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The effect of high temperature on reactive powder concrete

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HIGHLIGHTS

- This paper presents the results of study on properties of RPC at high temperatures.
- The results clearly reveal use of RPC without polypropylene fiber was not suitable.
- The properties of RPC with polypropylene fiber were also discussed.
- The addition of 1% polypropylene fibers in RPC is recommended.

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ABSTRACT

The properties of reactive powder concrete with different plastic fiber ratios were investigated at different temperatures. Samples with the dimensions 7 × 7 × 7 cm were produced using CEM I 52.5 R cement, quartz sand, quartz powder, silica fume, steel wire, a superplasticizer, polypropylene fibers, and water. To achieve high strength the concrete specimens were subjected to compression after casting and accelerated curing. After the curing process, the concrete was exposed to temperatures of 20, 100, 400, 700, and 900 °C for 3 h. A cooling regime was slowly applied to the air after the heating process. Compressive strength, unit weight, and ultrasonic pulse velocity tests were performed on the samples. The physical structures and compressive strengths of the samples were examined.

1. Introduction

Reactive powder concrete (RPC) is a type of concrete is characterized by high doses of fine-grained cement and a low water–cement ratio. RPC was, developed by researchers in a laboratory at Bouygues, in Paris in the early 1990s; the first study of RPC was conducted by Richard and Cheyrezy. The world's first RPC structure the Sherbrooke Bridge in Canada was erected in July 1997 [1,2]. Due to a relatively high production cost, RPC is only employed in restricted areas. The global use of RPC is rapidly increasing, particularly in Europe where numerous studies have been conducted. RPC is also used in the defense industry, in nuclear power plants, and in weapons factories. In Europe, RPC is also applied to the construction of bridges and viaducts to reduce their cross-sectional areas. In Turkey, RPC is used in the production of manhole covers and storm grates. Numerous studies of RPC have been performed. One of these studies discusses the production of ultra-high performance cementitious composites with maximum compressive strengths of 350 MPa. To ensure an optimum mixture with a precise distribution of all grains during setting, a reduced water–cement ratio of concrete, an optimum use of silica fume with a high fineness, a homogeneous distribution of the mixture, and the use of short steel wire to increase the ductility of the concrete and to obtain a high strength, the study suggests the application of compressive force when placing the mixture in molds and a subsequent application of pressure steam during curing [3]. In another study, compressive and flexural tests were performed on two types of RPC (RPC200 and RPC800). Compressive force was not applied to RPC200 during curing. The samples were cured at 90 °C and maximum compressive strengths in the range 170–200 MPa were achieved. A maximum compressive force of 50 MPa was applied to RPC800 during curing at temperatures that ranged from 250 to 400 °C to achieve compressive strengths in the range 490–680 MPa. The high strengths can be attributed not only to the low water–cement ratios but also to the use of silica fume and steel fibers. In addition to water curing, steam curing, and autoclave curing is also favorable [4–7]. Another method for achieving high strength is the application of pressure. Samples exposed to a compressive force of 25 MPa yielded 220 MPa, whereas samples exposed to compressive forces below 100 MPa yielded a maximum compressive strength of 475.24 MPa [8,9]. The shrinkage value of RPC was two times higher than the shrinkage value of ordinary concrete [10]. During the process, researchers had

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difficulty creating a homogeneous RPC mixture; however, this problem was solved by adding a superplasticizer [11]. The mechanical properties, such as compressive strength and fracture energy, of mixtures with thin steel fibers were investigated. The study concluded that the amount of steel fibers had a significant effect on compressive strength and fracture energy [12]. The final strength was sufficient evidence that autoclave curing is the best type of curing for RPC because it increases the strength of RPC by 20–30% [13].

One particular study demonstrated that the fire performance of highly flowable RPC should be investigated prior to its application in building construction. The results of a series of fire resistance tests indicated that the residual compressive strength of RPC decreases with the duration of a fire. Compared with high-performance concrete and ordinary concrete, RPC exhibits not only a higher fire endurance temperature but also a larger residual compressive strength after a fire; as a result, RPC can be used to save lives during fires [14]. The influence of temperature, steel fiber content, hold time, dimension of specimens, and explosive spalling in the 20–800 °C temperature range were examined. The experimental results indicate that 2% steel fibers (volume content) can prevent explosive spalling of RPC and significantly enhance the compressive and tensile strength of RPC. The cube compressive strength decreases at 100 °C, increases at temperatures in the 200 to 500 °C range and decreases at temperatures above 600 °C. Below 300 °C, the cube compressive strength of RPC increases as the fiber content increases but decreases above 300 °C as the fiber content increases [15]. An experimental study was performed on the compressive stress–strain relationships of RPC with various steel fiber contents after exposure to temperatures in the 20–900 °C range. Steel fiber volume dosages of 1%, 2%, and 3% were employed in the study. The results indicate that the compressive strength and elastic modulus of RPC initially increase but subsequently decrease with increasing temperature, and the elastic modulus decreases more rapidly than the compressive strength. The peak strain and peak ultimate strain are 600 °C and 700 °C, respectively; they increase exponentially prior to the peak points [16]. A study of the compressive properties and microstructures of RPC mixed with steel fibers and polypropylene fibers after exposure to temperatures in the 20–900 °C range was conducted. The effects of heating temperature, fiber content, and specimen size on the compressive properties were analyzed. The microstructures of RPC at various high temperatures were investigated by scanning electron microscopy (SEM). The results indicate that the compressive strength of hybrid fiber-reinforced RPC initially increases but subsequently decreases with increasing temperature and the degradation of macro-mechanical properties can be attributed to the deterioration of the microstructure of RPC. Based on the experimental results, equations for the relationship between compressive strength and heating temperature are established. Compared with normal-strength and high-strength concretes, hybrid fiber-reinforced RPC exhibits excellent resistance to high temperatures [17]. The experimental results indicate that the residual compressive strength of RPC after heating at temperatures in the range 200–300 °C significantly increases at room temperature but significantly decreases at temperatures above 300 °C. The residual peak strains of RPC also initially increase to temperatures in the 400–500 °C range but gradually decrease above 500 °C [18].

High-strength concrete (HSC) is increasingly employed in numerous building applications in which structural fire safety is a major design consideration [19]. The fire resistance of HSC is minimal due to the low number of air voids inside HSC. At high temperatures, the free water inside HSC evaporates but water vapor is not able to escape due to the dense structure of the material. As a result, spalling is produced on the concrete surface. To solve this problem, a new product that contains fiber-reinforced polypropylene was used. Polypropylene fibers melt at high temperatures, which enable water to freely drain from the structure [20]. When high-strength concrete with polypropylene fibers is heated to 170 °C, the fibers readily melt and volatilize, which creates additional porosity and small channels in the concrete. The SEM analysis showed supplementary pores and small channels in the concrete due to fiber melting. The mechanical tests showed minor changes in compressive strength, modulus of elasticity, and splitting tensile strength, which may be due to the melting of the polypropylene fibers [21].

2. Experimental study

2.1. Materials

Cement: Type R CEM I 52.5 cement was employed in the experiment. The physical and chemical properties of this cement are listed in Table 1.

Silica fume: Silica fume is a waste material that is generated during the manufacture of silicon or silicon-ferrous. Silica fume is less than 0.5 μm in size. The entire experimental study was performed using 940-U-type silica fume from the Elkem Company in İstanbul-Turkey. The physical and chemical properties of the silica fume are listed in Table 2.

Superplasticizer: Modified lignosulfonate superplasticizer produced by the Sika Company was used. The properties of the superplasticizer are listed in Table 3.

Quartz sand and powder: Quartz mineral is extremely tough and robust compared with other minerals. The powder and sand were obtained from the Çeliktaş Company. The powder detected in the RPC is a combination of quartz and silica powder. The granulometry of the sand is provided in Fig. 1 and the properties of the sand and powder are listed in Table 4.

Steel fiber: The steel wires were obtained from the Bekaert Company. Brass-coated steel was used to prevent corrosion. Small steel fibers were employed to reduce mixing and placing problems. The properties of the steel fiber are listed in Table 5.

Polypropylene fiber: This fiber melts during a fire, which prevents concrete from spalling. The properties of the polypropylene fiber, which was obtained from the Bekaert Company, are listed in Table 6. The fiber used in the mixtures is shown in Fig. 2.

Water: Eskişehir tap water was used. The chemical analysis of the drinkable water is displayed in Table 7.

2.2. Method and tests

RPC was produced according to the mixture ratios shown in Table 8. Polypropylene fiber was added according to the following ratios: 0%, 0.5%, 1.0%, and 1.5%. The dimensions of the mold used in this study are 7 × 7 × 7 cm. The RPC mixtures were placed in molds and the steel plates were subsequently placed against both sides of the mold with an applied pressure of 80 MPa to ensure adequate compaction, as shown in Fig. 3. The samples were cured in 90 °C water for three days.

Table 2
Properties of silica fume.

SiO_2	H_2O	LOI	45 μ (%)	Loose unit weight	Firm unit weight
>90	<1	<3	<1,5	200-350	500-700

Table 1
Properties of cement.

Content	MgO	CaO	$Na_2O + 0.66\ K_2O$	SO_3	Cl^-	LOI	Insoluble residue
%	1.16	1.11	0.70	2.67	0.01>	1.72	0.58
Spec. gravity	Fineness (cm^2/g)	Initial set (min)	Final set (min)	Expansion (mm)	Compressive strength (MPa)		
					2-day	28-day	
3.13	4198	166	202	1.1	32.4	62.6	