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Research Article

Mechanical and Failure Criteria of Air-Entrained Concrete under Triaxial Compression Load after Rapid Freeze-Thaw Cycles

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The experiment study on the air-entrained concrete of 100 mm cubes under triaxial compression with different intermediate stress ratio $\alpha_2 = \sigma_2^D : \sigma_3^D$ was carried out using a hydraulic-servo testing system. The influence of rapid freeze-thaw cycles and intermediate stress ratio on the triaxial compressive strength σ_3^D was analyzed according to the experimental results, respectively. The experimental results of air-entrained concrete obtained from the study in this paper and the triaxial compression experimental results of plain concrete got through the same triaxial-testing-system were compared and analyzed. The conclusion was that the triaxial compressive strength is greater than the biaxial and uniaxial compressive strength after the same rapid freeze-thaw cycles, and the increased percentage of triaxial compressive strength over biaxial compressive strength or uniaxial compressive strength is dependent on the middle stress. The experimental data is useful for precise analysis of concrete member or concrete structure under the action complex stress state.

1. Introduction

In cold regions, such as northern China, Russia, Canada, and northern Europe, the performance (e.g., strength, deformation and elasticity modulus) deterioration of concrete applied in practical engineering can be caused by the action of rapid freeze-thaw cycles. Özgan and Serin [1] investigated the effect of freeze-thaw cycles on asphalt concrete materials according to Marshall stability values and ultrasonic velocity and so forth. The value of fracture parameters of lightweight concrete after different freeze-thaw cycles was determined through a three-point bending test in [2]. The weight loss, pulse velocity, and resonance frequency of silica fume concrete after the action of freeze-thaw cycles were reported in [3]. The influence of freeze-thaw cycles on the behavior (compressive strength, weight loss, and relative pulse velocity) of concrete with synthetic fibre additions was studied in [4]. The experimental results show that the freeze-thaw cycles can cause the degradation of the strength and deformation properties of asphalt concrete, lightweight aggregate concrete, silica fume concrete, and so forth.

Several kinds of mechanisms, such as "microscopic ice lens growth" [5] and "hydraulic pressure" [6] could be used to explain the frost damage in concrete. Some researches demonstrated that the inner structures and material properties of concrete have more significant effect on this damage degree than the external environment [7–9]. And the internal structure of concrete may be affected by the frost damage caused by the inner pressure and the associated micro cracks. Based on this, air-entrained agent is added to the concrete to make air-entrained concrete. One of the advantages of air-entrained concrete is its greater resistance to damage caused by freeze-thaw cycles [10–12] which make it especially suitable in the construction of dam, long span bridges, and offshore oil platforms in cold environment. So far, air-entrained concrete [13] has been widely used in the field

Table 1: Mix proportions of air-entrained concrete.

w/c	Cement (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Air-entraining agents (kg/m^3)	Air content (%)
0.40	412.67	586.83	1186.00	164.30	1.03	5.80

of hydraulic engineering and civil engineering. However, a lot of experimental tests are carried out to determine the freeze-thaw durability of different type concrete, while, for air-entrained concrete, the research is still comparatively rare. Pheeraphan and Leung [14] studied the freeze-thaw resistance of microwave cured air-entrained concrete. According to the test results of Pheeraphan and Leung, the freeze-thaw durability of high w/c concrete will be impaired by microwave curing. Shang et al. [15] investigated the weight loss, relative dynamic modulus of elasticity, tensile strength, compressive strength, cubic compressive strength, and cleavage strength of air-entrained concrete after different freeze-thaw cycles. And it can be seen from [14, 15], for air-entrained concrete or other types of concrete, that most of the previous researchers mainly focused their attention on the dynamic elastic modulus, weight loss, flexural strength, and uniaxial compression strength after different freeze-thaw cycles. Meanwhile, in civil engineering, it can be well-known that concrete materials in member of structure (e.g., shear walls, thin shells, and slabs) are essentially in a complex stress state: such as biaxial compression, triaxial tension-tension-compression, triaxial compression [16–19]. For refined calculation, the behavior of concrete materials under a stress state of multiaxial loads should be examined carefully. The mechanical performance of plain concrete under biaxial and triaxial compression was studied after freeze-thaw cycles [20–22]. Wang and Song [23] investigated the failure criterion of the haydite concrete under triaxial loading. The strength criterion of lightweight aggregate concrete under multiaxial loads was also studied based on the unified twin-shear strength theory [24].

According to experimental results in the literature, it has been realized that although a large number of test data are available regarding the triaxial compression behavior of plain concrete and some special concrete, very little information on the behavior of air-entrained concrete under triaxial stress state can be found, especially the behavior of air-entrained concrete under triaxial compressive loads after the action of different rapid freeze-thaw cycles. Many literatures [1–4, 9–12, 19–21] illustrated that the strength and peak strain in concrete are influenced significantly by the inner damage caused by freeze-thaw cycles. Hanjari [25] pointed out that the results obtained from the undamaged concrete can not be applied directly for the frost-damaged concrete.

In order to better understand and predict the performance of structure and member made with air-entrained concrete material, the mechanical properties of air-entrained concrete should be figured out. Shang [26] investigated the triaxial compression behavior of air-concrete with stress ratio $\sigma_2^D : \sigma_3^D = 1.00 : 1.00$. The experiment on strength behavior of air-entrained concrete under triaxial compression load with $\sigma_1^D : \sigma_3^D = 0.10 : 1.00$ after rapid freeze-thaw cycles was carried out. Results obtained from the experimental studies will be used to develop a simple relationship between mechanical behavior and number of rapid freeze-thaw cycles for air-entrained concrete. The relationship can be used as input to computer programs to analyze the behavior of air-entrained concrete structural members subjected to different rapid freeze-thaw cycles.

2. Experimental Program

2.1. Materials and Mix Proportions. The 42.5# Ordinary Portland cement (the compressive strength should reach 22.0 MPa and 42.5 MPa at days 3 and 28; the flexural strength should reach 4.0 MPa and 6.5 MPa at days 3 and 28), tap water, river sand (fineness modulus was 2.6), crushed natural stone aggregate (diameter ranges from 5 mm to 20 mm), and air-entrained admixture (rosin soap air-entraining agent was used) were used in this experimental study. The proportions by weight of cement: water: sand: coarse aggregate are 1 : 0.4 : 1.42 : 2.87. The mixing proportions in this experiment were given in Table 1. The air content of the concrete mixture was 5.8% after mixing. The compressive strength of 28 days is 25.64 MPa.

2.2. Specimen and Testing Programs. In this experiment study, horizontal forced action mixer with 0.1 m^3 was used to elaborate the mixture. The following mixing procedure was used: first, fine aggregate, coarse aggregate, and cement were put into the mixer and the components were mixed for 1 minute; then, tap water was added and continued to stir for 2~3 minute; next, the fresh concrete material was cast in cubical molds with size 100 mm × 100 mm × 100 mm and a vibrating table with size 1 m × 1 m was used to compact concrete. After the fresh concrete was mixed, the air content was measured with air-content measuring instrument. At the same time, freshly cast specimens were kept in the molds for 24 hours. Finally, they were demoulded and stored in a curing room which can keep 95 percent relative humidity and the temperature of 20 ± 3°C. At 24 days of age, some air-entrained concrete specimens were taken out from the curing room and immersed in water for 4 days.

According to "the test method of long-term and durability on ordinary concrete" [21, 27], the rapid freeze-thaw tests were performed in a rapid freeze-thaw apparatus at 28 days of age for concrete specimen. In a single rapid freeze-thaw cycle, the center temperature of the specimens should cool from 6°C to −15°C and then warm to 6°C during about 2.5–3 h. The temperature of the concrete specimens was measured and controlled by a Pt sensor embedded in the center of concrete specimen. And the test is similar to the ASTMC 666, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing" [28]. In a single cycle according to

(a) Loading direction and surface crack of specimen under triaxial compression load

(b) Failure mode and surface cracks of air-entrained concrete under triaxial compression after rapid freeze-thaw cycles

(c) Fracture surface of air-entrained concrete under triaxial compression load after 400 rapid freeze-thaw cycles

Figure 1: The failure mode and fracture surface of air-entrained concrete specimen after different freeze-thaw cycles.

ASTMC 666, the temperature of the specimens cools from 4.4 to −17.8°C and then warms to 4.4°C within 2 to 5 h.

And the triaxial compression experiment was carried out in a triaxial-testing-system [21, 29]. The stress ratios were $\alpha = \sigma_1^D : \sigma_2^D : \sigma_3^D = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$. The relationship of principal compressive stresses was expressed as $\sigma_1^D \leq \sigma_2^D \leq \sigma_3^D$ (compression stress denoted as positive). The friction between loading plate of testing machine and surface of concrete specimen will affect the experimental results; in order to eliminate the influence of friction, the friction-reducing pads [30] (consisting of three plastic membranes with three layers of butter between them) were used which were placed between the specimen and the loading plate.

3. Results and Discussions

3.1. Failure Modes. Figure 1(a) gives the triaxial compression loading direction for air-entrained concrete specimens. The triaxial compression failure mode and surface crack of air-entrained concrete specimen after different freeze-thaw cycles were given in Figure 1(b).

A gradual failure was observed in the triaxial compression experiment on air-entrained concrete specimens after different freeze-thaw cycles. The failure surfaces are "neat surfaces" and cracks pass through the "broken aggregate." The failure surface contained fractures through both cement mortar and coarse aggregate. A typical fracture surface of an air-entrained concrete specimen is shown in Figure 1(c).

Under triaxial compression load with stress ratios $\alpha = \sigma_1^D : \sigma_2^D : \sigma_3^D = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$, the failure mode of the specimens was slant-shear failure, which was caused by the splitting tensile strain along σ_1^D direction. The angle between the direction of σ_3^D and the crack was about 20°∼30°. There were two cracks on σ_2^D surfaces; the number of cracks on the σ_3^D surfaces was one or two, respectively.

Under triaxial compression load with stress ratios $\alpha = \sigma_1 : \sigma_2 : \sigma_3 = 0.05 : 1 : 1$, $0.1 : 1 : 1$, $0.15 : 1 : 1$, and $0.2 : 1 : 1$ in [26], the failure mode of the specimens of air-entrained concrete specimen was parallel plate-type fragments mode and slant-shear failure mode; the angle between the crack and the direction of σ_3 was about 20°∼30° when the stress ratios were $\alpha = 0.1 : 1 : 1$, $0.15 : 1 : 1$, and $0.2 : 1 : 1$; the angle between the crack and the direction of σ_3 was about 10°∼20° when $\alpha = 0.05 : 1 : 1$; and parallel plate-type fragments were formed on the surface of σ_2 and σ_3 under triaxial compression load with stress ratios $\alpha = \sigma_1 : \sigma_2 : \sigma_3 = 0 : 1.00 : 1.00$. According to the experiment results of plain concrete conducted on the same triaxial-testing-system with this paper [20], the splitting cracks in slice shapes were formed on surface of σ_2 and σ_3 under triaxial compression load with stress ratios $\alpha = \sigma_1 : \sigma_2 : \sigma_3 = 0.1 : 1 : 1$, and the slant-shear cracks are in good agreement with experimental results obtained in this paper when triaxial compression stress ratios are $\alpha = \sigma_1 : \sigma_2 : \sigma_3 = 0.1 : 0.25 : 1.0$; $0.1 : 0.5 : 1.0$; $0.1 : 0.75 : 1.0$. Reference [20] studied triaxial compression strength of plain concrete through experiment, and three failure modes were observed in this experiment, which are (1) splitting cracks in slice shapes, (2) splitting cracks in column shapes, and (3) flow and deformation.

3.2. Experimental Results. Table 2 listed the test results of air-entrained concrete under triaxial compression load with different intermediate stress ratio $\alpha_2 = \sigma_2^D : \sigma_3^D$ after rapid freeze-thaw cycles. The compressive stresses σ_1^D, σ_2^D, and σ_3^D were got through dividing compressive loads with loading area ($0.01\,\text{m}^2$). σ_{oct}^D and τ_{oct}^D are the normal stress and the shear stress in octahedral stress space after different freeze-thaw cycles [20, 31] which can be computed from

Table 2: Experimental results of air-entrained concrete under triaxial compression after rapid freeze-thaw cycles (MPa).

Freeze-thaw cycles	α	σ_1^D	σ_2^D	σ_3^D	σ_{oct}^D	τ_{oct}^D	σ_{oct}^D/f_c	τ_{oct}^D/f_c
0	0.1 : 0.25 : 1	10.45	24.38	95.81	43.55	37.39	1.70	1.46
	0.1 : 0.5 : 1	11.84	52.92	105.39	56.72	38.29	2.21	1.49
	0.1 : 0.75 : 1	9.96	69.30	92.35	57.20	34.71	2.23	1.35
	0.1 : 1 : 1	10.04	85.01	85.22	60.09	35.39	2.34	1.38
100	0.1 : 0.25 : 1	10.45	24.29	95.40	43.38	37.22	1.69	1.45
	0.1 : 0.5 : 1	10.98	49.92	99.60	53.5	36.27	2.09	1.41
	0.1 : 0.75 : 1	9.95	66.92	89.20	55.36	33.37	2.16	1.30
	0.1 : 1 : 1	10.13	84.51	84.75	59.80	35.12	2.33	1.37
200	0.1 : 0.25 : 1	9.49	21.62	84.95	38.69	33.09	1.51	1.29
	0.1 : 0.5 : 1	9.32	42.45	84.48	45.42	30.76	1.77	1.20
	0.1 : 0.75 : 1	8.82	59.55	79.46	49.28	29.74	1.92	1.16
	0.1 : 1 : 1	8.77	73.12	73.33	51.74	30.38	2.02	1.19
300	0.1 : 0.25 : 1	7.15	16.20	63.46	28.94	24.69	1.13	0.96
	0.1 : 0.5 : 1	8.22	37.14	73.92	39.76	26.89	1.553	1.05
	0.1 : 0.75 : 1	8.58	57.09	76.09	47.25	28.42	1.843	1.11
	0.1 : 1 : 1	7.87	66.10	66.33	46.77	27.50	1.823	1.07
400	0.1 : 0.25 : 1	6.66	15.41	60.51	27.53	23.59	1.07	0.92
	0.1 : 0.5 : 1	7.49	34.22	68.25	36.65	24.86	1.43	0.97
	0.1 : 0.75 : 1	6.92	45.52	60.70	37.71	22.64	1.47	0.88
	0.1 : 1 : 1	7.57	59.55	59.97	42.36	24.60	1.65	0.96

the following: $\tau_{oct}^D = (1/3)(\sigma_1^D + \sigma_2^D + \sigma_3^D)$ and $\sigma_{oct}^D = (1/3)\sqrt{(\sigma_1^D - \sigma_2^D)^2 + (\sigma_2^D - \sigma_3^D)^2 + (\sigma_3^D - \sigma_1^D)^2}$.

3.2.1. Effect of Rapid Freeze-Thaw Cycles on Peak Stress σ_3^D. The effect of rapid freeze-thaw cycles on strength of air-entrained concrete under triaxial compression load with different stress ratio was depicted in Figure 2. Table 3 demonstrates the loss of ultimate strength of air-entrained concrete under triaxial compression with increasing the rapid freeze-thaw cycles. It can be got from Figure 2 and Table 3 that the principal stress σ_3^D decreases as number of rapid freeze-thaw cycles increases. The reduction of triaxial compression strength of air-entrained concrete is slower than that of uniaxial and biaxial compression strength as number of rapid freeze-thaw cycles increases. After the action of 200 rapid freeze-thaw cycles, the uniaxial compression strength and biaxial equal compression strength decreased to 81.0 and 83.1 percent of those prior to the rapid freeze-thaw cycles, respectively; meanwhile, under the action of triaxial compression with stress ratio $\alpha = 0.10 : 1.00 : 1.00$, the strength decreased to 86.05 percent of that prior to the rapid freeze-thaw cycles. After the action of 200 rapid freeze-thaw cycles, the strength under triaxial compression with stress ratios $\alpha = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$ varied from 80.16% to 88.67% of initial value prior to freeze-thaw cycles.

For air-entrained concrete specimen under triaxial compression with stress ratios $\alpha = 0.05 : 1.00 : 1.00$, $0.10 : 1.00 : 1.00$, $0.15 : 1.00 : 1.00$, and $0.20 : 1.00 : 1.00$ [26], the strength after the action of 200 rapid freeze-thaw cycles varied from 83.15% to 93.82% of that prior to rapid freeze-thaw cycles. The effect of rapid freeze-thaw cycles on strength of air-entrained concrete under triaxial compression load with stress ratios $0 : 1.0 : 1.0$, $0.05 : 1.0 : 1.0$, $0.15 : 1.0 : 1.0$, and $0.2 : 1.0 : 1.0$ was given in Table 3. The effect of rapid freeze-thaw cycles on strength of plain concrete under triaxial compression load with stress ratios $\alpha = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$ was given in Table 4 as well.

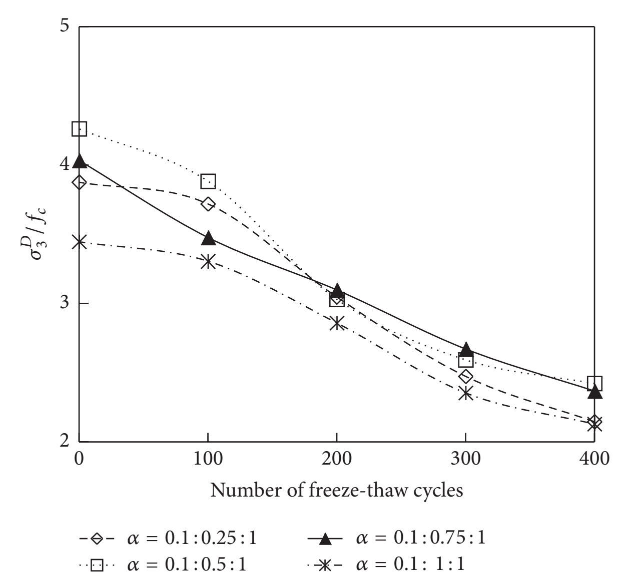

Figure 2: Effect of rapid freeze-thaw cycles on triaxial compressive strength under different intermediate stress ratio.

Table 3: Loss of ultimate strength of air-entrained concrete under triaxial compression load with rapid freeze-thaw cycles (%).

Stress ratio	Number of rapid freeze-thaw cycles			
	100	200	300	400
0.1 : 0.25 : 1.0	99.57	88.67	66.24	63.16
0.1 : 0.50 : 1.0	94.51	80.16	70.14	64.76
0.1 : 0.75 : 1.0	96.59	86.04	82.39	65.73
0.1 : 1.0 : 1.0	99.45	86.05	77.83	70.37
Uniaxial compression	90.36	81.05	65.02	47.31
Biaxial equal compression	92.09	83.15	68.50	56.67
0 : 1.0 : 1.0 in [26]	92.09	83.15	68.50	56.67
0.05 : 1.0 : 1.0 in [26]	94.32	89.54	75.67	68.23
0.15 : 1.0 : 1.0 in [26]	96.63	93.82	89.12	81.00
0.2 : 1.0 : 1.0 in [26]	98.29	91.88	86.08	86.61

Table 4: Loss of ultimate strength of plain concrete under triaxial compression with rapid freeze-thaw cycles (%).

Stress ratio	Number of rapid freeze-thaw cycles		
	25	50	75
0.1 : 0.25 : 1.0	95.88	89.13	80.38
0.1 : 0.50 : 1.0	96.68	93.30	90.65
0.1 : 0.75 : 1.0	98.20	93.18	87.04
0.1 : 1.0 : 1.0	96.50	92.80	89.38

For plain concrete specimens of 100 mm cube, the mechanical properties under the action of uniaxial compression load, biaxial compression load, and triaxial compression load with stress ratios $\alpha = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$ after 0, 25, 50, and 75 freeze-thaw cycles have been investigated by Shang et al. [20]. According to the information in [20], the same conclusion that the reduction of triaxial compressive strength is slower than that of uniaxial and biaxial compression strength with increasing the number of rapid freeze-thaw cycles was got. To illustrate, after the action of 75 rapid freeze-thaw cycles, compared with the initial strength of plain concrete under triaxial compression load with stress ratio $\alpha = 0.10 : 1.00 : 1.00$ prior to the rapid freeze-thaw cycles, the triaxial compressive strength decreased to 89.4 percent of initial value, while the biaxial equal compression strength and uniaxial compression strength decreased to 78.3 and 63.4 percent of initial value prior to the rapid freeze-thaw cycles, respectively. And, for plain specimen under triaxial compression with stress ratios $\alpha = 0.10 : 0.25 : 1.00$, $0.10 : 0.50 : 1.00$, $0.10 : 0.75 : 1.00$, and $0.10 : 1.00 : 1.00$ [20], the strength after the action of 75 rapid freeze-thaw cycles varied from 80.38% to 90.65% of initial value prior to rapid freeze-thaw cycles. It can be obtained from Table 3 that the effect of rapid freeze-thaw cycles on mechanical behavior (triaxial compression strength, biaxial compression strength, or uniaxial compression strength) of air-entrained concrete is much greater than that on mechanical behavior of plain concrete. That is, compared with plain concrete, air-entrained concrete is more applicable to be used in the cold regions.

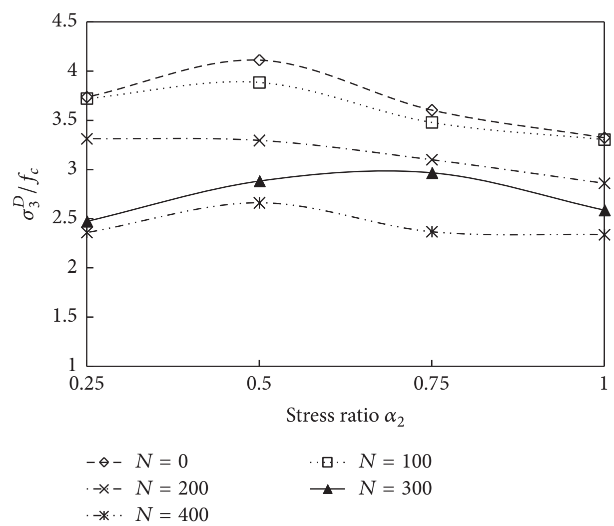

Figure 3: Influence of middle stress ratio α_2 on triaxial compressive strength after rapid freeze-thaw cycles.

3.2.2. Effect of Stress Ratio α_2 on Peak Stress σ_3^D. According to the experiment result of air-entrained concrete after the same rapid freeze-thaw cycles listed in Table 2, compared with the uniaxial compression strength, the triaxial compression strength improved greatly due to the action of lateral compression stress. Under the action of triaxial compression load, the increasing percentage of ultimate strength after different freeze-thaw cycles compared with uniaxial compression strength prior to freeze-thaw cycles is shown in Figure 3. Just as demonstrated in Figure 3, the triaxial compressive strength with all stress ratios is greater than the uniaxial compressive strength after the same rapid freeze-thaw cycles. And the improved value will change with the change of stress ratio of triaxial compression. After the action of 0, 100, and 400 rapid freeze-thaw cycles, the triaxial compressive strength is largest when the stress ratio was equal to $0.10 : 0.50 : 1.00$. Consistent with this, for plain concrete under triaxial compression, the same conclusion was got in [20]. According to the experimental results in [20], for plain concrete subjected to 0, 25, 50, and 75 rapid freeze-thaw cycles, the improved value

Table 5: Increased percentage of triaxial compression strength over uniaxial compression strength (%).

Stress ratio	Number of rapid freeze-thaw cycles								
	Test results of air-entrained concrete					Test results of plain concrete in [16]			
	0	100	200	300	400	0	25	50	75
0.1 : 0.25 : 1.0	3.74	4.11	3.60	3.32	3.74	3.94	3.78	3.51	3.16
0.1 : 0.50 : 1.0	3.72	3.88	3.48	3.31	3.72	4.15	4.01	3.87	3.76
0.1 : 0.75 : 1.0	3.31	3.29	3.10	2.86	3.31	3.71	3.64	3.45	3.23
0.1 : 1.0 : 1.0	2.48	2.88	2.97	2.59	2.48	3.28	3.16	3.04	2.93

Table 6: The value of a_1, a_2, a_3, and r.

	Stress ratio			
	0.05 : 1.0 : 1	0.1 : 0.25 : 1	0.1 : 0.5 : 1	0.1 : 0.75 : 1
a_1	0.1902	−0.0051	−0.0739	0.0490
a_2	0.5250	0.8608	0.7091	0.5842
a_3	−0.0161	−0.0004	0.0077	−0.0061
r	0.998	1.00	1.00	1.00

of triaxial compressive strength over uniaxial compression strength is largest when triaxial compression stress ratio $\alpha = 0.10 : 0.50 : 1.00$.

For air-entrained concrete under triaxial compression with different stress ratios prior to rapid freeze-thaw cycles, the ratio between triaxial compression strength and uniaxial compressive strength varied from 2.48 to 3.74. And, after the action of 300 rapid freeze-thaw cycles, the ratio between triaxial compression strength and uniaxial compression strength varied from 2.59 to 3.32.

Meanwhile, for plain concrete under triaxial compression load with different stress ratios prior to rapid freeze-thaw cycles [20], the ratio between triaxial compression strength and uniaxial compression strength varied from 3.28 to 4.15, and, after the action of 50 rapid freeze-thaw cycles, the ratio varied to be from 3.04 to 3.87 times the uniaxial compression strength. The increased percentage of triaxial compression strength over uniaxial compression strength for air-entrained-concrete and plain concrete is shown in Table 5.

3.3. Failure Criteria. The failure criteria expressed in shear stress τ_{oct} and normal stress σ_{oct} in octahedral stress space [20, 31] can be proposed as follows:

$$\frac{\tau_{\text{oct}}}{f_c} = a_1 + a_2 \frac{\sigma_{\text{oct}}}{f_c} + a_3 N, \quad (1)$$

where a_1, a_2, and a_3 are the regress parameters, respectively, N is the number of rapid freeze-thaw cycles, the correlative coefficient r can be got through regression of the test results of air-entrained concrete under triaxial compression load after the action of different rapid freeze-thaw cycles, and the values of a_1, a_2, a_3, and r were given in Table 6.

Figure 4 gives the testing results of air-entrained concrete under triaxial compression load and the computed results obtained according to (1). Through comparing the test results

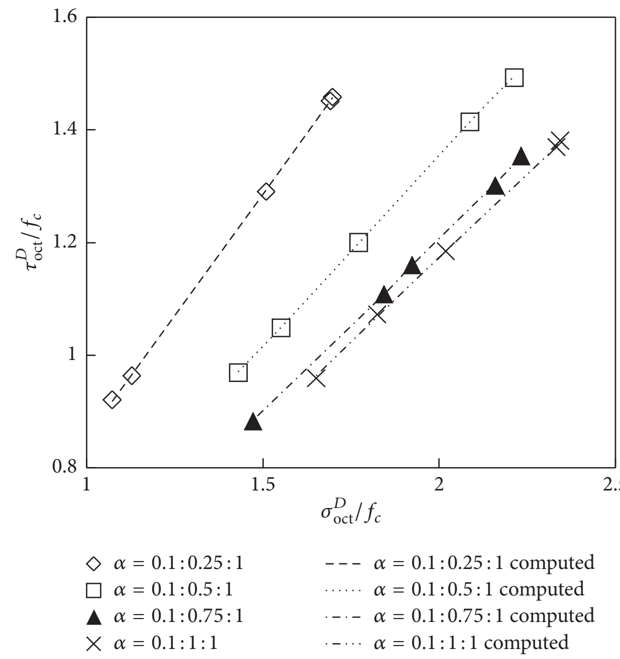

Figure 4: Test results of triaxial compressive strength after rapid freeze-thaw cycles in octahedral stress space.

with the computed results, it can be seen from Figure 2 that they are in good agreement.

3.4. Discussion. The deterioration of concrete material will be caused by the action of rapid freeze-thaw cycles. Compared with plain concrete, the form of the bubble in air-entrained concrete is more uniform due to the introduction of air-entraining agent. Under the effect of rapid freeze-thaw cycles, the existence of the bubble could relieve the internal expansion pressure caused when the water freezes. Then, after the action of same rapid freeze-thaw cycles, the strength loss of air-entrained concrete under triaxial compression load is lower than that of plain concrete.

The damage of concrete under triaxial compression load, biaxial compression load, and uniaxial compression load is caused by the transverse cracking. Compared with concrete specimen under uniaxial compression load, the existence of lateral compression stress σ_2^D under biaxial compression will have inhibitory effect on lateral expansion or lateral cracking in the direction of σ_2^D, and the existence of lateral compression stresses σ_1^D and σ_2^D under triaxial compression will have inhibitory effect on lateral expansion or lateral cracking in the direction of σ_1^D and σ_2^D. So the triaxial compression strength and biaxial compression strength of air-entrained concrete are higher than uniaxial compression strength, and the triaxial compression strength is higher than biaxial compression strength due to the fact that there are inhibitory effect in the direction of σ_1^D and σ_2^D.

4. Conclusions

Based upon the test results in the study and the discussion on the experiment results, the following conclusions and recommendations can be got:

(1) For air-entrained concrete under triaxial compression load, the effect of the action of rapid freeze-thaw cycles did not change the failure mode; slant-shear failure caused by the splitting tensile strain along σ_1^D direction was observed, and the angle between the crack and the direction of σ_3^D was about 20°~30°. There were two cracks on σ_2^D surface; the number of cracks on σ_3^D surface was one or two, respectively.

(2) The triaxial compressive strength with all stress ratios is greater than the biaxial and uniaxial compressive strength after the same rapid freeze-thaw cycles; the increased percentage of triaxial compressive strength over biaxial compressive strength or uniaxial compressive strength is dependent on the middle stress.

(3) The triaxial compression strength of air-entrained concrete decreases as number of rapid freeze-thaw cycles increases. The reduction of triaxial compression strength of air-entrained concrete is slower than that of uniaxial and biaxial compression strength as number of rapid freeze-thaw cycles increases.

(4) The failure criteria taking account of the action of stress ratio and rapid freeze-thaw cycles in octahedral stress space were suggested.

Competing Interests

The authors declare that they have no conflict of interests.

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