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Performance evaluation of RPC exposed to high temperature combining ultrasonic test: A case study

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HIGHLIGHTS

- Relatively bigger specimens employed to reveal the residual compressive strength of RPC exposed to elevated temperature.
- Ultrasonic testing involved for performance evaluation of RPC subjected to fire.
- Establishment of compressive strength-ultrasonic velocity curves of damaged RPC after fire exposure.

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ABSTRACT

Reactive powder concrete (RPC) with different volume fractions of steel fibers were fabricated into test specimens with dimensions of 100 × 100×100 mm for compressive strength tests and ultrasonic tests at 20, 100, 200, 300, 400, 500, 600, 700 and 800 °C, respectively. The testing results indicated that as the steel fiber content increased, the critical temperature of the explosive spalling of RPC increased correspondingly. It is also found that the incorporation of 2.5% steel fibers can effectively inhibit explosive spalling. Additionally, when the target temperature rose, the rate of mass loss of the steel-fiber-reinforced RPC increased (quickly at the beginning and slowly thereafter), and the critical temperature was determined to be 300 °C. The influence of variation in the steel fiber content on the mass loss rate of the RPC was relatively less. Moreover, the ultrasonic pulse velocity of the steel-fiber-reinforced RPC showed a decreasing trend as the temperature rose, and the descending rate initially accelerated and then slowed down. A regression equation was established, to show the correlation of the ultrasonic pulse velocity and compressive strength with temperature for RPC exposed to elevated temperatures.

1. Introduction

Reactive powder concrete (RPC) is a novel cementitious material with ultra-high strength, high toughness, superior durability, and low porosity. In the past decade, numerous research has been conducted to improve the performance of pavement [1,2], including RPC since it was introduced from France in the 1990s. Richard and Cheyrezy (the developers of RPC) proposed basic principles for designing and manufacturing RPC [3]. Kang et al. [4] performed three-point bending tests on ultra-high strength concrete with different fiber contents, found the linear relationship between flexural strength and fiber content, and suggested a trilinear model for easier analysis and design. Owing to its favorite performance, RPC has been widely applied in municipal and military construction [5,6], e.g., the pedestrian bridges built in Sherbrook, Canada, 1997 [7] and in Changsha, China, 2016.

The compressive strength of concrete exposed to elevated temperatures is of vital importance in the evaluation of structural damage after fire exposure. Relatively systematic investigations on the temperature performance of normal concrete (NC) and high-strength concrete (HSC) exposed to high temperature have been conducted. Researches [8–12] have shown that the residual compressive strength of the NC and HSC displayed a decreasing trend as the temperature rose. The strength was very low after the NC and HSC were exposed to temperatures higher than 800 °C, which failed to satisfy the structural requirements. However, around 300–400 °C, the HSC strength remained approximately the same. Due to its compact structure, HSC tended to undergo explosive spalling at high temperature [13]. Besides, steel fibers were found to be effective to inhibit high-temperature explosive spalling [12].

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RPC contains no coarse aggregate and consequently possesses denser structure than HSC and NC [2]. The blending of steel fibers further improves its mechanical performance. As a result, the performance of RPC both under and after elevated temperatures exposure may vary from NC and HSC. Currently, there is no consensus on the residual compressive-strength behavior of RPC exposed to elevated temperatures, as well as on the result of the size effect. Comparing with NC and HPC, RPC not only showed a relatively high fire-resisting temperature, but also retained a relatively high residual compressive strength after fire exposure [14]. When combined with steel fibers, RPC showed better resistance against explosive spalling damage [15]. The occurrence of RPC high-temperature explosive spalling resulted from a combination of vapor pressure, thermal stress and random cracks. The inner defects of RPC at elevated temperatures were greatly influenced by the size effect, and compared to small-sized test specimens (a length shorter than 70.7 mm), the larger test specimens (a length greater than 100 mm) could better reflect the actual conditions of RPC when a fire occurred [16–18].

The complexity in the variation of the concrete structure after fire introduces a relatively large difficulty in carrying out the performance evaluation and damage assessment. Simple equipment, easy operation, safe detection and low cost are characteristic features of the ultrasonic method, hence it is widely applied in engineering practice. Related studies found that ultrasonic method employed to analyze the relation between the residual strength of various NC and HSC was feasible [19,20]. Canbaz found that the ultrasonic pulse velocity of RPC exposed to elevated temperatures showed a descending trend as the temperature rose [21]. However, systematic investigations on performance evaluation of RPC after fire, particularly ultrasonic testing method, have rarely been reported so far.

By studying the performance of RPC exposed to high temperature (such as apparent phenomenon, compressive strength, technique of assessment), it is beneficial to structural performance and damage evaluation after fires. In this paper, the explosive spalling behavior of RPC was exposed to 20, 100, 200, 300, 400, 500, 600, 700, and 800 °C, respectively. Relatively larger specimens (100 mm × 100 mm × 100 mm) were prepared for compressive strength tests and ultrasonic velocity tests. Additionally, ultrasonic test were employed to analyze the relation between compressive strength tests and ultrasonic velocity tests.

2. Experimental design

2.1. Raw materials

Ordinary Portland cement (P.O graded as 42.5R in China), silica fume, silica sand, silica powder, polycarboxylate superplasticizer were employed to manufacture the cementitious RPC matrix. The steel fiber with average length of 8 mm and diameter of 0.12 mm was also involved. The physical properties of used materials were shown in Table 1.

Table 1
Physical properties of materials.

Materials	Physical properties
Cement	Ordinary Portland cement
Silica fume	average particle size: 88 nm Specific surface area: 18,700 m^2/kg
Silica sand	particle size:0.9 ~ 2 mm Density: 2650 kg/m^3
Silica powder	average particle size: 50.1 μm Density: 2630 kg/m^3
Superplasticizer	Type: powder and polycarboxylate solid content: 98 ± 1%
Steel fiber	Type: round-straight shape length:8 mm, diameter: 0.12 mm Tensile strength: >2000 MPa

2.2. Specimen preparation and curing

Seven groups of steel-fiber-reinforced RPC specimens were prepared with various volume fractions of steel fibers. The detailed mix proportions are listed in Table 2. Specimens with the size of 100 mm × 100 mm × 100 mm were prepared for compressive strength tests and ultrasonic tests.

The RPC was fabricated in a single horizontal-axis forced concrete mixer. When mixing, the pre-weighed cement, fly ash, silica fume, silica sand, silica flour, and the water-reducing agent were poured into the mixer for 6 min of dry mixing; then, water was slowly added during the 6 min mixing process; finally, steel fibers were evenly added and mixed for 6 min. The well-mixed RPC slurries were poured into different steel dies, and were molded by vibratory compaction to cover the surface with a thin film. Subsequently, the dies were removed after the molds were left standing for 24 h in a standard environment; The test specimens were then placed and maintained in hot water at 95 °C for 72 h, and after the hot-water maintenance was completed they were placed in a standard maintenance room for 56 d; Finally, the specimens were placed in the lab for natural drying for 28 d.

2.3. High-temperature experiments devices and procedures

The device for high-temperature experiments mainly consisted of two parts: a test furnace and a temperature control system, as shown in Fig. 1. The test furnace had a structure of two half-cylindrical furnace bodies, and consisted of major components such as a furnace chamber, furnace tile, furnace lid, heating wire, insulation cottons, a thermocouple, etc. The furnace was a hollow cylinder. The temperature control system was a 2100-series intelligent controller configured to realize a goal of maximally achieving a uniform environment temperature inside the furnace.

The target temperatures of experimental design were severally 200, 300, 400, 500, 600, 700, and 800 °C; the electric furnace was used for heating and the heating rate was controlled by program configured temperature control system. Prior to the high-temperature experiments, all of the test specimens were first placed in an oven to be dried at 105 ± 5 °C for 24 h, and then the specimens were retrieved and naturally cooled to room temperature, thereby excluding the influence of moisture content on the experiments. In the experiments, the heating rate was controlled at 5 °C/min and kept constant for 3 h after the target temperature was obtained, such that the temperature of the furnace was ensured to be the same as the inner temperature of the test specimens. The power supply was then cut off, and the furnace was naturally cooled to 300 °C, approximately. Furthermore, the asbestos lid was opened for the furnace during the cooling procedure. The heating curves of the furnace chamber at each target temperature are shown in Fig. 2. After the end of high-temperature experiments, the samples were cooled slowly up to room temperature in the ambient air. Then, unit weight, ultrasonic pulse velocity, and compressive strength tests were performed.

2.4. Procedures of ultrasonic testing

The non-metal ultrasonic tester used in the experiment was manufactured by Wuhan Rocksea Co., Ltd. Specimens were detected using the method specified in *Technical Specification for Detecting Strength of Concrete by Ultrasonic-rebound Combined Method* (CECES02: 2005), and measurement points were placed in quadrisection points in the diagonals of two opposite faces (non-mold faces). Each specimen was tested three times, and the mean of three experimental readings was used as the sound velocity of the specimen.

2.5. Procedures for compressive strength tests

The compressive experiments were carried out in a YAW-3000 microcomputer-controlled, electro-hydraulic servo pressure testing machine according to requirements specified in *Standard for Evaluation of Concrete Compressive Strength* (GB 50107-2010), and the loading rate of the experiment was kept in the range of 8 kN/s to 12 kN/s.

3. High-temperature experiments

3.1. Determination of explosive spalling critical temperature

The RPC doped with different steel-fiber contents showed different explosive spalling conditions (temperature when RPC test specimens with the same steel-fiber content are explosively spalled and the number of spalled pieces exceeds half of the total amount upon termination of the constant-temperature period is defined as the critical temperature). When not reinforced by the steel fibers, the critical temperature of the plain-RPC was 400 °C, and the critical temperatures of RPC-0.5, RPC-1, RPC-1.5, and RPC-2 were separately 400, 500, 600, and 700 °C, respectively. Further, during the entire experiments, RPC-2.5 and RPC-3 produced