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Case study

Investigation on spalling resistance of ultra-high-strength concrete under rapid heating and rapid cooling

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ABSTRACT

Effects of the fiber type, dosage and length on the explosive spalling of ultra-high-strength concrete under rapid heating and rapid cooling were experimentally investigated. The mechanism of spalling resistance was examined by comprehensive thermal analysis, X-ray diffraction analysis, scanning electron microscopy and mercury porosimetry. The burst time is extended but the spalling is unaffected by the addition of steel fiber. The spalling resistance is improved with the addition of polypropylene (PP) fiber or PP and steel fibers. Ultra-high-strength concrete with 0.20% (vol.) PP fiber has excellent spalling resistance. The resistance to explosive spalling is enhanced with 12- or 19-mm-long PP fibers. PP fiber improves the spalling resistance mainly through the formation of tubular channels.

1. Introduction

With the expansion and densification of urban and rural construction, there are frequent building collapses due to the deterioration of building materials in fires. The fuel source of a fire affects the effect of the fire on surrounding concrete buildings. For example, the temperature of surrounding buildings rapidly rises above 1000 °C in the event of a tunnel or oil industry fire, while the temperature of surrounding buildings rapidly decreases to ambient temperature following an explosion involving a flammable and explosive gas, liquid or solid. In the case of such combustion or explosions, surrounding concrete buildings must have good resistance against rapid heating and rapid cooling. However, concrete, and especially high-strength concrete, readily undergoes explosive spalling in a fire or at high temperature [1]. In addition, with the rapid development of large and high engineering constructions in recent years, ultra-high strength concrete is more widely applied in the construction industry. There is thus a need for research on the spalling resistance of ultra-high-strength concrete under conditions of rapid heating and rapid cooling.

The explosive spalling phenomenon was put forward by Hertz [2] as early as 1984. There was serious spalling damage of 100-MPa concrete in the English–French Channel Tunnel in 1996 [3], which encouraged many countries and regions to carry out relevant research. Research on the high-temperature spalling mechanism of concrete [4,5] has considered the vapor pressure mechanism to be the primary cause. Kalifa [6] showed the feasibility of the vapor pressure mechanism by measuring the internal vapor pressure of concrete. On the basis of this mechanism, fusible organic fibers have been added to high-strength, high-performance concrete to improve the concrete's resistance to explosive spalling in a fire or at high temperature [7,8]. Doherty [9,10] studied the effects of the fiber type and length on spalling damage. In addition, Li [11,12]

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and Anson [13,14] respectively studied the effects of the aggregate and moisture content on spalling damage. Many scholars have investigated the effect of the heating speed of concrete. Chen [15] studied the spalling damage to 109-MPa concrete heated at a slow rate of 10–20 °C/min. Fellcetti [16] studied the spalling damage to 189-MPa concrete heated at the slow rate of 1 °C/min; and Durrani [17] explored the spalling damage to 89-MPa concrete heated rapidly at 30–90 °C/min. Studies of spalling damage have thus mainly focused on high-strength and high-performance concrete, while the heating rate has been relatively slow. However, there has been little research on the spalling damage to ultra-high-strength concrete, and even less under conditions of rapid heating and rapid cooling.

This paper investigates the mechanism of spalling resistance in ultra-high-strength concrete mixed with fibers of different types, dosages and lengths under the severe condition in which a specimen is put in a muffle furnace that has been preheated to 1000 °C for 10 min and then instantly placed in an environment at 25 °C.

2. Experimental

2.1. Raw materials

Ordinary Portland cement with a classification of 52.5R (density: 3150 kg/m^3, specific surface area: 448 m^2/kg) was sourced from Tangshan Jidong Cement Company Limited in Hebei province, China. Silica fume (density: 2230 kg/m^3, specific surface area: 13,050 m^2/kg) was incorporated as high-strength mineral admixtures, and was supplied by Bocheng Silicon Corporation of China Limited in Gansu province, China. Silica sand in the size range of 40–300 mesh and with density of 2.87 g/cm^3 was supplied by Dajin New Material Company Limited. Quartzose sand as fine aggregates was supplied by Sand Corporation, Beijing, China. The density and fineness modulus of the fine aggregates were 2710 kg/m^3 and 2.4, respectively. Straight steel fiber coated with copper was supplied by Yutian Zhitai Steel Fiber Manufacturing Company Limited in Hebei province, China. The density, length, diameter and compressive strength of the steel fiber were respectively 7800 kg/m^3, 15 mm, 0.22 mm and 2850 MPa. Polypropylene (PP) fiber with density of 910 kg/m^3, length of 6 mm, 9 mm, 12 mm and 19 mm and equivalent diameter of 26.13 μm was supplied by Rongnaier Engineering Materials Company Limited, Beijing, China. To obtain the desired workability of the fresh concrete, polycarboxylic water-reducing agent with solid content of 24% was supplied by Basf Chemical Building Materials (China) Company Limited, Beijing, China.

2.2. Mix proportions of concrete

Mix proportions of the concrete are given in Table 1.

2.3. Experimental methods

2.3.1. Specimen preparation

Raw materials were weighed accurately to obtain the proportions given in Table 1. Solid raw materials were first mixed well for 45 s with a mixer, and liquid was then added and the mixture stirred to ensure fluidity. The total mixing time was 6 min. In the case that steel fibers were added to the mixture, the fibers were mixed in slowly after a total mixing time of approximately 3 min. Slump flow was immediately measured without vibration. The prepared pastes with an appropriate slump flow of 260 ± 20 mm were then placed, one half at a time, into a mold with dimensions of 40 mm × 40 mm × 160 mm. Two groups of specimens were thus prepared, and three specimens from each group were used in all tests. The specimens were demolded after 24 h of mixing with water. All specimens were cured in a standard curing room (relative humidity exceeding 95%, temperature of 20 °C) for 28 days. Specimens were then divided into the two groups. One group of specimens were cured in a dry air room (relative humidity of 55%–65%, temperature of 20 °C) for 14 days, at which time the spalling resistance was measured. The other group of specimens was used in the strength comparison experiment.

2.3.2. Experimental method of high temperature

A muffle furnace was heated and maintained at 1000 °C for 30 min. A specimen at room temperature was put into the preheated furnace. After 10 min, the specimen was rapidly taken out and placed in a room having a temperature of about 25 °C. As the temperature of the specimen reached approximately 100 °C, the specimen was placed in a dryer so as to isolate the air, and the specimen remained in the dryer until the strength test. The change in the environment temperature for the specimen is shown in Fig. 1.

Table 1
Mix proportions of concrete.

Water/binder ratio	Silica sand/binder ratio	High strength admixture/binder ratio	PP fiber (V%)	Steer fiber (V%)	Aggregate (V%)
0.18	0.61	20	0.20	0	10

Note: 1) The length of PP fiber was 12 mm in this study unless otherwise stated. 2) The dosage of water-reducing agent was adjusted by slump flow vibration.