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The properties of reactive powder concrete using PP fiber and pozzolanic materials at elevated temperature

Hong-seok Jang[a], Hyoung-seok So[b], Seungyoung So[c,*]

[a] Department of Architectural Engineering, Chonbuk National University, Jeonju 561-756, Republic of Korea
[b] Department of Architectural Engineering, Seonam University, 439, Chunhyang-ro, Namwon-si 55724, Republic of Korea
[c] Research Center of Industrial Technology, Department of Architectural Engineering, Chonbuk National University, Jeonju 561-756, Republic of Korea

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ABSTRACT

This study investigates the effect of a polypropylene (PP) fiber to provide improved spalling protection of practical modified Reactive Powder Concrete (RPC) subjected to fire. And Optimum levels of fiber contents for spalling protection with a less adverse effect on workability are provided based on the results of the fire test. The results showed that the modified RPC significantly reduced the content of cement and silica fume compared to the conventional RPC mixture by the combination of ternary pozzolanic materials (silica fume, blast furnace slag, and fly ash) and the mechanical performance of the modified RPC under high temperatures was superior to that of the conventional RPC mixture with only silica fume. The modified RPC shows no explosion occurring even at 0.2% of PP fiber (PP/Binder %) content and can improve spalling protection by providing connections between low decrease workability.

1. Introduction

High-temperature exposure of concrete can lead to the risk of concrete spalling and consequently, to the damage of the entire structure. High-strength concrete, in particular, is susceptible to spalling in fire [1]. Since the earliest reports that discussed the issue of the fire resistance of concrete, beginning with ACI's report in 1919 [2], the addition of fibers to concrete has been suggested by several researchers [3–10]. Concrete exposed to fire spalls owing to two phenomena: (1) the restrained thermal dilation of the water inside the concrete pores, which generates biaxial compressive stress parallel to the heated surface, subsequently leading to tensile stress developing in the direction perpendicular to the heated surface [11]; and (2) the build-up of pressure in the concrete pores as a consequence of the physically/chemically bound water in the cement vaporizing, thereby loading tensile stress in the heated concrete microstructure [12].

The second mechanism has recently been investigated by comparing the vapor pressure of aterinside concrete pores with the saturated vapor pressure of water in the specimens [13,14]. Several studies have examined the synergistic effect of various combinations of fibers on the behavior of high-performance concrete exposed to fire [15,16] and found that some combinations of fibers increased the fire-resistance of the high-performance concrete. Researchers have also reported how various fibers affected the mechanical properties of cement-based materials at high temperatures [17–19].

Recently, RPC has shown some promise as a new generation of concrete with advanced mechanical properties in the construction field. RPC has a compressive strength in the range of 200–800 MPa, a modulus of rupture in the range of 25–150 MPa, and a fracture energy in the range of 12–40 kJ/m^2 [20]. Due to its outstanding structural performance, the use of RPC has significantly increased in engineering practices such as infrastructure construction, construction of nuclear facilities, and underground tunnel construction in recent years. RPC has been developed through homogeneity and microstructure enhancement techniques for cementitious materials.

Recently, various studies have been carried out to develop RPC that is more practical and economically feasible [21,22]. Abouzar (2004) performed research to develop a lightweight reactive powder concrete, while Halit et al. (2009) reported that RPC with compressive strength as high as 250 MPa could be obtained through steam curing and the combination of various pozzolanic materials such as fly ash and blast furnace slag. Especially, studies on the fire performance and structural behavior of RPC exposed to high temperatures are insufficient and a few experimental works are currently underway. However, the fire performance of RPC is of significant concern and needs to be investigated prior to the application to building construction.

* Correspondence to: Chonbuk National University Engineering 1, 125 ho, Department of Architectural, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 561-756, Republic of Korea.
E-mail address: archiso@jbnu.ac.kr (S. So).

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Many factors essential to understanding the structural behavior and fire performance (including explosive spalling) of RPC at elevated temperatures, still need to be studied in more detail.

In this study, the modified RPC was manufactured using a combination of ternary pozzolanic materials and to investigate experimentally the effect of the PP fibers on spalling protection of RPC so as to find the optimum combination of PP fibers and the minimum fiber requirement of mixed PP fibers that is economical yet provides sufficient fire resistance and less adverse effects on workability. The mechanical properties and microstructure characteristics of the modified RPC at elevated temperature were investigated, and the results were compared to the conventional RPC mixture.

2. Experimental methods

2.1. Materials

Ordinary Portland Cement (OPC), as specified in Korean Standard L 5201, and ternary pozzolanic materials (silica fume, blast furnace slag, and fly ash) were used. Table 1 provides the chemical composition of OPC and pozzolanic materials. Aggregate was used by mixing domestic quartz sand with a particle size of 0.3–0.5 mm and quartz sand with a particle size of 0.15–0.3 mm. The density of quartz sand was 2.65 g/cm^3 and its silica content (SiO_2) was more than 82%. Crushed crystalline quartz powder with a particle size of 0–45 μm and a specific gravity of 2.65 g/cm^3 was used in this study as filler. A high elasticity steel fiber with a 15 mm length, 0.5 mm diameter, and 1195 MPa tensile strength was used. Poly-carboxylate super-plasticizer, which complied with ASTM C494 specifications, was used to maintain the table-flow of mixtures to 125 ± 5 mm. PP fiber of 13 mm length, 20 μm diameter, 0.91 g/cm^3 density, and 165 °C melting temperature was used to reduce the build-up of internal vapor pressure in RPC to control the explosive spalling.

2.2. Mixing of specimens and curing

The modified RPC using ternary pozzolanic materials was manufactured through preliminary tests based on the existing mix proportion of RPC [23,24]. The mix proportions are presented in Table 2. SF25 type in Table 2 was the basic mix proportion of the conventional RPC, where silica fume was mixed at 25% of the mass of cement (SF/C=0.25), which was made for comparative analysis with the modified RPC in terms of fire performance and mechanical properties under high temperature. Quartz sand 0.15–0.3 mm in size and quartz powder with a particle size of 0–45 μm were also used in the modified RPC to obtain the closest packing and improve the packing of the concrete matrix.

The mix proportion of pozzolanic materials increased to 65%, and as a result, the unit weight of cement was greatly reduced compared to the conventional RPC mixture (PZ65 type). The combination of steel and polypropylene fibers was used to prevent explosive spalling and improve the residual mechanical properties of RPC exposed to high temperature; the contents of steel and PP fibers were determined by the preliminary experiments [24].

As shown in Table 2, the contents of PP fiber were 0.1%, 0.2%, 0.5% and 1.0%, respectively. The specimens used for compressive and specimens used for the flexural strength test were 40×40×160 mm prisms. All specimens were removed from the steel moulds 1 d (24 h) later, cured with hot water at 90 °C for 3 days (heating rate of 49 °C/h), and then air-dried at a constant temperature and room humidity (20 ± 2 °C and RH60 ± 5%, respectively) before the test.

2.3. Test items and method

2.3.1. Fire resistance test

A series of fire tests was conducted on all RPCs at 4 days using the electric furnace at six different target temperatures: 200 °C, 400 °C, 500 °C, 600 °C, 800 °C, and 1000 °C. The heating rate was set to 10 °C/min. When the temperature inside the furnace reached the target temperature, the temperature was maintained for 2 h to render the specimens temperature homogenous [25]. The specimens were then cooled to room temperature naturally in the furnace. After the fire tests, the specimens were visually inspected to determine whether or not explosive spalling had occurred.

2.3.2. Compressive, flexural, and splitting tensile strength

Compressive and flexural strengths were measured in accordance with Korean Standard F 2405, F 2408 (one-point flexural beam test), and F 2423, respectively. The weight loss, and the residual compressive and flexural strengths were measured for the specimens, which were placed indoors for 2 days after the fire test [26,27]; the results were compared with those of the specimens before the fire test.

2.3.3. Thermogravimetric analysis

The primary hydration products of cement paste including C-S-H gel, calcium hydroxide ($Ca(OH)_2$), and calcium aluminate have different decomposition (or dehydration) mechanisms and temperature ranges when they are subjected to high temperatures. Hence, the microstructural changes in the RPC specimens subjected to different fire temperatures can be characterized by conducting a series of thermogravimetric analyses (TGA and DTG). In this study, the samples for the analyses were collected from the inner core of each specimen, steam-cured for 4 days, and the weight of each sample was set to be within the range of 38–48 mg. Each sample placed in the TG analyzer was heated from room temperature to 1000 °C at a constant heating rate of 40 °C/min. The weight loss of each TGA sample was measured for each temperature.

2.3.4. Microstructure analysis

To examine the microstructural changes of various RPC specimens exposed to different target temperatures, pore structure analysis by mercury intrusion porosimetry (MIP). The samples of about 5 mm for MIP analysis were collected from the inner core of the specimens and immediately soaked in acetone to stop further hydration. The samples were then dried in a vacuum oven at 105 °C for 24 h before testing to achieve a constant weight. The samples were subjected to a maximum pressure of up to 413 MPa. Cylindrical pore geometry, a constant contact angle of 130°, and a constant surface tension of 485 dynes/cm

Table 1
Chemical composition and physical properties of raw materials.

Sample	Chemical Composition (%)							Specific gravity	Blaine fineness (cm^2/g)
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	NaO_2+K_2O		
OPC	20.57	63.03	5.48	3.18	3.41	2.23	0.52	3.15	3267
SF	94	0.8	0.5	2.0	0.9	0.2	1.0	2.2	200,000
BFS	33.1	40.59	13.76	0.85	7.22	1.65	–	2.88	8000
FA	53.08	2.61	25.25	12.84	1.37	2.1	0.06	2.21	3678

*SF: Silica Fume, BFS: Blast Furnace Slag, FA: Fly Ash