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Mechanical behavior and chloride penetration of high strength concrete under freeze-thaw attack

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ABSTRACT

This paper proposes an experimental study to investigate the freeze-thaw (FT) effects on mechanical behavior and chloride diffusion in high strength concrete. Sets of high strength concrete cubes are cyclically frozen in range from + 18 °C to − 20 °C. The mechanical property and the chloride penetration tests are performed on the specimens after 0, 5, 10…95, and 100 FT cycles. FT effects on surface scaling damage, compressive strength, elastic modulus, stress-strain relationship and chloride resistance of high strength concrete are clarified. Also, a simple model is discussed and verified to predict the chloride concentration of high strength concrete attacked by FT cycles. Results show that the behavior of high strength concrete depends on the number of FT cycles. Visible damages appear in concrete after about 40 FT cycles. Before 25–60 FT cycles, no significant difference exists in FT-caused weight loss between normal strength concrete and high strength concrete. Beyond this, the FT-caused weight loss in normal strength concrete becomes faster than that in high strength concrete. FT damage decreases the compressive strength, the elastic modulus and the chloride resistance of concrete, but increases its ductility. In the present test, the compressive strength and elastic modulus decrease about 32% and 24% after 100 FT cycles, respectively. The surface chloride concentration and chloride diffusion coefficient increase to about twice of the control values.

1. Introduction

In the cold regions, the durability of concrete is significantly affected by the freeze-thaw (FT) attack. This attack on concrete due to the phase transformation associated with the water freezing. Two essential damages are usually induced: surface scaling and internal damage (Fagerlund, 2004; Powers, 1945). The former is caused by the freezing of water in concrete surface and its main effects are the weight loss and the reduction of concrete cover. The latter is caused by the frosting of internal moisture within concrete pores, leading to the generation and disintegration of micro-cracks. The internal damage affects the compressive strength, tensile strength, elastic modulus and bond behavior (Hanjaria et al., 2011). For the structures subjected to marine or deicing salt attack, the FT damage may also affect the chloride penetration and accelerate the corrosion of reinforcement embedded in concrete (Berto et al., 2015). These pronounced damages in concrete and embedded reinforcement adversely affect the durability and service life of concrete structures (Skalny et al., 2002).

The FT resistance on concrete have attracted a lot of attention. Scholars have acknowledged that the FT resistance of concrete is affected by many factors, such as the pore structure of concrete, water/cement (*w*/*c*) ratio, air entrainment and aggregate (Basheer et al., 2005; Chatterji, 2003; Mohamed et al., 2000). Some studies have also been performed to observe the damage process of concrete exposed to coupling salts attack/fatigue load and FT cycles (Jiang et al., 2015; Qiao et al., 2015). However, a few studies have been conducted on chloride penetration in concrete after FT attack. The effects of FT damage on chloride penetration of concrete are not well understood. Some experimental tests have been performed to clarify the FT effects on the mechanical behavior of normal strength concrete. It was found that FT cycles decrease both the elastic modulus and the compressive strength of concrete (Duan et al., 2011; Hanjaria et al., 2011; Shang and Song, 2006). The concrete compressive strength is an important factor affected the residual behavior of concrete after FT attack (Duan et al., 2011; Shang and Song, 2007). Therefore, the residual behavior of high strength concrete could be different with that of the normal strength concrete. More studies are required to clarify the effects of FT damage on the mechanical behavior of high strength concrete.

Nowadays, many studies have also focused on the FT effects on the special concretes, such as the fly ash concrete, recycled concrete, waste

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glass sludge concrete, light weight concrete and high strength concrete. It has been reported that the partial replacement of fine natural aggregate by fine recycled concrete aggregate is not detrimental to the FT resistance of concrete (Bogas et al., 2016). The use of waste glass sludge can improve the durability of concrete subjected to the coupling effects of FT and de-icing salt (Kim et al., 2014). The FT resistance of the light weight concrete depends mainly on the pore structure of aggregate (Mao and Ayuta, 2008). The FT resistance of the high strength concrete is considered to be better than that of the normal strength concrete, because the paste quality of the high strength concrete is improved by reducing the *w/c* ratio (Foy et al., 1988; Gagné et al., 1990; Hammer and Sellevold, 1990; Pigeon et al., 1991). A recent study has demonstrated that the significant improvement of air-entrainment in concrete salt frost resistance in high strength concrete (Liu and Hansen, 2016). However, there is still a lack of full understanding for the mechanical behavior and chloride penetration in high strength concrete subjected to FT attack.

In the present study, an extensive testing program is conducted to investigate the mechanical behavior and chloride penetration in high strength concrete after FT attack. The mechanical property test and the chloride penetration test are performed on the specimens after different FT cycles. FT effects on the surface scaling, weight loss, water content, compressive strength, elastic modulus, stress-strain relationship and the chloride penetration in high strength concrete are discussed and clarified. A simple model is discussed and verified to predict the chloride concentration of high strength concrete attacked by FT cycles. Several conclusions are then drawn based on the proposed study.

2. Experimental program

2.1. Details of specimens

In the present study, the portland cement and Grade II fly ash from thermal power station are used. The water/binder ratio is 0.2, and the replacement ratio of cement by fly ash is 20%. The natural mineral aggregates with the diameter between 5 mm and 20 mm is used as the coarse aggregate, and the river sand with a fineness modulus of 2.71 is used as the fine aggregate. A naphthalene series water reducer with the weight ratio of 1.0% is used to improve the rheology of fresh concrete. The mixture proportion of concrete used in the present test is listed in Table 1.

One hundred and twenty-six cubic specimens with dimension of 100 × 100 × 100 mm are designed and produced from a single batch of concrete. The concrete is mixed by a 0.3 m^3 forced mixer. The cement, fly ash, sand and coarse aggregate are batched by weight and premixed for 1 min. Then, the water reducer and water are added and mixed for 3 min. The concrete specimens are casted in steel molds. After that, all the specimens are subjected to an external electric vibrator for facilitating the compaction and finishing using a metal trowel. The specimens are de-molded after 24 h and then cured in a standard curing chamber at 20 ± 2 °C and 97–100% relative humidity for 28 days. The compressive strengths of the concrete are tested and listed in Table 1.

2.2. Freeze-thaw cycle

The cyclic freeze-thaw test is performed in an accelerated FT testing apparatus shown in Fig. 1 (a). Temperature in the apparatus ranges from − 20 ± 2 °C to 18 ± 2 °C. Before the test, the specimens are immersed in the sodium chloride solution with concentration of 3.5% (in weight) for 3 or 4 days. Then, the saturated specimens are subjected to the testing apparatus. In a single FT cycle, the temperature cools to − 20 ± 2 °C within 1 h and keeps constant at this value for 5 h. Then, the 3.5% sodium sulfate solution is injected into the apparatus within 1 h and is heated to increase the temperature. The apparatus keeps at 18 ± 2 °C at the next 5 h. After that, the sodium chloride solution is evacuated and the temperature cools to − 20 ± 2 °C again. It takes 12 h for each FT cycle. The temperature and duration of exposure follow the requirements of the freeze and thaw testing in GB/T 50082 (2009).

After every 5 FT cycles, i.e. at the end of 0, 5, 10, 15 … 95, and 100 FT cycles, six specimens are taken out form the apparatus. The sodium chloride solution on the specimen surface is wiped off and the weight of the saturated specimen (w_s) is measured. Then, these specimens are dried in an oven and the dry weight (w_d) is determined. The weight loss and the saturated water content of the specimens are calculated as follows

$$\Delta w_l = \frac{w_0 - w_d}{w_0} \times 100 \tag{1}$$

$$w_w = \frac{w_s - w_d}{w_d} \times 100 \tag{2}$$

where Δw_l and w_w are the normalized weight loss and saturated water content of specimen, respectively; w_0 is the dry weight of specimen before the FT cycle.

2.3. Mechanical property test

The six specimens with similar FT cycles are then divided into two groups: three specimens are used for chloride penetration test and the others are subjected to the uniaxial compressive test. Details about the chloride penetration test can be seen in the following section. The compressive test on the specimens is conducted according to GB/T 50081 (2002). The test is made by an electro hydraulic servo-controlled machine, as shown in Fig. 1(b) and (c). The load force applied and the corresponding deformation on the specimens are automatically measured by the machine during the test. Then, the compressive stress and the strain can be determined as follows

$$\sigma = \frac{F}{A_s} \tag{3}$$

$$\varepsilon = \frac{\Delta l_s}{l_s} \tag{4}$$

where σ and ε are the compressive stress and the corresponding strain of specimens under the applied loaded, respectively; F and Δl_s are the applied load and the corresponding deformation measured by the test machine, respectively; A_s and l_s are the section area and the side length of specimens, which are taken as 0.01 m^2 and 0.1 m in the present test, respectively.

It should be noted that the dimension of the cubic specimens is 100 × 100 × 100 mm, which is not the standard specimen demanded by GB/T 50081 for the concrete compressive strength test. A coefficient of 0.95 is used to modify the calculated stress by Eq. (3) (GB/T50081, 2002).

Table 1
Mixture proportion and compressive strength of concrete.

Water/binder ratio	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water reducer (%)	28 day compressive strength (MPa)
0.2	400	100	100	700	1100	1.0	91.77