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Damage of concrete experiencing flexural fatigue load and closed freeze/thaw cycles simultaneously

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ABSTRACT

The damage evolution of concrete subjected to 4-point flexural fatigue load and closed freeze/thaw cycles simultaneously was experimentally studied. The responses on a separate fatigue load at 20 °C and −25 °C were tested to simulate the specimens with "thawed" or "frozen" pore water respectively. This damage, characterized by the residual strain, is 15.7% lower of the "frozen" state and 30.8% higher caused by the two loads than that of the "thawed" state. More interfacial cracking related signals were observed in the frequency domain using acoustic emission. The micrographys illustrate the cracks originate from the two damage sources, referring to the pores and the interfacial zones.

1. Introduction

Practical civil concrete structures, such as bridges and highway pavements are expected to resist millions of cycles of repeated loads during their service life. It is widely accepted that damage accumulation of concrete is preceded by deterioration of pore structure and growth of microcracks in concrete as a result of cyclic mechanical loads. However, the environmental factors, such as freeze/thaw, deicing salts, chloride ions and carbon dioxide in marine have effects on concrete simultaneously. The combined attack of mechanical loads and environmental actions leads to premature deterioration of materials. This deterioration can be broadly divided into the two types of failure: drastic deterioration of the durability of concrete (i.e. permeability) and unstable propagation of the major fatigue cracks.

In the cold climate regions, the combined loading of flexural fatigue and freeze/thaw has introduced a great concern of specialists. Ueda [1] and Hasan et al. [2,3] found more ductile softening behavior of the frost-damaged concrete than the one undamaged by simulating the damage process on mesoscale. Trottier and Forgeron [4,5] found that the residual mechanical properties of concrete subjected to fatigue load or freeze/thaw alternatively were equivalent or even better than that when only one load was applied. Lappa [6] obtained the similar conclusions. It seems hard to explain this from the point of view of damage accumulation. A possible explanation is that the fatigue cycle is too scattering to be a appropriate index to characterize the damage or most of the testings are alternative or indirect. However, they still have laid a good foundation for further exploration on the real damage process of concrete experiencing the two loads simultaneously.

With the environmental chamber, we firstly studied the response of concrete on flexural fatigue load together with closed freeze/thaw without water uptake. This work here is not intended to perfectly simulate loading and exposure conditions, but to begin to make a preliminary understanding about the complex deterioration mechanisms of concrete at work in nature.

2. Experimental programmes

2.1. Specimens

Concrete containing type I Portland cement was used. Fresh air content was 4–6%. The w/c was 0.42. The 28 d compressive strength and the fracture modulus were 35.4 MPa and 8.2 MPa respectively. All the specimens for testing were 90 d age moist cured at 20 ± 2 °C. The specimens were prepared in the size of 70 mm × 70 mm × 280 mm.

2.2. Test methods

2.2.1. Set-up of loading system

The test system, i.e. MTS810 with an environmental chamber is shown in Fig. 1a, by which the circular temperature can be

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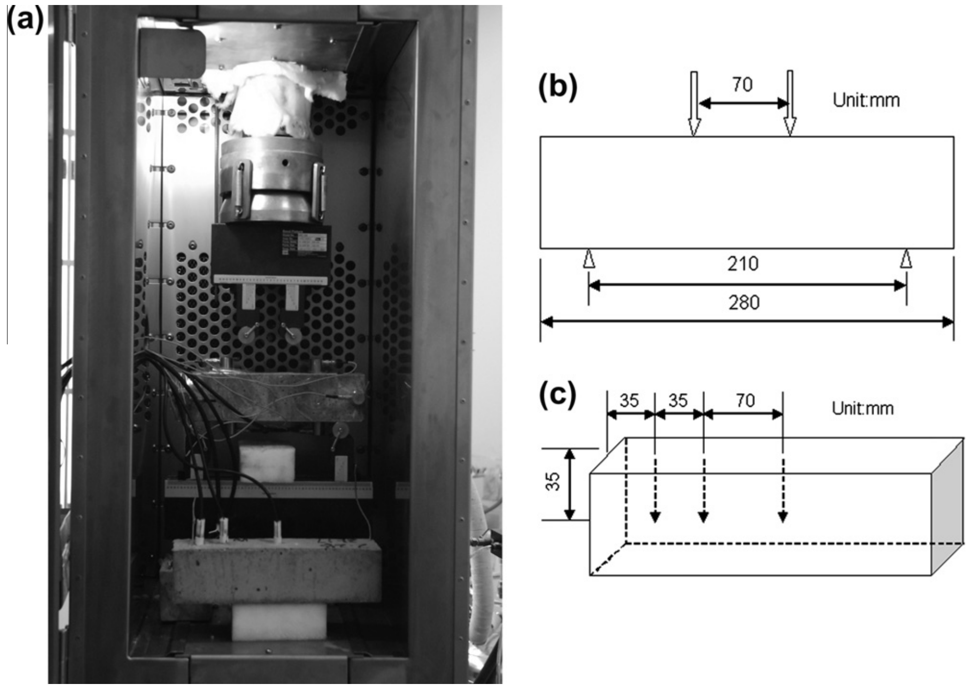

Fig. 1. Schematic view of test setup: (a) loading condition, (b) four point flexural loading, and (c) locations of temperature measured.

controlled using liquid nitrogen as cryogen. Fig. 1b illustrates the loading setup of 4-point flexural fatigue schematically. The responses of concrete under the three kinds of loading conditions, referring to simultaneous fatigue load and freeze/thaw, a separate fatigue load at 20 °C ("thawed" state) and −25 °C ("frozen" state) were studied. Table 1 presents all the loading conditions in detail to ease description later. 5–6 h were required for the temperature to be equilibrium at 20 °C or −25 °C of F(20) and F(−25) before the fatigue load was applied.

The specimens were saturated under water until constant weight before testing, followed by all the surfaces being sealed with silicon glue to prevent water evaporation. The endurance limit ($N_f > 200 \times 10^4$) was determined to be approximately 0.65 in a sinusoidal waveform at a frequency 10 Hz. Therefore, the stress level 0.6 was used.

2.2.2. Temperature

The temperature inside was measured with a separate specimen in the same fashion as the specimen being loaded. The plastic tubes were embedded at the locations during casting as seen in Fig. 1c. The tubes were sealed with the materials, like GoreTex cap at the bottom, through which only water vapour can pass. Three sensors were inserted into the tubes to measure both humidity and temperature with the accuracy 0.01%.

2.2.3. Strain

The longitudinal strain of the pure flexural section was measured with fiber brag grating-based (FBG) sensors with 60 mm gauge length. According to the shift of the Bragg wavelength which had already been calibrated before the testing, the strain was read directly. A demodulator was used for data collection with a frequency 100 Hz.

Table 1
Description of the three kinds of loading conditions.

Condition	Loading conditions	Average fatigue life
F(20)	Fatigue loading at 20 °C (reference)	34,59,035
F(−25)	Fatigue loading at −25 °C (frozen state)	36,67,103
F(F/T)	Simultaneous fatigue loading and freeze/thaw	>40,00,000

2.2.4. Acoustic emission

The damage evolution was monitored with acoustic emission (AE) system. Two transducers with the resonant frequency 150 kHz (R15) were attached on the ends of the specimen. The threshold value was set as 40 dB to reduce the noise from the surrounding environment.

2.2.5. Electrical resistivity

The temperature range of freeze/thaw cycle should be determined to make sure that the temperature inside of the materials is low enough for the pore water to form ice. Therefore, the electrical resistivity of the specimen was measured at the specific temperatures.

The two copper sheets were placed at the two ends of the specimen during casting to be used as the electrical electrodes. DC electrical resistivity was measured over the length in the longitude direction.

The specimens were put in a temperature controlled chamber. The temperature was kept at 5 °C, 0 °C, −5 °C, −10 °C, −15 °C, and −20 °C respectively for 4–5 h until a stable value was read.

2.2.6. Micro-structure

The damaged specimens were prepared for microscopy observation as the following way. The pure flexural part (70 mm × 70 mm × 70 mm) was cut into slices with 10 mm thick by wet saw. The slices were oven dried for 2 days at 50 °C until constant mass, and then vacuumed for 2 days. A low viscosity epoxy mixture with the hardener were added on the surface of the slice when the vacuum pump was still running. The specimens were kept under vacuum for one more day until the epoxy was dry. After that the slices were taken out to be grinded and polished very carefully. Observations were performed by scanning the surface of the specimen at 200×. The representative images were selected for illustration.