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Fire performance of highly flowable reactive powder concrete

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ABSTRACT

The fire performance of highly flowable reactive powder concrete (RPC) is of importance and necessary to be investigated prior to the application to building construction. By conducting a series of fire resistance tests, it is found that the residual compressive strength of RPC decreases with increasing fire duration. As compared to high performance concrete (HPC) and ordinary concrete (OC), the studied RPC not only has a higher fire endurance temperature but also possesses a larger residual compressive strength after fire. In addition, the experimental results of thermogravimetric analyses on RPC, HPC and OC specimens suffered from the same fire temperature and duration indicate that the total weight loss of RPC is lower than others. Besides excellent workability and high compressive strength, the studied RPC could provide better fire resistance than HPC and OC, and thus is applicable to building materials.

1. Introduction

The mechanical properties and durability of concrete are significantly affected by the overall porosity and pore size distribution in cement paste. To enhance the properties of concrete, some microstructural improvement techniques need to be developed and are employed in producing a high-strength and durable concrete. For example, reactive powder concrete (RPC) composed of fine powders such as silica fume, sand and crushed quartz were proposed and characterized by Cheyrezy et al. [1–4]. The particle sizes of fine powders used in RPC is in the range of 0.02–600 μm.

Through the techniques of elimination of coarse aggregates, introduction of pozzolanic material and curing under pressure and high temperature, the overall porosity and critical crack size in cement paste are dramatically reduced. Consequently, the compressive strength of hardened RPC can be increased up to 200–800 MPa [5–7]. However, the flow value of fresh RPC is too low to be used as a construction material due to the use of a lower water/cement ratio. A mix proportion is proposed here to improve the rheological property of RPC used as a building material by discarding the use of steel fibers and by increasing the water/cement ratio. The compressive strength of the studied RPC is inevitably reduced but still larger than that of high performance concrete (HPC) and ordinary concrete (OC). In general, HPC in Taiwan is required to satisfy the following properties: the compressive strength higher than 35 MPa, the slump larger than 200 mm and the flow value larger than 100%. With the unique properties of high compressive strength and excellent workability, RPC with high fluidity used as a building material is feasible and promising. However, the fire performance of the highly flowable RPC becomes critical and needs to be investigated in detail before it is used in building construction.

Fire endurance temperature and residual compressive strength are the two important parameters used to evaluate the fire performance of a building material after fire or at elevated temperatures. The reduction of fire resistance is mainly attributed to the explosive spalling of concrete under a fire. Kodur [8] showed that the explosive spalling of a concrete is affected by its compressive strength, density, moisture content and the fire intensity it experienced. In existing literatures [9–13], the fire resistances of high-strength concrete and ordinary concrete were experimentally studied and then compared to each other. It was found that high-strength concrete is more prone to explosive spalling than ordinary concrete due to its higher density, lower permeability and moisture migration at elevated temperatures. It was demonstrated that the explosive spalling of HPC under certain thermal and mechanical stresses is more likely to occur because of its brittleness [14–16]. For heavy weight concretes, ilmenite concrete is more fire-resistant than gravel and barite concretes [17]. The above experimental results indicate that the exposure of a concrete to higher temperatures leads to a reduction of its compressive strength. Some previous studies [18–20] suggested that silica fume could improve the microstructure of cement paste and the mechanical properties and durability of a concrete due to its pozzolanic reaction with hydrated products.

Highly flowable RPC not only has a better workability but also has a higher compressive strength as compared to HPC and OC. Hence, RPC is an adequate repair material [21,22] that can be utilized for concrete structures. However, the fire performance of RPC is important and should be investigated before it is used as a building material. Up to now, the fire performance of RPC has been paid no attention. In the paper, the fire endurance temperatures of RPC,

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HPC and OC specimens tested in a furnace heated up according to JIS A1304 method were first determined. In addition, the compressive strengths of RPC, HPC and OC specimens suffered from different fire durations of 0, 30, 60, 90 and 120 min at a constant temperature 500 ± 50 °C were measured. Moreover, the changes of microstructures of RPC, HPC and OC specimens suffered from different fire durations at a constant temperature were characterized by conducting a series of thermogravimetric analyses. As a result, the effects of fire duration on the weight losses and residual compressive strengths of RPC, HPC and OC specimens are discussed and then compared to each other. On the basis of experimental results, the feasibility for the use of highly flowable RPC as a building material is evaluated.

2. Materials and methods

2.1. Materials and mix proportion

The highly flowable reactive powder concrete studied here is composed of type II portland cement (denoted by C), quartz sand (Q_s), quartz powder (Q_p), silica fume (S_i), super-plasticizer (SP) and water (W). The mix proportion of the studied highly flowable RPC is listed in Table 1. Here, the dosage of super-plasticizer is expressed as a weight fraction of the binders used for producing highly flowable RPC. After complete mixing, RPC slurry was cast into cylindrical steel moulds with an inner diameter of 100 mm and a height of 200 mm. One day later, the RPC specimens were removed from steel moulds and then cured in an autoclave at a high temperature of 150 °C and under a high pressure of 0.5 MPa for lasting 8 h. Next, the RPC specimens were air-dried at a temperature of 25 + 2 °C for 27 days.

The mix proportions of OC and HPC specimens are listed in Table 2. The physical and geometrical properties of coarse aggregates and fine sands used for producing OC and HPC specimens are listed in Table 3. Similarly, OC slurry and HPC slurry were separately cast into cylindrical steel moulds with the same inner diameter and height as those used for RPC specimens. The OC and HPC specimens were removed from steel moulds one day later, but cured in water for another 20 days and then air-dried at a temperature of 25 ± 2 °C for additional 7 days.

Table 1
The mix proportion of highly flowable RPC

	W/B	C (kgf/m^3)	W (kgf/m^3)	S_i (kgf/m^3)	Q_s (kgf/m^3)	Q_p (kgf/m^3)	SP (%)	Flow value (%)	Unit weight (kgf/m^3)
RPC	0.28	740	261	74	1258	118	1	200	2458

Table 2
The mix proportions of OC and HPC

	W/C	C (kgf/m^3)	W (kgf/m^3)	Coarse aggregate (kgf/m^3)	Fine sand (kgf/m^3)	SP (%)	Unit weight (kgf/m^3)
OC	0.6	350	210	772	852	–	2185
HPC	0.31	548	170	772	852	1.2	2349

Table 3
Physical and geometrical properties of coarse aggregates and fine sands

		Grading	
		Sieve size (mm)	Percentage retained (wt%)
Coarse aggregate			
Specific gravity	2.66	9.50	40.8
Moisture content (%)	1.09	4.75	49.4
Fineness modulus	6.25	2.36	5.6
		1.18	2.5
		0.60	1.7
		0.30	0.0
		0.15	0.0
		Pan	0.0
Fine aggregate			
Specific gravity	2.61	4.75	4.2
Moisture content (%)	2.10	2.36	9.3
Fineness modulus	2.82	1.18	14.8
		0.60	28.8
		0.30	25.9
		0.15	13.0
		Pan	4.0

2.2. Fire endurance temperature tests

The fire endurance temperature of a concrete is an important material property employed to evaluate its fire resistance at higher temperatures. Hence, a series of fire endurance temperature tests on RPC, HPC and OC specimens were conducted to measure their fire endurance temperatures and then compared to each other. Three cylindrical specimens with a diameter of 100 mm and a height of 200 mm were first cast for RPC, HPC and OC, respectively. At the same time, a thermocouple was installed at the center of each cylindrical specimen to measure the actual temperature inside each specimen during a fire endurance temperature testing. One day later, all RPC, HPC and OC specimens were removed from steel moulds. Then, the HPC and OC specimens were cured in water for 20 days and air-dried at a temperature of 25 ± 2 °C for additional 7 days. The RPC specimens, however, were cured in an autoclave at a high temperature of 150 °C and under a high pressure of 0.5 MPa for 8 h and then air-dried at a temperature of 25 ± 2 °C for 27 days. All RPC, HPC and OC specimens were simultaneously placed inside a heavy-oil burning furnace at the Fire Protection and Safety Research Center of National Cheng Kung University as shown in Fig. 1. The temperature of the heavy-oil burning furnace was heated up according to JIS A1304 method. The standard temperature–time heating curve of JIS A1304 method is shown in Fig. 2. During a fire endurance temperature testing, the actual temperatures of all cylindrical specimens were recorded by a data logger connected to the thermocouples inside them.

2.3. Fire duration tests

The residual compressive strengths of RPC, HPC and OC specimens suffered from different fire duration but same fire temperature were measured by conducting a series of fire duration tests. Fifteen cylindrical specimens with a diameter of 75 mm and a height of 150 mm were first cast for RPC, HPC and OC. At the same time, a thermocouple was installed at the center of each cylindrical specimen to measure the actual temperature inside each specimen. The curing procedures of RPC, HPC and OC specimens used for fire duration tests were the same as those used for fire endurance temperature tests. After 28 days curing, all RPC, HPC and OC cylindrical specimens were placed in the heavy-oil burning furnace as stated previously at a fixed fire temperature of 500 ± 50 °C. Different fire durations of 0, 30, 60, 90 and 120 min were considered here. In each case of fire duration, three cylindrical specimens were tested and recorded for RPC, HPC and OC separately. After being suffered from different fire durations at a fixed temperature of 500 ± 50 °C all RPC, HPC and OC cylindrical specimens were first cooled down to room temperature and then mechanically tested to determine their residual compressive strengths. It is expected that the correlations between residual compressive strengths and fire durations for the three different concretes can be obtained from the experimental results of fire duration tests.

2.4. Thermogravimetric analyses

The primary hydration products of cement paste including C–S–H colloid, calcium hydroxide and calcium aluminate have different decomposition mechanisms and temperature ranges when they are subjected to higher temperatures. Typically,

Fig. 1. The heavy-oil burning furnace at the Fire Protection and Safety Research Center of National Cheng Kung University.