-reducing material and measure, same casting and curing after different cycles of freezing and thawing.

3.4. Failure criterion

The biaxial strength (obtained by experimental tests) envelopes for plain concrete under biaxial compression after different cycles of freeze–thaw are shown in Fig. 3.

Using regression analysis, the test results of the plain concrete after different numbers of freezing and thawing cycles (with three layers of butter used as a friction reducing pad) led to the formula of the biaxial compressive strength, taking the following form:

$$\frac{\sigma_3}{f_c} = \frac{f_1(N) + f_2(N) \times \alpha}{(1+\alpha)^2} \quad for\ 0 \le N \le 75 \tag{1}$$

where: $\alpha = \sigma_2/\sigma_3$ (for $0 < \alpha < 1$), N is the number of freezing and thawing cycles; α is the stress ratio; f_c is the uniaxial compressive strength of plain concrete prior to the freezing and thawing cycles. $f_1(N)$ and $f_2(N)$ are functions of N. The formulae of $f_1(N)$ and $f_2(N)$ are as follows:

$$\begin{cases} f_1(N) = -0.0050544 \times N + 1.02214 \\ f_2(N) = -0.0087264 \times N + 3.75944 \end{cases}$$

Fig. 3 gives the comparison of Eq. (1) and the test values.

3.5. Deformation characteristic

The following discussion will be limited to the principal strains ε_3 measured on the specimens at the peak stress σ_3. The influence of the freeze–thaw cycles on the principal strain ε_3 under biaxial compression with various stress ratios is presented in Fig. 4. It can be seen from Table 3 and Fig. 4 that the principal strains ε_3 under biaxial compression with the same stress ratio increased as the freeze–thaw cycles were repeated. After 50 cycles of freeze–

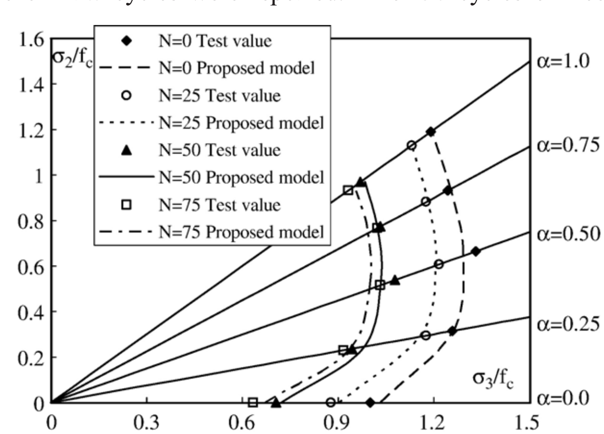

Fig. 3. Failure envelopes in principal stress space of concrete under biaxial compression subjected to freezing and thawing cycles.

thaw, the principal strain under biaxial compression with the stress ratio $\alpha=0.50$ increased to 1.65 times that prior to the freeze–thaw cycles; however, the principal strain under biaxial compression with the stress ratio $\alpha=0.75$ increased to 1.59 times that prior to the freeze–thaw cycles.

The principal strain ε_3 under biaxial compression was greater than that under uniaxial compression for the same cycles of freeze–thaw. For example, the strain under biaxial compression varied from 1.14 to 1.39 times the uniaxial compressive strain after 25 cycles of freeze–thaw, and after 75 cycles of freeze–thaw, it varied from 1.08 to 1.40 times the uniaxial compression strain. The principal strain increase depends on the stress ratio after the same cycles of freeze–thaw. The maximum strain under biaxial compression occurs at the stress ratio of 0.25 after the same cycles of freeze–thaw. For example, after 50 cycles of freeze–thaw, the strain under biaxial compression with the stress ratio $\alpha=0.25$ was approximately 1.40 times the uniaxial compressive strain.

3.6. The elastic modulus

It can be seen from Table 3 that the elastic modulus under biaxial compression and uniaxial compression decreased as the number of freeze–thaw cycles increased. After 50 cycles of freeze–thaw, the elastic modulus under uniaxial compression decreased to 62% of that prior to the freeze–thaw cycles; and the elastic modulus under biaxial compression with the stress ratio $\alpha=0.50$ decreased to 59% of that under the same stress ratio prior to the freeze–thaw cycles. The influence of the freeze–thaw cycles on the elastic modulus under various stress ratios is presented in Fig. 5.

The elastic modulus under biaxial compression increased as the stress ratio increased for the same cycles of freeze–thaw. The finding is consistent with the statement reported earlier by Mahboubi and Ajorloo [23] that the elastic modulus increases as the confining increases. It can be seen from Table 3 that the elastic modulus is at the maximum when the stress ratio $\alpha=1.0$ for the same cycles of freeze–thaw. For example, after 50 cycles of freeze–thaw, the maximum elastic modulus under the stress ratio $\alpha=1.0$ was approximately 1.21 times that under uniaxial

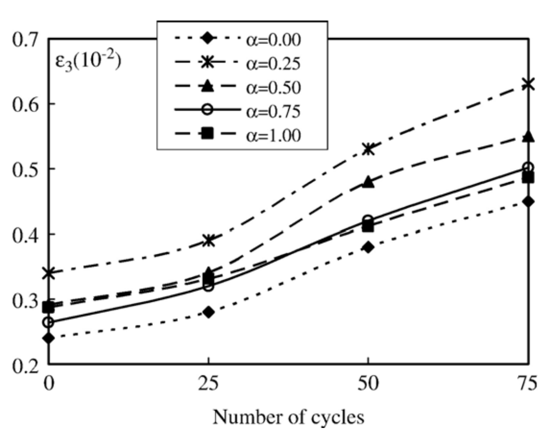

Fig. 4. Influence of freezing and thawing cycles on the principal strain ε_3 under various stress ratios.

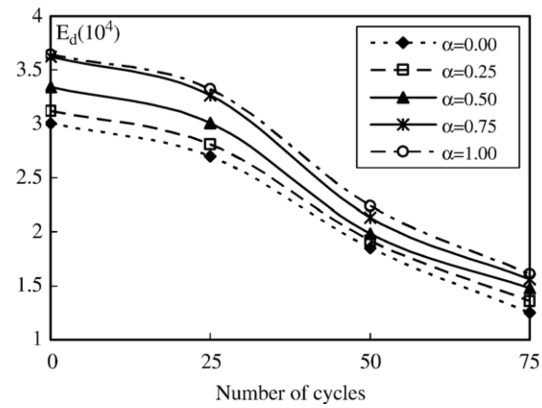

Fig. 5. Influence of freezing and thawing cycles on the elastic modulus E_d under various stress ratios.

compression state. The influence of stress ratio on the elastic modulus changes little as the freeze–thaw cycles are repeated. For example, the elastic modulus under biaxial compression varied from 1.04 to 1.23 of that under uniaxial compression state after 25 cycles of freeze–thaw; while after 75 cycles of freeze–thaw, it varied from 1.09 to 1.29 of that under uniaxial compression state.

3.7. Stress–strain relationships

Fig. 6(a–d) depicts the stress–strain curves for plain concrete under biaxial compression subjected to different cycles of freezing and thawing. It can be seen from Fig. 6 that the difference in shape of stress–strain curves for plain concrete can be attributed to the influence of the freeze–thaw cycles and the stress ratio. It is clear that introducing a confinement stress in the σ_2 direction has a pronounced effect on the strength and deformation behavior in the direction of the principal stress σ_3.

From Fig. 6(a–d), it is apparent that the principal strain ε_3 corresponding to the peak stress σ_3 increases as the freeze–thaw cycles are repeated. It can also be noticed from Fig. 6 that the principal stress σ_3 was at the maximum when the stress ratio $\alpha=0.50$ after the same cycles of freeze–thaw, and the ratio of biaxial compressive strength σ_3 to uniaxial compressive strength becomes large as freeze–thaw cycles are repeated; the principal strain was at the maximum when the stress ratio $\alpha=0.25$ after the same cycles of freezing and thawing. It was also observed that the initial tangent inclination of the stress–strain curves for biaxial compression is relatively steep with the increase of stress ratio α, because of the influence of the transverse confinement stress. The length of the liner part in the stress–strain curves under biaxial compression is larger than that under uniaxial compression after the same cycles of freeze–thaw; in addition, the length of the liner part increases with the stress ratio increase.

3.8. Discussion of freeze–thaw cycling damage of concrete

The deterioration in the biaxial behavior of plain concrete after cycles of freeze–thaw was caused by the formation and growth of

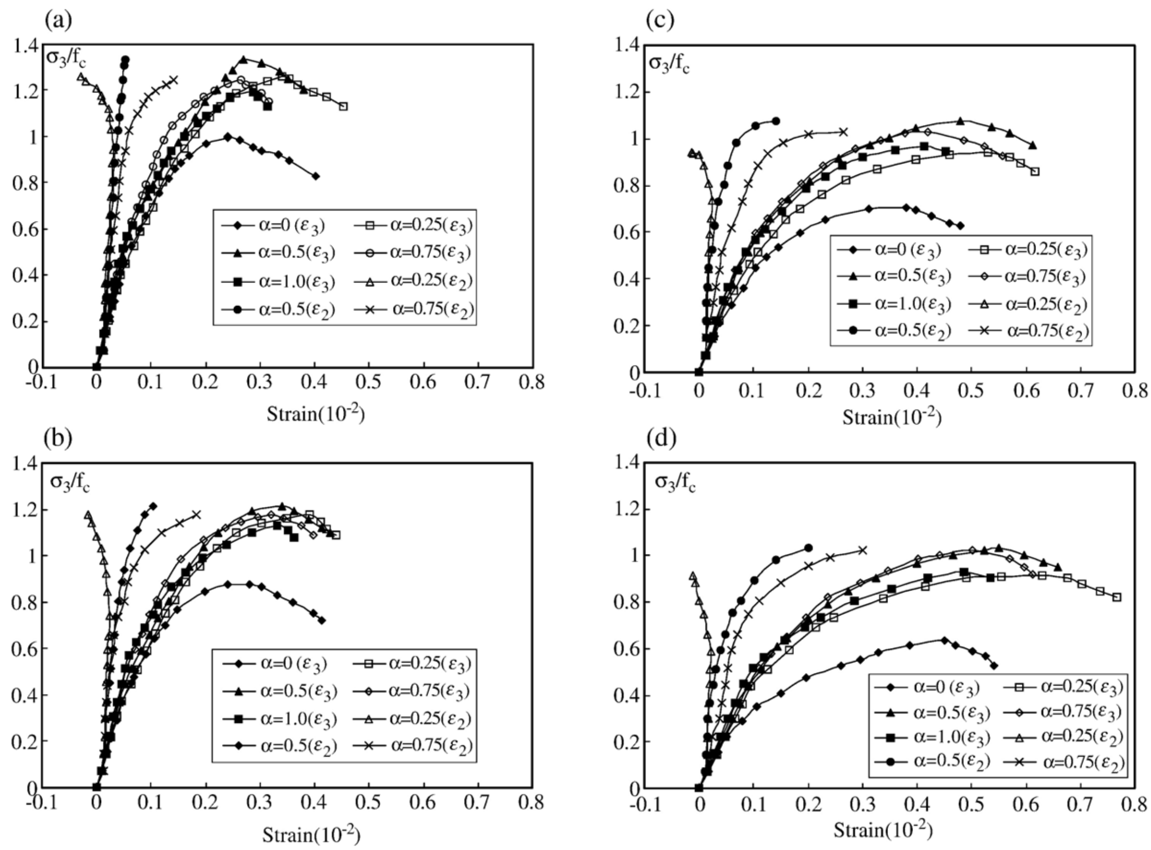

Fig. 6. Stress–strain curves for plain concrete under biaxial compression after different cycles of freezing and thawing, (a) stress–strain curves for plain concrete under biaxial compression prior to the freezing and thawing cycles, (b) stress–strain curves for plain concrete under biaxial compression subjected to 25 freezing and thawing cycles, (c) stress–strain curves for plain concrete under biaxial compression subjected to 50 freezing and thawing cycles, (d) stress–strain curves for plain concrete under biaxial compression subjected to 75 freezing and thawing cycles.

micro-cracks. Concrete is a three-phase composite structure at microscopic scale, a cement matrix, aggregate and the interfacial transition zone between the two. Micro-cracks exist at the interfaces between the cement matrix and aggregate even prior to any load and environmental effects. Such micro-cracks are formed due to drying and thermal shrinkage mismatch of aggregate particles and cement-based matrix during the curing. A part of these micro-cracks may absorb water that may be frozen and expand at low temperatures under the repeated freeze–thaw cycles, the formation of new micro-cracks will be caused when the expansion stresses coupled with the thermal stresses have exceeded the tensile strength of concrete. Considering the concrete specimen under biaxial compression, the initiation and growth of every new crack will reduce the load carrying area. This reduction in load carrying area further causes an increase in the stress concentration at critical crack tips. So the compressive strength of plain concrete under biaxial compression decreased when freeze–thaw cycles were repeated. Gao et al. [24] reported that the micro-cracks within high performance lightweight aggregate concrete are the major factors leading to the reduction in frost resistance and durability. Cracks are mainly created within the cement paste, the interface between cement paste and aggregate. The main reason for inducing cracks on the freeze–thaw cycles of concrete is the freezing of water and its expansion. The second is the thermal stress developed during the repeated freeze–thaw action. Soroushian and Elzafraney [25] stated that different damaging effects (compression, impact, freeze–thaw, fatigue, freeze–thaw+compression) produced different changes in the extent and nature of micro-crack propagation within concrete. Compression increased the length, width and area fraction of micro-cracks; while freeze–thaw effect on undamaged specimens yielded less tortuous micro-crack growth paths.

On the other hand, as the damage of concrete by freeze–thaw cycles increases, the plastic strain increases. This phenomenon occurs because the greater the damage is, the lesser compression the concrete elements can carry; these elements reach their plastic point more quickly, resulting in a higher plastic strain at the same maximum mechanical equivalent strain level. This means that the biaxial compressive strain at the peak stress will increase with increase of the freeze–thaw cycles. In addition, internal cracking in the concrete during the freeze–thaw cycles causes a very high degradation in initial stiffness.

4. Conclusion

Based on the test results, the following conclusions can be obtained:

1. The effect of freezing and thawing cycles on plain concrete did not change the failure modes; also, providing a small

confinement stress σ_2 changed the failure modes from the common column-type to shear-type and parallel plate-type;

2. The ultimate strength under biaxial compression decreases as the freeze–thaw cycles are repeated; the ultimate strength under biaxial compression with all stress ratios is greater than the uniaxial compressive strength for the same cycles of freeze–thaw;
3. The strain ε_3 at the peak stress under biaxial compression increases as the freeze–thaw cycles are repeated; the strain under biaxial compression with all stress ratios was greater than the uniaxial compressive strain after the same cycles of freeze–thaw;
4. The formula of the biaxial compressive strength in principal stress space is proposed.

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