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Evaluation of freeze-thaw damage on concrete material and prestressed concrete specimens

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HIGHLIGHTS

- We study the microscopic and macroscopic freeze-thaw damage on concrete material.
- We investigate the freeze-thaw prestress loss of the bonded and unbonded specimens.
- Severe microscopic damages occur after 200 freeze-thaw cycles.
- Prestress loss from the intact to the completed damaged status is about 5% of σ_{con}.
- Influence of grouting on freeze-thaw prestress loss depends on grout damage status.

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ABSTRACT

The pore structure of the hardened concrete and the microscopic changes of a few selected pores throughout the freeze-thaw test were investigated by a method combining RapidAir and digital metalloscope. Traditional tests were also performed to evaluate the macroscopic change caused by freeze-thaw cycles (FTCs). The investigation shows that the concrete material, of which the spacing factor is 0.405 mm and the air content is 2.38%, can still withstand more than 300 FTCs. Severe microscopic damages occurred after approximately 200 FTCs and the freeze-thaw damage were gradually aggravated afterwards. Prestress forces have a remarkable impact on the failure pattern under FTCs. It was further found that the compressive strength as an indicator is more reliable than the relative dynamic modulus of elasticity in evaluating the freeze-thaw damage on concrete material. In addition, the test and analysis show that the measured prestress losses of bonded specimen are larger than that of unbounded specimen under the attack of FTCs due to the duct grouting effect. The ultimate freeze-thaw prestress loss is about 5% of σ_{con} for both the bonded and unbonded specimens because the grouting cement paste will eventually be completely destroyed.

1. Introduction

Freeze-thaw cycles (FTCs) can cause severe deterioration in reinforced concrete structures and prestressed concrete structures due to the nature of porous structure in concrete material. The microscopic porous structure inside the concrete material makes it capable of absorbing and holding water [1]. As the ambient temperature drops below 0 °C, ice will form inside the pores of concrete and the volume of water and ice mixture will increase, introducing pore pressure inside the porous concrete material. If the tensile stress in concrete caused by pore pressure exceeds the tensile strength of the pore structure, freeze-thaw induced micro-cracks will occur. Then, as the ambient temperature rises above 0 °C, more water will be absorbed into the pores and new micro-cracks. Therefore, freeze-thaw damage will be aggravated during the next freezing process [2–5].

In order to find out the freeze-thaw damage mechanism of concrete material and to quantify this damage, experiments with the

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help of advanced measuring techniques have been performed in recent years. The Scanning Electron Microscopy (SEM) is widely used in the investigation of concrete exposed to rapid freeze-thaw in water, which shed lights on the micro-cracking, water-transporting and self-healing mechanism of concrete material [6–9]. Similar to SEM, another feasible method to investigate the concrete material property is to inspect the concrete samples treated by Fluorescent Liquid Replacement (FLR) under an optical microscope, which produced more contrasting pictures of pores and micro-cracks [10–12]. Although the microscopic changes of concrete due to FTCs could be observed and evaluated with these methods, these microscopic changes cannot be monitored continuously in real time. The used samples will be discarded after each test while the new samples for microscopic observation must be sawed from the concrete specimens and then be polished to meet the microscopy requirements.

In addition to these direct observation methods, mercury intrusion porosimetry (MIP), low temperature calorimetry (CAL), X-ray computed tomography (CT), etc. were also employed to evaluate the pore systems [5,13–16]. The MIP is a quite simple test method. The operational principle is to describe the pore distribution according to the correlation between mercury pressure and pore volume. Before the MIP test, the concrete samples need to be dried, which would bring additional damages to the pore structure of samples. Compared with the MIP, the CAL is a better and very useful tool in investigating the pore structure in hardened concrete because the pre-drying process is not necessary. However, it should be noted that both the MIP and the CAL will introduce extra damages into pore structure: in the MIP test, the drying process and the high pressure applied to the sample can alter the pore structure; in the CAL test, ice formation in pores under the very low temperature (−60 °C) can also bring extra stress inside the sample [5,13]. Hence, these destructive methods might be inappropriate for the measurements of pore structure system in concrete. The CT technology is a promising non-destructive tool to obtain the 3D portrait of pores and cracks in concrete through image-reconstruction [12]. Sicat et al. [14] applied this technique in their tests and succeeded in obtaining the increase of the void ratio during FTCs. Although some CT images were shown in their research work, the nature of freeze-thaw damage in concrete, i.e. the initiation and propagation of micro-cracks, was not discussed. Besides, it is really a challenging task for the existing CT system to detect micro-cracks with width ranging from 10 to 50 μm in full-scale concrete specimens, and the concrete specimens are usually over 5 cm in laboratory dimension [12]. Considering the pros and cons of the above mentioned methods, a new method combining RapidAir and digital metalloscope was employed in this study to monitor the microscopic changes of a few selected pores throughout the completed freeze-thaw test.

The changes in microscopic structure of concrete material have significant influence on the macroscopic performances of the concrete specimen. In recent years, several research groups focused on the degradation of mechanical performances of concrete material, e.g. compressive strength, Young's modulus, etc., under the attack of FTCs. Shang et al. investigated the strength and deformation of plain concrete under uniaxial, biaxial, and triaxial compression after FTCs based on a series of experiments [17–20]. Duan, Jin, & Qian [21] proposed the stress-strain relationships of frozen-thawed confined and unconfined concrete specimens. Hasan, et al. investigated influence of freeze-thaw damage on the mechanical behaviour of concrete, such as the strength, stiffness, deformation capacity and the stress-strain relationship of frost-damaged concrete subjected to fatigue loading [1,22]. As a supplement to the freeze-thaw damage database and in order to investigate the correlation between the microscopic and macroscopic freeze-thaw damages, traditional tests, such as concrete compression test, surface check and relative dynamic modulus of elasticity (RDME) test, were also performed in this study.

With the development of experimental techniques, freeze-thaw tests were also performed on reinforced concrete members to investigate this deterioration effect on concrete structures on the basis of FTCs tests of concrete material. Diao, Sun, Cheng, & Ye [23] investigated the coupling effects of corrosive solution, FTCs, and persistent bending loads on the structural behaviour of reinforced concrete beams and reinforced air-entrained concrete beams respectively, and found that a persistent load together with FTCs would damage the beams more severely than pure FTCs. Zandi Hanjari, Kettil & Lundgren [24] tried to simulate the bending tests of frost-damaged reinforced concrete beams performed by Hassanzadeh & Fagerlund [25] with Diana finite element model analysis, in which the changes of failure mode and of failure load caused by internal freeze-thaw damage in the tests were well predicted. Although the above mentioned research have improved the understanding of freeze-thaw damaged concrete structures, further investigations are still necessary and some new tests have been carried out, for example, the test on the effect of FTCs on prestressed concrete structures. In the previous study of the authors' research group [26], the deterioration in flexural behaviours of prestressed concrete beams subjected to FTCs was reported. Moreover, the prestress losses of prestressed concrete beams due to FTCs were also measured and analysed by this group [2]. However, some important features of prestressed concrete structures under FTCs attack are still not clear. Little research has been carried out on the duct grouting effect on the prestress loss due to FTCs. Furthermore, even less research has been carried out on the remaining effective prestress in the concrete specimens after the concrete material is completely damaged by the FTCs attack. The study in this paper focuses on these key problems of prestressed concrete specimens under the attack of FTCs by using novel experimental methods.

In this work, an experimental programme comprised over 350 FTCs was performed on a series of small-scale and large-scale concrete specimens: (i) to continuously evaluate the microscopic and macroscopic freeze-thaw damages of concrete; (ii) to compare the prestress loss of bonded prestressed concrete specimen with that of unbounded when both of them are subjected to FTCs; and (iii) to analyse the prestress losses of post-tensioned concrete members subjected to FTCs from intact condition to concrete material failure condition. Moreover, it should be noted that in this paper the small-scale concrete specimen is used for the microscopic observations after freeze-thaw attack while the large-scale specimens are used for macroscopic tests.

2. Experimental programme

2.1. Materials

The components and mix design for the concrete material are specified in Tables 1 and 2. The measured cubic compressive

Table 1
Materials for the concrete mix.

Components	Materials
Cement	P·II, 42.5R
Water	Tap water
Fine aggregates	River sand, Fineness module 2.4
Coarse aggregates	Crushed stone, 5–20 mm
Fly ash	Class I fly ash
Additives	JM-9 composite water reducing agent

Note: 'P·II' represents 'Type II Portland cement'; 'JM-9' is the name of composite water reducing agent used for the concrete in this test (Jiangsu Sobute New Materials Limited, Nanjing, China).