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Fire Safety Journal 41 (2006) 115–121

FIRE SAFETY JOURNAL

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On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures

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Received 16 January 2005; received in revised form 1 September 2005; accepted 16 November 2005
Available online 4 January 2006

Abstract

Cubes of $100 \times 100 \times 100\,mm^3$ and cylinders of $100 \times 100 \times 515\,mm^3$ were designed and fabricated with C50, C80 and C100 high-performance concrete (HPC) mixed with and without polypropylene (PP) fibres, respectively. These specimens were heated in an electric furnace, approximately following the curve of ISO-834, with a series of target temperatures ranging from 20 to 900 °C. No explosive spalling was observed during the fire test on HPC specimens with PP fibres, whereas some spalling occurred for HPC specimens without PP fibres. The relationship between the mass loss and the exposure temperature was investigated. In addition, the heated and cooled cubes and prisms were tested under monotonic compressive loading and four-point bending loading, respectively. The degradation of both the residual compressive strength and the residual flexural strength was analyzed. Furthermore, the effects of PP fibres on the residual mechanical strength of HPC specimens at elevated temperatures were also investigated. Finally, a fire-resistance design curve relating the residual compressive strength to temperature, as well as a design curve relating the residual flexural strength to temperature, were proposed based on the statistical analysis of the test data.

Keywords: High-performance concrete (HPC); Polypropylene (PP) fibres; Elevated temperature; Compressive strength; Flexural strength

1. Introduction

While the strength, workability and durability of high-performance concrete (HPC) are usually greatly superior to those of conventional concrete at ambient temperature [1], their failure is sometimes rapid and dramatic when exposed to a fire, characterized by explosive spalling [2]. Explosive spalling is a particularly dangerous type of failure and may affect the integrity and stability of a concrete structure. Although it is controversial whether HPC (also known as high-strength concrete (HSC)) is more susceptible to explosive spalling than normal strength concrete (NSC) [3], many investigations have confirmed that HPC is more likely to exhibit explosive spalling at least at the material level [4–9]. To combat explosive spalling, several investigations by researchers such as Hammer [10], Nishida et al. [11] and Atkinson [12], have been carried out, which revealed that the application of polypropylene (PP) fibres in concrete may considerably reduce the amount of spalling for HPC at high temperatures. Both experimental and theoretical studies have shown [10–12] that at elevated temperatures, PP fibres melt and create channels through which the water vapour pressure built-up within HPC as temperatures rise is released. This release of the vapour pressure significantly reduces the spalling tendency of HPC under fire conditions [13–16].

When PP fibres are utilized to control fresh and hardened properties of cement-based materials at ambient temperature, it has been found that PP fibres can decrease the plastic shrinkage [17], and they also have a minor effect on the compressive and flexural strengths. The effect on strength, in fact, has been reported to be contradictory [17,18]. Therefore, the beneficial effect of avoiding or reducing explosive spalling raises the question of how much PP fibres will affect the residual mechanical behaviour of HPC exposed to elevated temperatures. The investigation on cement paste by Komonen and Penttala

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doi:10.1016/j.firesaf.2005.11.004

Nomenclature

f_{cu}^{20}, f_f^{20} compressive strength and flexural strength of HPC at 20 °C, respectively
f_{cu}^{T}, f_f^{T} residual compressive strength and flexural strength of HPC at T, respectively
m^{20} mass of HPC at 20 °C
R value of correlation coefficient
T exposure temperature
Δm^T mass loss at T

[19] have indicated that inclusion of PP fibres produces a finer residual capillary pore structure, decreases residual compressive strength and improves residual flexural strength when temperature ranged from 150 to 440 °C, whereas the residual flexural strength decreases considerably when temperature rises beyond 440–520 °C. Furthermore, Poon et al. [20] have concluded that inclusion of PP fibres results in a quicker loss of the compressive strength and toughness of concrete (besides Portland cement, cement both with and without metakaolin or silica fume were included in their research) after exposure to elevated temperature (up to 800 °C). However, they also have found that the residual compressive strength of HPC with ordinary Portland cement containing PP fibres (0.22% by volume) increases 4.6% after exposure to 600 °C, while it decreases 3.2% after exposure to 800 °C, compared with that for HPC without PP fibres. From their investigation, it may be deduced that the effects of PP fibres on the residual mechanical strength of HPCs after exposure to elevated temperatures still need to be further studied.

The objective of this investigation is to increase the understanding of residual strengths of HPC prepared with and without PP fibres after exposure to temperatures ranging from 20 to 900 °C. Three concrete grades were chosen, viz., C50, C80 and C100 (Chinese Standard GB 175-1999). Simple expressions were then proposed to obtain both the residual compressive strength and the residual flexural strength corresponding to a particular exposure temperature.

2. Test specimens

2.1. Materials

The materials used in this investigation included

- an ordinary Portland cement conforming to 42.5 R in accordance with the Chinese Standard GB 175-1999,
- S90 blast-furnace slag,
- silica fume,
- river sand with fitness modulus of 2.50,
- calcareous crushed stone (5–15 mm, for C100) or siliceous crushed stone (5–20 mm, for C50 and C80),
- superplasticizer with a brand of Mighty-100,
- city tap water, and
- commercially available PP fibres (specification: 15 mm in maximum length, 45 μm in diameter and with 165 °C melt point).

2.2. Mixture proportion

The mixture proportions of C50, C80 and C100 with PP fibres are illustrated in Table 1. Except for the absence of PP fibres, the mix design for HPCs without PP fibres was the same as for the corresponding series of HPCs with PP fibres. The concrete mixtures were made in a laboratory pan mixer. The cement, blast furnace slag or silica fume were placed first and dry-mixed for about 2 min. When the PP fibres were utilized, they were added thereafter and strewed into the rotating mixer to avoid any fibre balling. After 5 min of mixing, water was added, followed by another 2 min of mixing. The fine and coarse aggregates and superplasticizer were then finally mixed and stirred for 3–5 min. A slump test was done to determine the concrete workability, and the mean slump of the freshly mixed concrete was found to be more than 220 mm. The series of batches were, respectively, cast in three parallel $100 \times 100 \times 100\,mm^3$ cubic steel moulds and three parallel $100 \times 100 \times 515\,mm^3$ prism steel moulds, then compacted on a vibration table. They were demoulded on the following day and were cured in a fog room (20 ± 2 °C, 95% relative humidity). The specimens were taken out of the curing room 28 days later, and dried under natural conditions until the fire testing day. The cube and prism specimens were used to obtain the residual compressive and flexural strengths at elevated temperatures, respectively.

Table 1
Mix proportions of HPC with PP fibres (unit: kg/m^3)

Grade	Cement	Blast-furnace slag	Silica fume	Water	Sand	Siliceous crushed stone 5–20 mm	Calcareous crushed stone 5–15 mm	Superplasticizer	PP fibres
C50	261	261	0	178	684	1023	0	5.2	1.8
C80	324	216	0	162	688	1030	0	6.2	1.8
C100	540	0	60	150	660	0	1150	7.8	1.8