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Triaxial T–C–C behavior of air-entrained concrete after freeze–thaw cycles

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ABSTRACT

This paper presents results of triaxial tensile–compressive–compressive (T–C–C) tests on air-entrained concrete with uniaxial compressive strength of 25.64 MPa before and after 100, 200, 300, 400 cycles of freeze–thaw. The strength, failure mode and the direction of the crack of air-entrained concrete specimens under T–C–C were observed and measured, respectively. The influence of number of freeze–thaw cycles and stress ratio on the T–C–C strength was analyzed, respectively. Based on the experimental data, a failure criterion with the number of freeze–thaw cycles and stress ratio parameters under T–C–C stress states is proposed. The formulated failure criteria for air-entrained concrete can be used, e.g., in finite-element simulations. The decrease in strength by acting a compressive–tensile stress state related to the uniaxial compressive strength should be considered and this study is helpful to reveal the multiaxial mechanical properties of air-entrained structure enduring freeze–thaw cycles.

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1. Introduction

Concrete is the most widely used material in the world. It is relatively inexpensive because the raw materials are ubiquitous, but concrete poses numerous durability (Maltais et al., 2004; Mather, 2004; Meira et al., 2010) issues that result in high maintenance costs. For the durability of reinforcement concrete, the most concerns is freeze–thaw damage which is the primary factor to the depressing of performance of concrete structure in cold area. In cold regions around world, the formation and propagation of ice in concrete is a serious durability problem, which can threaten the durability and safety of the concrete structure, thus academics and engineers have attached more importance to it. If proper protective measures are not taken, concrete can be very rapidly destroyed in just a few freeze–thaw cycles. Air-entrainment (Atkins, 2010; Molero et al., 2012) is the most common practice used to protect concrete from frost action.

Fu et al. (2011) investigated the freeze–thaw resistance, microstructure, performance mechanism, inner freeze–thaw damage distribution and mechanics models of alkali-activated slag concrete. Richardson et al. (2011) studied the freeze–thaw durability of concrete with recycled demolition aggregate compared to virgin aggregate concrete. The experiment results showed that the concrete cubes made with recycled aggregate were slightly more durable than those made with virgin aggregate. Gokcea et al. (2004) investigated the freezing and thawing resistance when air-entrained or non-air-entrained concrete is used as recycled coarse aggregate into air-entrained concrete. The results showed that recycled coarse aggregate produced from non-air-entrained concrete caused poor freezing and thawing resistance in concrete even when the new system had a proper air entrainment. Shang et al. (2009) investigated the dynamic modulus of elasticity, weight loss, the cubic compressive strength, compressive strength, tensile strength and cleavage strength of air-entrained concrete after 0, 100, 200, 300, 400 cycles of freeze–thaw.

Stress state of the concrete material in actual structures (such as in shell structures) is very complex. Often, the complex stress state is considered as a uniaxial case for simplicity, although we know that the true uniaxial stress condition in actual structures is extremely rare. The existing decrease of ultimate strength due to combined tension-compression stress state may thus be ignored. With the wide use of computers and the finite element method in the design and analysis of concrete structures, the strength behavior of concrete under multiaxial stress conditions needs to be investigated. Very little information of the strength properties of concrete under triaxial T–C–C load has been provided. Wang and Song (2009) studied the mechanical characteristics of mass concrete specimens with three-graded aggregate 5–80 mm and wet-screened concrete specimens with two-graded aggregate 5–40 mm under triaxial compression-compression-tension. Multiaxial tensile–compressive tests were performed on plain high-performance concrete at all kinds of stress ratios after exposure to normal and high temperatures by He and Song (2010). Dalian University of Technology (Song, 2002) has investigated the strength behavior of steel fiber concrete under triaxial T–C–C. Based on this, this paper presents the experiment study of strength and failure criterion of air-entrained concrete under triaxial T–C–C stress states after freeze–thaw cycles using a large

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static-dynamic true triaxial machine. This study is helpful to reveal the multiaxial mechanical properties of air-entrained concrete structure enduring freeze–thaw cycles, and provides the experimental and theory foundations (testing data and correlated formula) for durability design, and structural safety assessment and maintenance of air-entrained concrete in cold regions.

2. Experimental procedures

2.1. Materials and mix proportions

In this investigation, a Chinese standard (GB175-2007) #32.5 Portland cement (GB175-2007, 2007), a crushed stone (diameter ranging from 5 mm to 20 mm) and natural river sand with fineness modulus of 2.6 were used. The water-cement ratio for the mixture of concrete was 0.50. These ingredients were mixed for about 1 min, at the same time, the air-entraining admixture was added into water and mixed them well combined, then the water was added slowly over a period of 1 min. Finally, the ingredients were mixed for about 2–3 min (GB/T 50081-2002, 2003). The air content of the specimen was 5.8% 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 (used to measure the strength) and 100 mm × 100 mm × 400 mm prisms (used to measure the temperature during the freeze–thaw cycles) casted horizontally in steel molds and compacted by a 1 m × 1 m vibrating table. All specimens were removed from the molds 24 h after casting and then cured in a curing room (20 ± 3 °C and 95% RH (relative humidity)) for 23 days according to "The test method of long-term and durability on ordinary concrete" (GB/T 50082-2009, 2009). Four days prior to testing of the freeze–thaw cycles, a portion of the specimens were then immersed in water according to GB/T 50082-2009. And after 28 days, the concrete specimens were placed into the freeze–thaw testing apparatus and the freeze–thaw cycling test was performed according to GB/T 50082-2009. These specimens were used to measure the strength of air-entrained concrete under T–C–C after 100, 200, 300 and 400 cycles of freeze–thaw, respectively. The other specimens were used to measure the T–C–C strength prior to freeze–thaw cycles. The maximum loading force was always applied to the surfaces that were perpendicular to the cast surfaces.

The temperature of the concrete samples was controlled by a Pt (platinum thermal) sensor embedded in the center of a 100 mm × 100 mm × 400 mm prisms specimen, and the sample center ranged from −17 ± 2 °C to 8 ± 2 °C. 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 T–C–C tests were conducted in a triaxial testing machine (Lü et al., 2001) (designed by State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology) that is capable of developing three independent compressive or tensile forces. The triaxial testing machine is shown in Fig. 1. The triaxial T–C–C stress ratios were $\alpha = \sigma_1{:}\sigma_2{:}\sigma_3 = -0.05{:}1{:}1$, $-0.1{:}1{:}1$, $-0.25{:}0.25{:}1$, $-0.25{:}0.5{:}1$, $-0.25{:}0.75{:}1$, $-0.25{:}1{:}1$. The three principal stresses and the three principal strains are expressed as $\sigma_3 \geq \sigma_2 \geq \sigma_1$, (compression denoted as positive). Fig. 2 shows the loading directions and the state of the specimen under triaxial T–C–C in triaxial experimental machine, respectively. The loading speed was 0.002 mm per second in the direction of σ_3. The loads in the three principal directions under T–C–C were monitored and recorded after 0, 100, 200, 300 and 400 cycles of freeze–thaw, respectively. Three layers of butter and three layers of plastic membrane were used as a friction-reducing pad in the direction of σ_2 and σ_3. A minimum of three specimens were tested for each batch.

Table 1
Mix proportions of concrete (/m^3).

w/c	Cement	Sand	Coarse aggregate	Water	air-entraining agents
0.4	412.67	586.83	1186	164.3	1.03

Fig. 1. The triaxial testing machine.

3. Results and discussions

3.1. Failure modes

Fig. 3 shows the concrete specimen for T–C–C experiment. Fig. 4 shows the loading mode and loading direction of air-entrained concrete

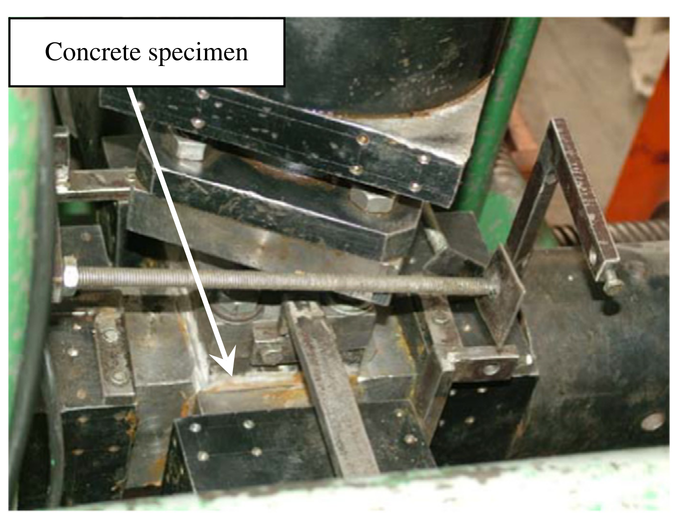

Fig. 2. The loading directions and the states of the specimen under triaxial T–C–C.

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