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Investigation of microstructural damage in shotcrete under a freeze–thaw environment

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HIGHLIGHTS

- The changing rule of axial compressive strength was disclosed.
- The distribution of micro-pores was investigated by CT during freeze–thaw cycles.
- The rule of micro-pores distribution was revealed during freeze–thaw cycles.

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ABSTRACT

Shotcrete is extensively used in underground engineering and other fields. In cold regions, the initial shotcrete lining of tunnels is repeatedly frozen and melted several times in a single year when temperatures alternately change. Thus, the freeze-proof durability of shotcrete is significantly impacted by the freeze–thaw cycle. Computed tomography (CT), a non-destructive scanning method, was adopted to demonstrate the process of shotcrete microstructural damage in a freeze–thaw environment. CT scanning results showed that looseness and slippage of the cement mortar became increasingly apparent and that the number of internal micro-pores significantly decreased with increasing number of freeze–thaw cycles. In addition, the axial compressive strengths of the shotcrete prism specimens significantly decreased. After 300 freeze–thaw cycles, the total number of micro-pores in specimens DR1-1 and DR1-2 decreased by 50.32% and 34.20%, respectively, and the axial compressive strength loss reached 63.78%.

1. Introduction

Concrete, as an important element of building construction, has been studied for many years. Given the complex internal structure of concrete, the relationship between its microstructure and mechanical properties is inadequately understood. Effective maintenance and management of concrete structures require evaluation of the degree of concrete damage. Several techniques are used to investigate concrete materials non-destructively, including the acoustic emission (AE) method [1,2], computed tomography (CT) [3–5], the nonlinear ultrasonic method [6], the elastic wave method [7,8] and the digital laminography method [9]. Among these methods, AE and CT are the most extensively applied.

Shotcrete was developed from concrete and has a history of nearly a hundred years. Given that shotcrete technology utilises a simple process with unique effects, low economic cost and mechanical advantages, the material is extensively used in underground engineering and other fields in China [10–12]. However, shotcrete is a porous brittle material. In cold regions, shotcrete is repeatedly frozen and melted several times in a single year when temperatures alternately change from hot to cold. During the freeze–thaw cycles, crevice water in shotcrete is frozen and melted, thereby causing damaging the shotcrete structure [13]. In the freeze–thaw process, the mechanical behaviour of shotcrete is associated with changes in micro-pores and cracks. However, this aspect of study is not adequately understood.

In this study, C25 shotcrete was selected as the research subject. The CT method was adopted to reveal inner changes in shotcrete specimens during several freeze–thaw cycles. The compressive strength of the prism specimens was also tested.

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2. Specimen, instruments and methods

2.1. Materials and specimen

The C25 shotcrete specimen used in the present study was composed of cement, water, sand and aggregates at a mixing ratio of 1.00:0.55:2.16:1.91. Ordinary Portland cement (strength grade: P.042.5), clean river sand (fineness modulus: 2.66) and good-grade crushed aggregates (particle size range: 5–10 mm) were utilised. The additives used in the test included HSP-FS accelerating agent (alkali-free), which accounted for 4.0 wt.% of the cement. This test adopted the wet-mix method, the process of which followed: First, about 30% of the total water consumption was added to and mixed with a mixture of sand and aggregates. Second, cement was added to and stirred with the mixture above. Finally, the remaining 70% of the total water consumption was added to the mixture, and all materials were thoroughly stirred in the spray gun before spraying. The shotcrete specimens were produced according to the big board spraying method specified in the Specifications for Bolt-shotcrete Support (GB 50086-2001, China) [14].

2.2. Experiment contents and instruments

The test items were analyzed as follows: (1) the inner structures of shotcrete specimens were scanned during the freeze–thaw cycles; X-ray CT and image analyses were also performed. (2) The prism compressive strengths of shotcrete specimens were tested during the freeze–thaw cycles. To determine the feasibility of shotcrete for practical applications, a YXLONY.CT Precision S CT scanner was used in the experiment. The maximum bearing capacity of the CT bed of the instrument was 500 kg, its scanning diameter was ϕ 0.8 m and its scanning accuracy was 0.1 mm. The CT test was designed based on these parameters and is further described in Section 3. To reveal the relationship between changes in inner structure of shotcrete and its mechanical properties, the prism compressive strength of the specimens was tested during the freeze–thaw cycles. Fig. 1 shows the main instruments used in this work.

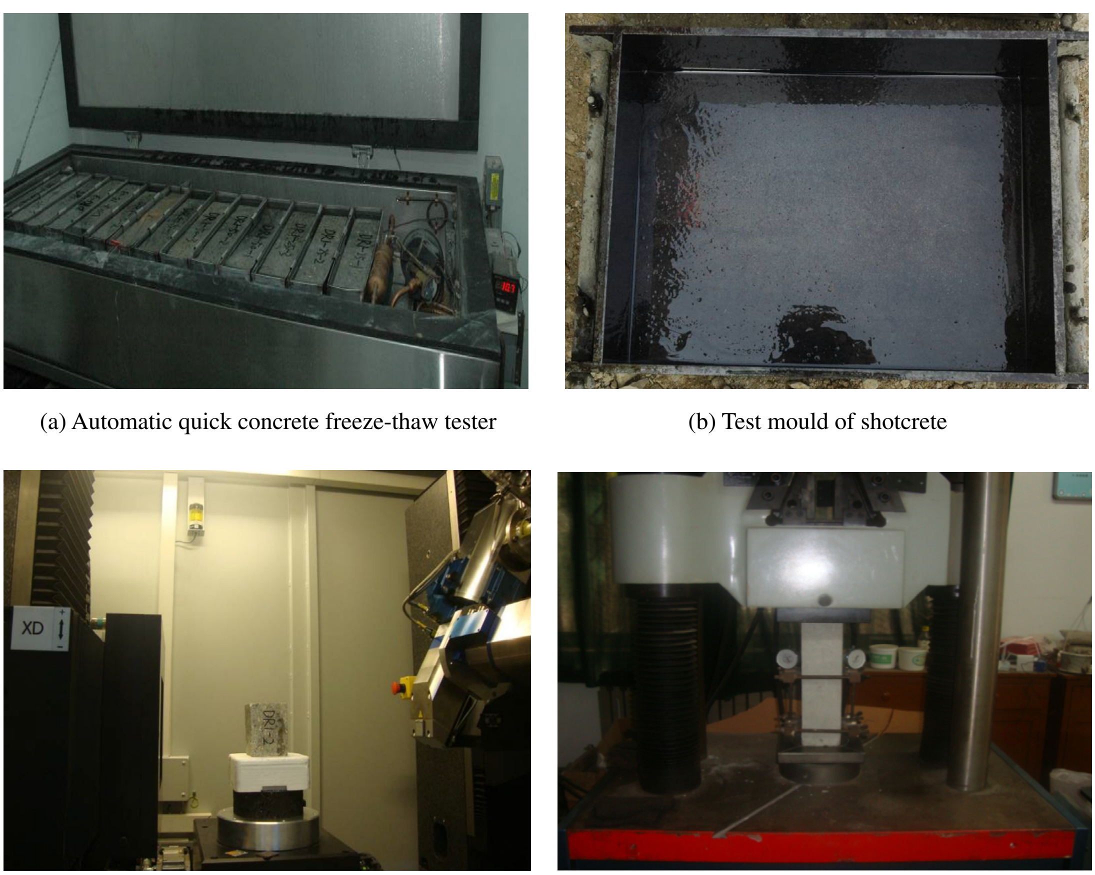
2.3. Experimental methods

Freeze–thaw cycle tests were performed using an automatic quick concrete freeze–thaw tester in the Frozen Earth Laboratory of Chang'an University, China. The freeze–thaw cycle was simulated 300 times and every freeze–thaw cycle run lasted for 2–4 h. The maximum and minimum temperature are 5 °C and −17 °C during freeze–thaw cycles respectively, and the error of temperature is ±2 °C. The quick-freezing method (GB/T 50082-2009, China) was used in the test [15].

3. Results and analysis of non-destructive CT scanning

CT combines the advantages of radial technology and computer technology. X-ray CT technology is widely used in engineering applications and can display the germinating position, expending route, cutting-through process of concrete cracks and relationship between cracks and aggregated mortar.

To reflect changes in the inner structure of the shotcrete specimens after different numbers of freeze–thaw cycles, non-destructive CT was utilised. VG Studio MAX 2.0, a professional visualisation program, was then used to analyse the scanning data.



(a) Automatic quick concrete freeze-thaw tester (b) Test mould of shotcrete

(c) Y.CT Precision S 3D CT scanner (d) WAW31000 multifunction servo control testing machine

Fig. 1. Experimental instruments used in the present work.