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Triaxial compressive strength of air-entrained concrete after freeze–thaw cycles

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ABSTRACT

The aim of this study is to characterize the behavior of air-concrete under triaxial compression with stress ratio $\alpha_2 = \sigma_2 : \sigma_3 = 1:1$, while changing stress ratio $\alpha_1 = \sigma_1 : \sigma_3$ from 0 to 0.2 after different cycles of freeze–thaw. 100 mm × 100 mm × 100 mm concrete cubes were tested in the experiment. Based on the experiment data, the influence of the stress ratio $\alpha_1 = \sigma_1 : \sigma_3$ and the number of freeze–thaw cycles on the ultimate compressive strength σ_3 are analyzed respectively. A failure criterion expressed in terms of octahedral stress with consideration of the influence of the freeze–thaw cycles is proposed.

1. Introduction

Durable concrete (Corinaldesi and Moriconi, 2004) may be defined as a concrete which retains its original form, quality and serviceability when exposed to its environment. Freezing and thawing cycling (Shang and Song, 2006; Yun et al., 2011) is one of the causes of concrete deterioration and failure. To protect concrete from freeze–thaw damage, it should be air-entrained (Zalocha and Kasperkiewicz, 2005; Zhang and Ansari, 2006) by adding air-entraining agent to the concrete mixture. The use of air-entraining agents results in concrete that is highly resistant to severe frost action and cycles of wetting and drying or freezing and thawing and has a high degree of workability and durability.

So air entrainment is recommended for nearly all concretes, principally to improve freeze–thaw and scaling resistance and so prolong service life when exposed to water and deicing chemicals in cold climate, and these make it particularly suited to use in the construction of dam, offshore oil platforms and long span bridges in cold environment. In practice, many structural elements such as slabs, thin shells and nuclear reactor pressure container are essentially under multiaxial stress states (Shang and Song, 2006; Shang et al., 2008; Vu et al., 2011). With the wide use of computers and the finite element method, it has become increasingly evident to know the information of air-entrained concrete under a triaxial stress state.

There is a great change in the properties of concrete after freeze–thaw cycles. The previous investigations conducted on the effect of freeze–thaw on properties of air-entrained concrete have focused on the relative dynamic modulus, mass change, uniaxial compression strength, and flexural strength (Pheeraphan and Leung, 1997; Shang et al., 2009). So the authors investigated the properties of air-entrained concrete under biaxial compression, the compression with constant confined stress after freeze–thaw cycles (Shang and Song, 2008; Song et al., 2007). However, these studies did not provide information on the behavior of air-entrained concrete under triaxial compression stress state after freeze–thaw cycles. Most of the available experimental results in literature on the strength of plain concrete (Lee et al., 2004) and steel fiber concrete (Torrenti, 1995) under triaxial compression were focused on the change of stress ratio $\alpha_2 = \sigma_2 : \sigma_3 = 1:1$, while keeping $\alpha_1 = \sigma_1 : \sigma_3$ a constant value. This paper investigated strength of the air-entrained concrete under triaxial compression with stress ratio $\alpha_2 = \sigma_2 : \sigma_3 = 1:1$, while changing $\alpha_1 = \sigma_1 : \sigma_3$ from 0 to 0.2 after different cycles of freeze–thaw.

2. Experiment

2.1. Materials and mix proportions

To carry out this study, local materials are utilized: ordinary #425 Portland cement (GB 175-1999, 1999), natural river sand with fineness modulus of 2.6, crushed stone aggregate (diameter ranging from 5 mm to 10 mm), tap water for mixing and curing and an air-entraining agent. The air content of air-entrained concrete measured after being mixed was 5.8%. The proportions of cement:water: sand:coarse aggregate were 1:0.4:1.42:2.87 by weight. It has a mean strength of 25.64 MPa in compression after 28 days. Table 1 shows the mixing proportions by weight of the mixture used in this test.

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Table 1
Mix proportions and major parameters of air-entrained concrete (kg/m^3).

Cement	Sand	Coarse aggregate	Water	Air-entraining agents
412.67	586.83	1186	164.3	1.03

2.2. Samples and testing programs

Concrete mixtures were prepared in a 0.1 m^3 laboratory mixer. The specimens were cast in a 100 mm×100 mm×100 mm cubical mold. The concrete specimen block is removed 24 h after casting and then cured in a curing room of 20±3 °C and 95% RH (relative humidity) for 27 days. But at approximately 4 days before being exposed to the freeze–thaw cycles, a portion of the specimens were taken out of the curing room and immersed in water. These specimens were put to the freeze–thaw apparatus, and were used to measure the triaxial compressive strength after different cycles of freeze–thaw.

The cyclic freeze–thaw test was conducted in the accelerated freeze–thaw testing apparatus according to "the test method of long-term and durability on ordinary concrete" (GB/T 50082-2009, 2009). 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 triaxial compressive tests were conducted in the large scale static and dynamic concrete hydraulic servo triaxial testing system (Song, 2002). The triaxial compression stress ratios $\alpha=\sigma_1:\sigma_2:\sigma_3=$ 0:1:1 (equal biaxial compression), 0.05:1:1, 0.1:1:1, 0.15:1:1, and 0.2:1:1were selected. The principal stresses are expressed as $\sigma_1\leq\sigma_2\leq\sigma_3$ (compression denoted as positive). The maximum loading force σ_3 was always applied to the surfaces that were perpendicular to the cast surfaces, and a minimum of three specimens were tested for each specimen type and stress ratio. Tests were done in stress-controlled mode, and all specimens were tested at a loading speed 20.0 MPa per minute in the direction of σ_3. In order to eliminate the restraint on the loading surfaces, the friction-reducing pads were placed between the platens and the specimens for all tests. The pads consist of three plastic membranes with three layers of butter between them (Lü and Song, 2002).

3. Results and discussions

3.1. Failure modes

Fig. 1(a) and (b) shows the failure mode and surface cracking of air-entrained concrete specimen under triaxial compression.

Table 2
Triaxial compressive strength of air-entrained concrete after freeze–thaw cycles (MPa).

Freeze–thaw cycles	Stress ratio $\alpha=\sigma_1:\sigma_2:\sigma_3$					
		0:1:1	0.05:1:1	0.1:1:1	0.15:1:1	0.2:1:1
0	σ_1^D	0	5.27	10.04	16.72	30.80
	σ_2^D	29.08	68.64	85.01	106.08	150.45
100	σ_1^D	0	5.68	10.13	16.11	30.51
	σ_2^D	26.78	64.74	84.51	102.51	147.87
200	σ_1^D	0	5.13	8.77	15.71	28.38
	σ_2^D	24.18	61.46	73.12	99.52	138.23
300	σ_1^D	0	3.96	7.87	15.09	26.64
	σ_2^D	19.92	51.94	66.10	94.54	129.51
400	σ_1^D	0	3.99	7.57	13.47	26.71
	σ_2^D	16.48	46.83	59.55	85.92	130.31

The splitting tensile strain along the direction of σ_1 was the cause of failure for triaxial compression. The experimental results showed that providing a small confinement stress along the directions of the principal stresses σ_1 and σ_2 changed the failure modes. Unlike the column-type fragments observed under uniaxial compression for concrete, it is parallel plate-type fragments and slant-shear failure under triaxial compression as shown in Fig. 1(a) and (b).

The failure modes of the specimens under triaxial compression with stress ratios $\alpha=\sigma_1:\sigma_2:\sigma_3=0.05:1:1, 0.1:1:1, 0.15:1:1,$ and $0.2:1:1$ were slant-shear cracks. When the stress ratios $\alpha=\sigma_1:\sigma_2:\sigma_3=0.1:1:1, 0.15:1:1,$ and $0.2:1:1$; the angle between the crack and the direction of σ_3 was about 20°–30° (Fig. 1(a)). There were two cracks in the surface of σ_2, the number of cracking in the surfaces of σ_3 was one and two respectively. When $\alpha=0.05:1:1$, the angle between the crack and the direction of σ_3 was about 10°–20°. There were three or more cracking in the surface of σ_2, and the number of cracking in the surfaces of σ_3 was at least two. The failure modes of the specimens under triaxial compression with stress ratios $\alpha=\sigma_1:\sigma_2:\sigma_3=0:1:1$ were parallel plate-type fragments which were formed on the surface of σ_2 and σ_3 (Fig. 1(b)). These studies also showed that providing a confinement stress along the principal stress σ_2 direction changed the failure modes from the common column-type to plate-type failure mode; furthermore, providing a small confinement stress along the minor principal stress σ_1 direction changed the failure modes from the plate-type failure mode to slant-shear failure.

3.2. Experimental results

Table 2 shows the experimental results of strength of air-entrained concrete under triaxial compression after different cycles of freeze–

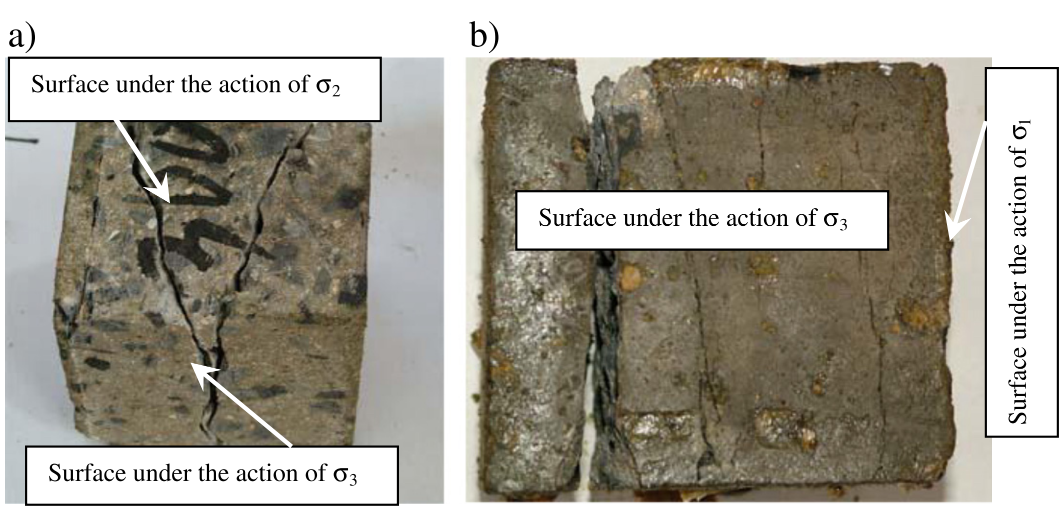

Fig. 1. The failure mode and surface cracking of air-entrained concrete specimen under triaxial compression.