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Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures

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Abstract

In this paper, an experimental investigation was conducted to explore the relationship between explosive spalling occurrence and residual mechanical properties of fiber-toughened high-performance concrete exposed to high temperatures. The residual mechanical properties measured include compressive strength, tensile splitting strength, and fracture energy. A series of concretes were prepared using OPC (ordinary Portland cement) and crushed limestone. Steel fiber, polypropylene fiber, and hybrid fiber (polypropylene fiber and steel fiber) were added to enhance fracture energy of the concretes. After exposure to high temperatures ranged from 200 to 800 °C, the residual mechanical properties of fiber-toughened high-performance concrete were investigated. For fiber concrete, although residual strength was decreased by exposure to high temperatures over 400 °C, residual fracture energy was significantly higher than that before heating. Incorporating hybrid fiber seems to be a promising way to enhance resistance of concrete to explosive spalling.

Keywords: Explosive spalling; Fiber reinforcement; Mechanical properties; High-performance concrete; Temperature

1. Introduction

Since 1990 high-performance concrete (HPC) has been increasingly developed for its superior performance, e.g. high strength, high durability and high workability. With these excellent properties, HPC can be applied in a variety of structures and buildings, such as bridges, tunnels, offshore structures, highways and other forms of infrastructures, and high-rise buildings[1–3]. However, some investigations revealed that HPC is prone to explosive spalling when subjected to fire, but the reasons for HPC's inferior thermal behavior are not fully understood [4–7]. As fire still constitutes a tremendous risk to the human society, the mechanism for HPC's explosive spalling remains an important problem to be solved.

Some previous reports [5,6,8] proved that explosive spalling is significantly associated with internal cracking. It was stated that the hydration products of cement decomposed quickly and resulted in serious cracks both within hardened cement paste and around aggregate particles, and pore pressure undoubtedly contributed to explosive spalling [9,10]. However, it was also explained that rapid heating of concrete specimens could cause internal cracks, due to stresses that developed when temperature difference between the core and the surface of a specimen exceeded a certain value [6]. Furthermore, it was also reported that cracking in concrete originated from the pores inside concrete [11]. Another investigation [10] found that moisture content and strength grade of concrete are two main factors governing thermally induced explosive spalling. If the strength of concrete is below a certain value, 60 MPa, no spalling will occur, even at a high moisture content level. When the concrete strength exceeds that strength value, the higher the moisture content, the greater the spalling probability, as long as the moisture content is greater than a threshold value. The effects of moisture content and strength on spalling confirm the vapor pressure build-up hypothesis as the mechanism for spalling [10].

In this experimental investigation, two parts of work, i.e. explosive spalling tests and mechanical property determinations, were conducted using five types of concrete, to identify the relationship between residual mechanical properties and

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Table 1
Mix proportion and 28-day compressive strength*

Type	W/B	Quantity (kg/m^3)							Strength (MPa)/ density (kg/m^3)
		C	SF	S	G	W	PP-F	S-F	
CHPC	0.26	535	64	597	1153	156	0	0	93.9/2506
PHPC	0.26	519	62	579	1122	151	1	0	80.6/2434
HHPC1	0.26	527	63	588	1138	154	0.6	40	109.6/2511
HHPC2	0.26	528	63	590	1140	154	0.3	70	109.2/2545
SHPC	0.26	518	62	578	1119	151	0	100	109.3/2528

*W/B for water/binder ratio (mass), C for ordinary Portland cement (OPC), SF for silica fume, S for sand, G for coarse aggregate, W for water, PP-F for 20 μm polypropylene fiber (PP fibre), and S-F for steel fiber, respectively.

explosive spalling occurrence of fiber-toughened high-performance concrete (FT-HPC) exposed to high temperatures.

2. Experimental details

2.1. General

Concretes were prepared using polypropylene fibers, steel fibers, and combinations of polypropylene and steel fibers. Specimens in the forms of 100×100×100 mm cubes and 100×100×300 mm beams were of five types of concrete designated by CHPC, P-HPC, HHPC1, HHPC2, and SHPC. Their mix proportions and compressive strengths are given in Table 1. The diameter of the polypropylene fiber (PP fiber) was 20 μm, while the diameter of steel fiber was 2 mm, as given in Table 2. Coarse aggregate of crushed limestone and ordinary Portland cement of 42.5 MPa grade were employed. Naphthalene based superplasticizer was used at a dosage from 1.0% to 2.5% of cement contents to maintain slump of mixtures around 150 mm.

After demolding at one day, the specimens were cured in water at 20 °C until 28-day age and then cured in air with temperature of 20 °C and 50% R.H.

2.2. Explosive spalling test

Spalling tests were conducted on fiber toughened concrete beams of 100×100×300 mm at 56-day age. Specimens were heated in an electric furnace at a rate of 10 °C/min. The heating rate was measured in the air at a position approximately 4 cm above the upper surface of a concrete specimen inside the electric furnace. This rate was the same as in heating for the determinations of strength and fracture energy. The temperature–time curve of the spalling tests with a target temperature of 600 °C is given in Fig. 1. The target temperature was maintained for 1 h. It was estimated, according to test results in a previous investigation [12], that temperature at the center of a specimen rose gradually to the target temperature from the first 20th minute during the 1 h period for maintaining temperature, which was then maintained for the left 40 min until electric heating was turned off. Since a fundamental understanding had been obtained on explosive spalling behavior of plain concrete [10], no spalling tests were conducted on CHPC (plain concrete with no fiber) in the present investigation.

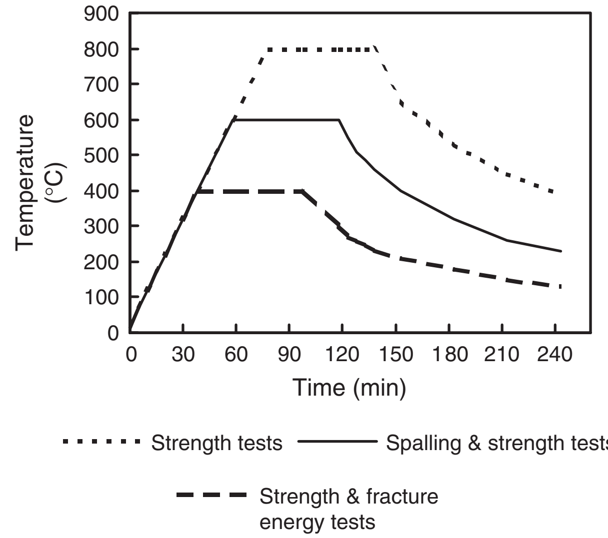

Fig. 1. Temperature–time curves in heating of the tests.

Table 2
Characteristics of fibers

Type	Density (g/cm^3)	Diameter	Length (mm)	Aspect ratio	Tensile strength (MPa)	Elastic modulus (GPa)
PP fiber	0.91	20 μm	20	1000	560–770	3.5
Steel fiber	7.80	2 mm	30	15	650–800	200

2.3. Determination of strength of concrete

Cube specimens of 100 mm size were employed for strength determination. At 56 days three specimens for each batch were dried at 105 °C for about two days in order to decease moisture content of concrete to a lower degree, so that the specimens for strength determination would not encounter explosive spalling when exposed to heating to 400, 600 or 800 °C [10]. The specimens were then heated in an electric furnace to temperatures of 400, 600 and 800 °C, respectively, at a heating rate of 10 °C/min. The target temperatures were maintained for 1 h. After the specimens had been allowed to cool naturally to room temperature, the residual mechanical properties were determined including compressive strength and tensile splitting strength after two days from heating. Determination of compressive strength and tensile splitting strength was according to the China standard GBJ 81-85 [13] which is similar to BS 1881: Part 116.

2.4. Determination of fracture energy

Notched beam specimens of 100×100×300 mm were employed for fracture energy determination. At 56 days two specimens for each batch were exposed to 105 °C for two days, and then heated to temperature of 400 °C at a heating rate of 10 °C/min. The target temperature was maintained for 1 h. After the specimens cooled naturally to room temperature, the

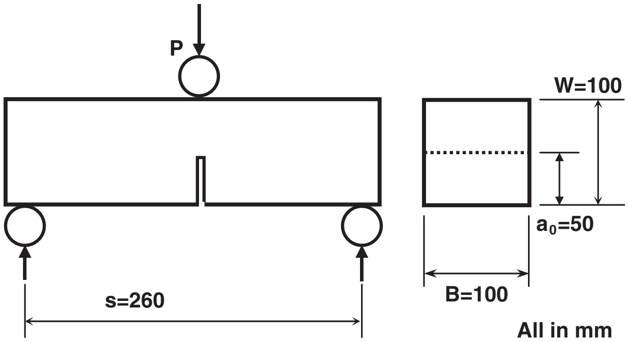

Fig. 2. Configuration of three-point bend specimen of notched beam.

residual fracture energy was determined. Fracture energy was determined according to a RILEM test method [14].

The configuration of the specimens is shown in Fig. 2. A notch was prepared during casting of specimens, to form a crack at the mid-span of each specimen prior to heating. In a three-point bending test on a beam specimen, mid-span deflection δ was recorded during the whole loading process until failure. The loading was in a displacement-control manner at a rate of 0.05 mm/min. From a load–deflection curve recorded, the fracture energy of concrete could be calculated by using Eq. (1) that is specified in the RILEM method [14].

$$G_F = \left[\int_0^{\delta_0} P(\delta)\mathrm{d}\delta + mg\delta_0\right] / A_{lig} \qquad (1)$$

where G_F=the fracture energy (J/m^2), $m=m_1+m_2$ (kg), $m_1=M\,s/L$ (weight of the beam between the support, calculated as the beam weight multiplied by s/L), M=mass of the specimen, m_2=weight of the part of the loading arrangement which is not attached to the machine but follows the beam until failure, s=span, L=length of the specimen, g=9.81 m/s^2, δ_0=the mid-span deflection of the specimen at failure (m), A_{lig}=area of the ligament (m^2), δ=mid-span deflection (m), P=load (N).

3. Results and discussion

3.1. Occurrence of explosive spalling

The statistical result of explosive spalling is given in Table 3. Among the four types of fiber toughened concrete subjected to spalling tests, three types suffered spalling. SHPC incorporating steel-fiber suffered significant spalling (7 out of 16 beams) while HHPC1, incorporating hybrid fiber (i.e. both polypropylene fiber of 0.6 kg/m^3 and steel fiber of 40 kg/m^3), behaved quite well and encountered little spalling. As explosive spalling is governed by a vapor-pressure mechanism [10], it is reasonable to consider that concrete incorporating PP fiber can provide a benefit to concrete so as to prevent it from explosive spalling, due to the fact that it is melted under temperature around 170 °C and hence moisture in concrete can escape through inter-connected pores to outside of concrete [10]. Nevertheless, the result that either PHPC or HHPC2 suffered spalling to a certain degree, suggests that there should be some factors other than PP fiber or vapor pressure influencing the occurrence of explosive spalling, which need further investigation.

Table 3
Occurrence of explosive spalling of concrete exposed to high temperatures

Type of concrete		SHPC	PHPC	HHPC1	HHPC2
Quantity of specimens		16	16	16	16
Quantity of specimens encountered spalling under T temperature	$T \leq 200$ °C	6	2	0	3
	200 °C $\leq T \leq$ 400 °C	1	0	0	0
	Total, $T \leq 800$ °C	7	2	0	3

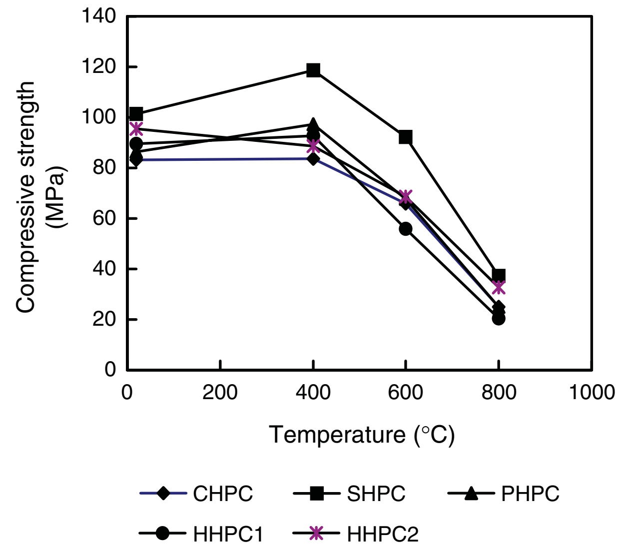

Fig. 3. Compressive strength of five types of concrete subjected to different temperatures.

3.2. Residual strength

The results of compressive strength and tensile splitting strength of concrete are given in Figs. 3 and 4, respectively. Each point in Figs. 3 and 4 was obtained from the average of

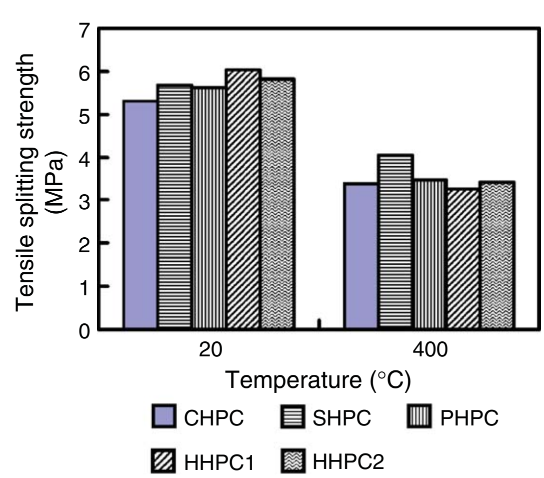

Fig. 4. Tensile splitting strength of five types of concrete before and after exposure to 400 °C.

tests on three cubes a batch. Fig. 3 shows that, high temperatures can be divided into two ranges in terms of effect on concrete strength loss, namely 20–400 °C and 400–800 °C. In the range 20–400 °C, the five types of concrete maintained their original strength. In the range 400–800 °C, these concretes lost most of their original strength, especially at temperature above 600 °C. Thus the range 400–800 °C may also be regarded as the critical temperature range for the strength loss of fibre concrete, which is similar to that of plain concrete without any fibers [15]. Compared with previous knowledge [16,17], the strength at 400 °C in this investigation was very high, which might be due to a shorter duration of exposure at the center of a cube specimen to temperature of 400 °C. Previous researches on plain HPC and fiber reinforced concrete indicate similar trends up to 250–400 °C [16,17].

The loss in tensile splitting strength is considerably sharp, which is clearly different from the more gradual loss of compressive strength. This is because that tensile strength is more sensitive to cracks either on macro- or on micro-scale which are caused by high temperatures to concrete [15]. From Figs. 3 and 4, it can be seen that SHPC maintained residual strength relatively high, while PHPC, HHPC1, and HHPC2 showed slightly lower residual strength, which may be attributed to PP fiber's melt and formation of inter-connected pores.

3.3. Residual fracture energy

The results of residual fracture energy of fiber concrete after exposure to 400 °C are given in Fig. 5. As a whole, fiber concrete had much higher fracture energy, especially those incorporating steel fiber, than plain concrete. For fiber concrete, although residual strength was decreased by exposure to high temperatures above 400 °C as shown in Figs. 3 and 4, residual fracture energy was significantly higher than that before heating. Such a phenomenon may be similar to the increase of fracture energy of plain concrete after exposure to temperatures up to 400 °C reported by previous investigations [18–21].

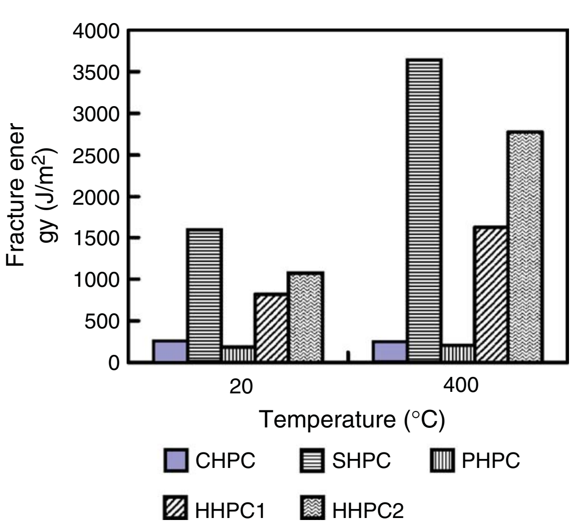

Fig. 5. Fracture energy of five types of concrete before and after exposure to 400 °C.

Nevertheless, the increase in fracture energy of fiber concrete after heating in the present investigation was significantly greater than that of plain concrete. It is estimated that a more pronounced fiber pullout process can take place during fracture of fiber-toughened concrete after heating, which should be a main reason for the increase in fracture energy after heating. Another possible reason for the increase in fracture energy may be the interlocking of aggregate during a fracture process, which should be an only factor in plain concrete contributing to the increase of fracture energy after exposure to elevated temperatures.

The results of residual fracture energy may be also correlated with the mechanism for explosive spalling of concrete. Although PP fiber is generally believed to be able to form an inter-connected pore system under temperatures above 170 °C, PHPC in this investigation encountered spalling as well. This phenomenon implies that in concrete incorporating PP fiber, even though polymer fiber could be melted under elevated temperatures, concrete at 0.26 water/binder ratio was so dense that it could still keep vapor pressure high enough to result in explosive spalling regardless of formation of the inter-connected pore system. In light of this point, steel fiber may be beneficial to help concrete overcome vapor pressure build-up under high temperatures and hence avoid occurrence of spalling. Therefore incorporating hybrid fiber seems to be a promising way to enhance resistance of concrete to thermally induced explosive spalling, which was experimentally confirmed by this investigation. The effect of steel fiber may be also related to its ability to prevent a crack passing inside concrete where moisture accumulates. As the amount of PP fiber seems too low to prevent fire spalling, another solution to overcome fire spalling may be to increase the amount of PP fiber, maybe to 2 kg/m^3.

4. Conclusions

Fiber concrete had much higher fracture energy, especially those incorporating steel fiber, than plain concrete, confirming the toughening effect of fiber on concrete. Furthermore, for fiber concrete, although residual strength was decreased by exposure to high temperatures above 400 °C, residual fracture energy was significantly higher than that before heating.

A more pronounced fiber pull-out process could take place during fracture of fiber concrete after heating than that before heating, which should be one of the reasons for the increase in fracture energy after heating. Another possible reason for the increase in fracture energy after heating might be the interlocking of aggregate during a fracture process, which should be an only factor in plain concrete contributing to the increase of fracture energy after exposure to elevated temperatures. In light of this point, steel fiber may be beneficial to help concrete overcome vapor pressure build-up under high temperatures and hence avoid occurrence of spalling. The result that polymer fiber concrete encountered spalling as well, implies that, even though polymer fiber could be melted under elevated temperatures, concrete at

0.26 water/binder ratio was so dense that it could still keep vapor pressure high enough to result in explosive spalling when polymer fiber was used lonely. Therefore incorporating hybrid fiber seems to be a promising way to enhance resistance of concrete to thermally induced explosive spalling, which was experimentally confirmed by this investigation.

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