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Residual compressive strength and freeze–thaw resistance of ordinary concrete after high temperature

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HIGHLIGHTS

- Strength of frozen & thawed concrete after 100–300 °C varies with the temperature.
- Freeze–thaw durability of concrete after high temperature reduces remarkably.
- Exposure time affects the freeze–thaw durability of concrete after fire greatly.

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ABSTRACT

Concrete structures generally behave well in fires. Although the influence of high temperature lower than 300 °C on residual compressive strength of ordinary concrete is limited, the effect of this high temperature on durability of ordinary concrete should be checked carefully. In this paper, two series of tests were conducted for two hundred and thirteen concrete cylinders with a diameter of 100 mm and a height of 200 mm. In the first series of tests, experimental investigations on residual compressive strength of the cylinders after different high temperatures (i.e., 100, 200, 300, 400, 500, and 600 °C) with various exposure times (i.e., 1, 2, 3, 4, 5, and 6 h) were carried out. For the specimens with 3 h exposure time, the residual compressive strength of the cylinders after high temperature and then cured in water for another 28 days was compared with the residual compressive strength of the cylinders after high temperature alone. In the second series of tests, the cylinders after high temperature were frozen and thawed for 25, 50, 75, and 100 cycles, respectively, and the weight loss and residual compressive strength of the frozen and thawed specimens were measured. Test results show that: (a) the residual compressive strength of the specimens after high temperature and then cured in water for another 28 days is always larger than that of the specimens after high temperature alone (especially in the test condition with higher exposure temperature); (b) the exposure time exceeding 3 h can no longer affect the residual compressive strength of the specimens after high temperature; (c) the temperatures ranging from 100 to 300 °C have certain influence on the residual compressive strength of the frozen and thawed specimens, and the residual compressive strengths of the specimens after 100, 200, and 300 °C and then subjected to 100 cycles of freezing and thawing are, respectively, 93%, 83%, and 67% of the residual compressive strength of the specimens without thermal treatment and only subjected to 100 cycles of freezing and thawing; (d) with the increasing of the exposure temperature, the residual compressive strength of the frozen and thawed specimens decreases gradually, and this trend becomes more significant when the number of freeze–thaw cycles is larger, implying that the freeze–thaw durability of ordinary concrete after high temperature reduces remarkably; and (e) the residual compressive strength of the frozen and thawed specimens continuously decreases with the increasing of the exposure time, this implies that the exposure time has great influence on the freeze–thaw durability of ordinary concrete after high temperature.

1. Introduction

Concrete material in structure is likely exposed to elevated temperature during fire. Mechanical properties of concrete after such an exposure are of great importance in terms of the safety and serviceability of buildings [1]. Although concrete is widely recognized as a fire-resistant material in construction industry, concrete undergoes severe changes in its chemical composition and physical properties when exposed to elevated temperature. A wide range of studies have been performed to investigate the properties of ordinary concrete after high temperature [2,3].

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Chang et al. established a complete compressive stress–strain relationship for concrete after heating to temperatures of 100–800 °C [4]. Metin experimentally investigated the effect of high temperature on residual strength of ordinary and high-performance concrete [5]. The tests were performed at five different temperatures (200, 400, 600, 800, and 1000 °C), and each temperature was maintained for 1 h after the desired temperature was reached. For ordinary concrete exposed to high temperature at an early age, the residual strength could recover to some extent after certain curing [6]. The recovered strength for the specimens cooled by sprayed water was higher than that for the specimens cooled in air when exposed to temperatures below 800 °C; when the maximum temperature exceeded 800 °C, the recovered strength for the specimens cooled by water spray was lower than that for the specimens cooled in air. But the residual strength of normal-aged ordinary concrete after exposing to elevated temperature and then cured in air did not recover apparently [7]. Referring to the effect of exposure time (i.e., a time period for which the desired temperature was maintained after this temperature was reached) on residual strength of ordinary concrete after high temperature, most of the existing researches focused on the exposure times of 1–3 h [5,6,20,29]. Shi et al. experimentally investigated the influences of sub-high temperature and its lasting time on concrete compressive strength [8]. In their tests, the exposure temperatures were 100–500 °C, and the exposure times were 6, 24, 36, 48, and 72 h. Test results showed that the exposure time had little effect on the concrete compressive strength. But in this literature, only the strength at high temperature (not the residual strength) was checked, and the exposure times were too long to match most of the actual fire scenarios.

With the deterioration of existing structures, durability of concrete is of great concern [9–11]. For the structures in cold areas, the freeze–thaw resistance of concrete is especially important. Generally, water–cement ratio and air content are the most dominant variables affecting the freeze–thaw durability of concrete [12–15]. In order to predict the accumulated damage by cyclic freeze–thaw, an optimized regression analysis from response surface method was performed [16]. The predicted results of relative dynamic modulus and residual strain for the specimens after 300 freeze–thaw cycles concurred well with the experimental results. Basheer and Cleland studied the freeze–thaw resistance of concrete treated with pore liners [17], and the results indicated that the surface treated concrete not only withstood the freezing and thawing but also improved the freeze–thaw resistance even in the case of the most porous concrete. In addition, existing research results indicated that the combined attack of mechanical loads and environmental actions leaded to premature deterioration of materials [18]. Now, an increasing trend towards the use of sustainable processes has led to recycled materials being incorporated into concrete. In literature [19], the freeze–thaw durability of concrete with recycled demolition aggregates was compared with that of virgin aggregate concrete.

In contrast with the researches reported in literatures [7,8], the residual compressive strength of ordinary concrete after high temperature and then cured in water for another 28 days has been investigated in this paper, and the effect of exposure times ranging from 1 h to 6 h on residual compressive strength of ordinary concrete after high temperature has been checked in this study. On the other hand, although there is great change in durability of concrete after high temperature [20–22], test data is now deficient about the freeze–thaw durability of concrete after elevated temperature. So the freeze–thaw resistance of ordinary concrete after high temperature is experimentally examined in this paper and compared with the freeze–thaw resistance of concrete without thermal treatment.

2. Experiment procedures

2.1. Specimen design and material properties

Due to the limitation of the internal dimensions of the freeze–thaw testing apparatus in Xi'an University of Architecture and Technology, concrete specimens with a diameter of 100 mm and a height of 200 mm were employed in this study according to the Standard for Test Method of Mechanical Properties on Ordinary Concrete (GB/T 50081-2002).

Two hundred and thirteen cylindrical specimens of 100 mm diameter by 200 mm height were cast in polyvinyl chloride (PVC) moulds. They were removed from the moulds 2 days after casting, and cured in air (relative humidity about 60%, and room temperature about 20 °C) for 28 days. Several 150 mm cubes were cast along with these cylindrical specimens, and the measured 28-day cubic compressive strength of the concrete was 35.4 MPa. Some of the cylindrical specimens are shown in Fig. 1. A summary of the details of the specimens is given in Table 1.

All the specimens are classified into five groups (i.e., Groups 1–5 in Table 1) and identified by the notation—S-T#E#W28FT#, where "*S*" stands for the cylindrical specimen, "*T*" indicates the exposure temperature (*T*20 = 20 °C, *T*100 = 100 °C, *T*200 = 200 °C, *T*300 = 300 °C, *T*400 = 400 °C, *T*500 = 500 °C, and *T*600 = 600 °C), "*E*" gives the exposure time (*E*1 = 1 h, *E*2 = 2 h, *E*3 = 3 h, *E*4 = 4 h, *E*5 = 5 h, and *E*6 = 6 h), W28 means curing in water for another 28 days after high temperature, and "FT" denotes the number of freeze–thaw cycles (FT25 = 25 cycles, FT50 = 50 cycles, FT75 = 75 cycles, and FT100 = 100 cycles). For instance, S-T200E3W28 indicates a cylindrical specimen after 200 °C high temperature with exposure time of 3 h and then cured in water for another 28 days, and S-T300E3FT75 indicates a cylindrical specimen after 300 °C high temperature with exposure time of 3 h and then frozen and thawed for 75 cycles. Here the exposure time denotes a time period for which the desired temperature was maintained after this temperature was reached.

The specimens in Group 2 are compared with those in Group 1 to examine the effect of exposure time on residual compressive strength of ordinary concrete after high temperature. The specimens in Group 3 are compared with those in Group 1 to check whether the residual compressive strength of ordinary concrete after elevated temperature can recover apparently during the following water curing process. The specimens in Group 4 are used to investigate the effect of high temperature on freeze–thaw durability of ordinary concrete after elevated temperature. The specimens in Group 5 are compared with those in Group 4 to illustrate the influence of exposure time on the freeze–thaw durability of ordinary concrete after high temperature.

The concrete prepared for all the specimens was from one batch of ready-mix concrete. The concrete was mainly made of Portland cement (P.O 42.5), natural crushed limestone (coarse aggregate) with about two size fractions (5–10 mm and 10–20 mm), river sand (fine aggregate, 0–4 mm), and fly ash. Mix proportion of the concrete is given in Table 2.

For making improvement on the test accuracy, both ends of each cylindrical specimen were ground to obtain smooth surfaces before the tests.

2.2. Thermal treatment and water curing

All the cylindrical specimens except S-T20, S-T20FT25, S-T20FT50, S-T20FT75 and S-T20FT100 were placed into an electric furnace 28 days after concrete casting. During the heating process, the temperature in the furnace increased to the desired value at a rate of 5 °C/min, and then the desired temperature was maintained for a certain exposure time (see Table 1). Subsequently, the specimens were cooled down naturally to about 200 °C in the opened furnace, and then were taken out of the furnace to reach the room temperature in air.

To investigate the recovering effect of water curing on residual compressive strength of ordinary concrete after high temperature, the specimens in Group 3 with 3 h exposure time were then cured in water for another 28 days.

Fig. 1. Cylindrical specimens in PVC moulds.