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

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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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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

The preparation as well as the curing of all the mixes was conducted in the State Key Laboratory for Concrete Material Research at Tongji University (Shanghai, China).

3. Fire test

3.1. Heating regime

The fire test was undertaken in a DRX-36 electric furnace (see Fig. 1). Temperatures were set at ten values, viz., 20, 100, 200,…,900 °C (with 100 °C per step). The temperature was increased in line with the ISO-834 fire curve. Fig. 2 shows the measured temperature along with the time. After having reached a target temperature, the temperature was maintained for about 3 h (soaking period). Under this regime, the temperature on the surface can be considered to be the same as the centre of the specimens [21]. Then the furnace door was opened, and the specimens were cooled down to the room temperature within the furnace. All the surface changes (i.e. colour and crack, etc.) of the specimens after the temperature exposure were observed and evaluated carefully. This will be addressed in detail in the following two sections.

Fig. 1. Furnace.

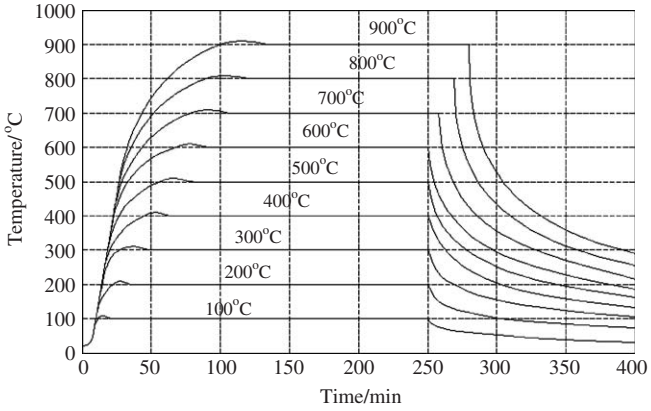

Fig. 2. Measured temperature–time curve of the furnace.

3.2. Mass loss

The masses of the cube specimens before and after exposure to high temperatures were determined, respectively, for the mass loss evaluation. The relative mass losses (i.e., the ratio of mass loss at elevated temperature to the original mass at ambient temperature) of all the investigated mixtures are presented in Fig. 3. For different elevated temperatures, Fig. 3 shows that the mass loss tends to increase when the HPCs are mixed with PP fibres. The variation of HPCs both with and without PP fibres versus exposure temperatures can be divided into three phases. Below 100 °C, little mass loss is observed, since abundant free water is not left in the hardened and dried HPCs. When temperature rises from 100 to 300 °C, the mass loss is significant owing to the release of both capillary water and gel water. Beyond 300 °C, the rate of mass loss comparatively slows down. It should be noted that mass loss rate increases again in C100 concrete when the temperature rises beyond 800 °C. This could be the consequence of the decomposition of calcareous aggregates, the release of CO_2 and the sloughing off of the concrete surface.

In order to reveal the influence of PP fibres on the mass loss of HPCs, all the measured relative mass losses of HPCs (i.e., C50, C80 and C100) with and without PP fibres are summarized in Fig. 4. Two linear regression equations shown in Fig. 4 are given as follows.

Without PP fibres:

$$\Delta m^T/m^{20} = 0.0001\,T - 0.0008\ (R = 0.97). \quad (1)$$

With PP fibres:

$$\Delta m^T/m^{20} = 0.0001\,T - 0.0009\ (R = 0.93), \quad (2)$$

where T is the exposure temperature (°C), Δm^T is the mass loss at T, m^{20} is the mass of HPC at 20 °C and R is the value of correlation coefficient.

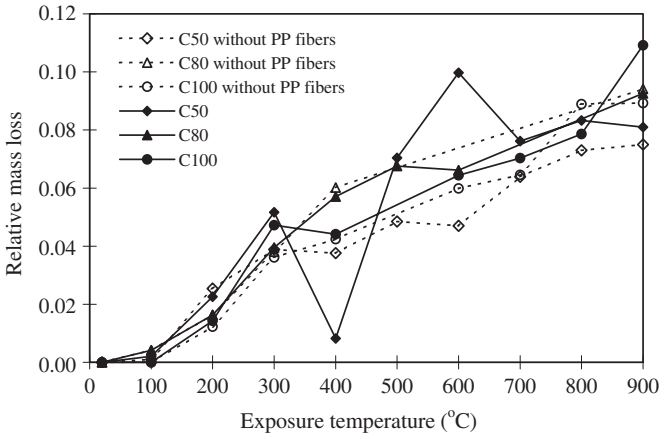

Fig. 3. Mass loss of HPC.

3.3. Spalling and surface colour

No explosive spalling occurred in the specimens with PP fibres during the fire testing. This confirms again that the PP fibres can markedly improve resistance against explosive spalling. However, explosive spalling was observed in the specimens without PP fibres at different elevated temperatures. In particular, specimens of grade C50 did not spall when the temperature was lower than 800 °C; specimens of grade C80 did not spall below 400 °C, beyond which they began to spall a bit; while the specimens of grade C100 spalled greatly beyond 500 °C. Thus, it may be inferred that the higher the grade of concrete (without PP fibres), the more likely it is to spall under a high temperature.

The change of concrete colour can be attributed to the change in texture and composition, expansion and crystal destruction during a fire [3]. This investigation demonstrated that the colour change on the surfaces had no obvious relation with the addition of PP fibres. This may be due to the fact that PP fibres melt when the temperature is beyond 165 °C. The variation of the colours under rising temperature can be identified under three main categories. Below 300 °C, the concrete colour does not change noticeably; i.e., the HPC with blast furnace slag remains light grey, while the HPC with silica fume stays dark grey. When temperatures are increased up to 400–600 °C, the HPC with blast furnace slag is dust-coloured, and the HPC with silica fume is caesious. Beyond 600 °C, the former is brown, while the latter is grey.

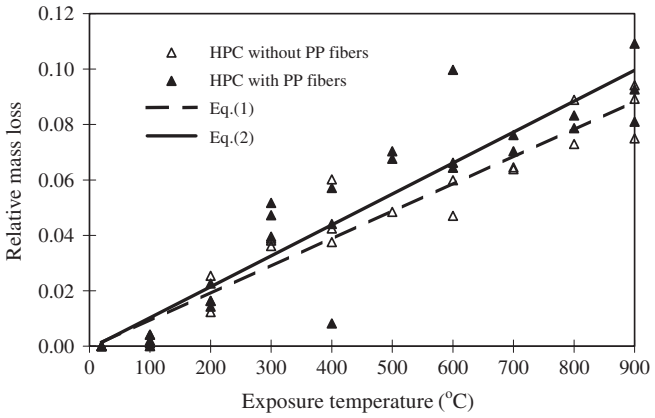

Fig. 4. Regression for mass loss of HPC.

4. Compression test results and discussion

4.1. Residual compressive strength

The equipment used for compression loading on cube specimens was a universal test machine YE-2000 with a compression capacity of 2000 kN. The compressive strength was tested according to the Chinese standard GB/T50081-2002. The average values of the residual compressive strength for all the tested specimens are listed in Table 2. It can be seen that the residual compressive strength of HPC decreases with rise in temperature regardless of the presence of PP fibres.

4.2. Discussion on residual compressive strength

Fig. 5 compares the relative residual compressive strength corresponding to concrete of different grades subjected to different exposure temperatures. The relative residual strength is defined as the ratio of residual compressive strength at elevated temperature to initial compressive strength at ambient temperature. Clearly, regardless of the presence of PP fibres, the strength of HPCs deteriorates when the exposure temperature is greater than 400 °C. Below 400 °C, the relative residual compressive strength does not change significantly, but beyond 400 °C it drops drastically. Generally speaking, for both the HPCs with and without PP fibres, the relative residual compressive strength of HPC with blast furnace slag (C50 and C80) was superior to that of HPC with silica fume (C100) under fire conditions. It implies that blast furnace slag may somewhat contribute to the residual

Table 2
Summary of the residual compressive strength (unit: MPa)

Exposure temperature (°C)	C50		C80		C100	
	Without PP fibres	With PP fibres	Without PP fibres	With PP fibres	Without PP fibres	With PP fibres
20	66.8	66.4	83.8	75.8	108.9	103.1
100	68.5	66.3	92.8	81.1	102.0	103.2
200	59.2	64.9	82.4	83.6	99.0	95.0
300	62.9	68.9	91.3	78.8	96.0	99.5
400	56.9	56.1	77.6	72.1	99.0	102.8
500	50.9	51.4	/	59.3	75.5	70.3
600	39.8	40.1	40.2	58.4	64.0	55.1
700	32.3	32.7	/	50.4	47.5	36.3
800	21.5	18.3	30.5	29.2	/	26.8
900	10.8	12.4	19.8	21.8	/	20.0

Note: / refers to explosive spalling; occurred more than once within three cubes.

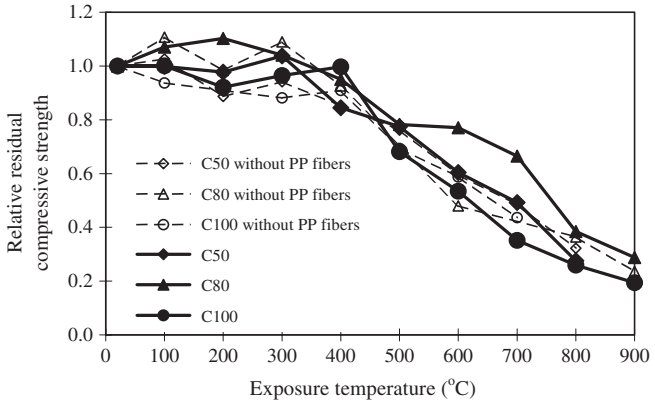

Fig. 5. Comparisons of the residual compressive strength of HPC.

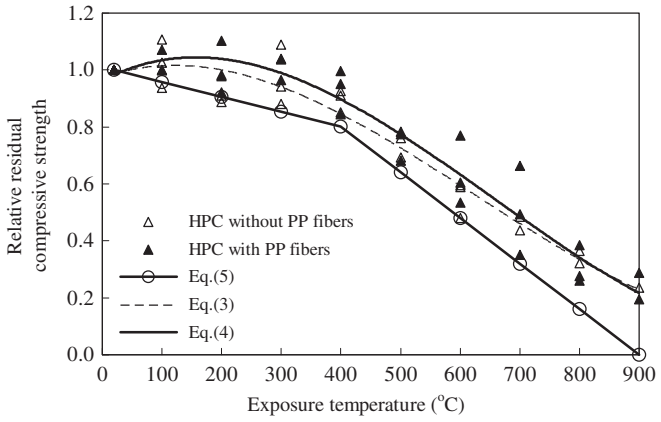

Fig. 6. Regression for the residual compressive strength of HPC.

compressive strength of HPCs at elevated temperatures, and the silica fume will have adverse effects beyond 400 °C.

In general, under the conditions of this experiment, the relative residual compressive strength of HPC with PP fibres was slightly greater than that of HPC without PP fibres. The main reasons may be explained as follows. PP fibres melt under high temperatures and form new channels to release the thermally induced pressures and, therefore, avoid excessive loss of compressive strength.

4.3. Relationship between residual compressive strength and exposure temperature

Without considering the different influences of the blast furnace slag and the silica fume, we have put all the data together and classified the results broadly under two categories—with and without PP fibres (as shown in Fig. 6). A third-order polynomial was then used to obtain regression curves for the relative residual compressive strength of HPCs at elevated temperatures. The regression analysis is shown in Fig. 6 and the corresponding formulae can be written as follows.

Without PP fibres:

$$f_{cu}^{T}/f_{cu}^{20} = 0.002(T/100)^3 - 0.03(T/100)^2 + 0.07(T/100) + 0.9737 \ (R = 0.97). \quad (3)$$

With PP fibres:

$$f_{cu}^{T}/f_{cu}^{20} = 0.002(T/100)^3 - 0.04(T/100)^2 + 0.11(T/100) + 0.9638 \ (R = 0.97). \quad (4)$$

For simplicity, and bearing the different degradation laws below and above 400 °C in mind, Eqs. (5a) and (5b) are recommended to estimate the relative residual compressive strength of HPCs, either with or without PP fibres. This associated curve to Eqs. (5a) and (5b) is also plotted in Fig. 6 for comparisons.

$$f_{cu}^{T}/f_{cu}^{20} = 1.011 - (T/1900), \quad T \leqslant 400\,^{\circ}\mathrm{C}, \quad (5a)$$

$$f_{cu}^{T}/f_{cu}^{20} = 1.440 - (T/625), \quad 400\,^{\circ}\mathrm{C} \leqslant T \leqslant 900\,^{\circ}\mathrm{C}, \quad (5b)$$

where T is the exposure temperature (°C), f_{cu}^{T} is the residual compressive strength of HPC at T, f_{cu}^{20} is the compressive strength of HPC at 20 °C and R is the correlation coefficient.

5. Flexural test results and discussion

5.1. Residual flexural strength

The flexural strength test was done by using an electronically controlled Universal Testing Machine CSS-44010, produced in Changchun, China. The adopted four-point loading method is in accordance with the Chinese standard GB/T50081-2002. The average values of the residual flexural strength of HPC prisms after heating are summarized in Table 3. It illustrates that under a rising temperature, the residual flexural strength decreases sharply and continuously, regardless of the presence of PP fibres.

5.2. Visual observations from rupture sections

After the flexural strength test, the appearance of the ruptured sections was carefully observed. The smoothness (i.e., the percentage of the cross-section areas of ruptured aggregates to those of all aggregates) of the ruptured sections for heated HPCs increased with increase in the strength grade, but decreased with increase of the exposure temperature. This phenomenon reflects that, with increase in the exposure temperature and concrete strength grade, the fracture energy of the interface between the aggregate and the cement paste will decrease. Compared with siliceous aggregates, the calcareous aggregates were more easily ruptured, which may be due to the fact that the interface between calcareous aggregate and paste was better than that between the siliceous aggregate and paste at elevated temperatures.

The colour change of the ruptured sections was also examined. When the temperature was lower than 400 °C, the colour in the centre part of the ruptured section was almost the same as on the surface. The colour distribution

Table 3
Summary of the residual flexural strength (unit: MPa)

Exposure temperature (°C)	C50		C80		C100	
	Without PP fibres	With PP fibres	Without PP fibres	With PP fibres	Without PP fibres	With PP fibres
20	5.54	5.99	5.90	6.26	6.26	7.18
100	5.80	5.33	4.97	6.50	6.76	7.00
200	5.80	5.80	5.68	6.30	3.34	5.12
300	4.22	3.77	5.00	5.11	4.39	3.77
400	2.91	2.84	3.77	3.90	2.41	2.98
500	1.94	2.02	2.86	2.61	1.39	1.02
600	1.08	0.83	1.96	1.80	0.37	1.78
700	0.61	0.76	/	1.29	/	0.33
800	0.69	0.50	/	0.77	/	0.15
900	0.45	0.50	/	0.51	/	0.10

Note: / refers to explosive spalling; occurred more than once within three prisms.

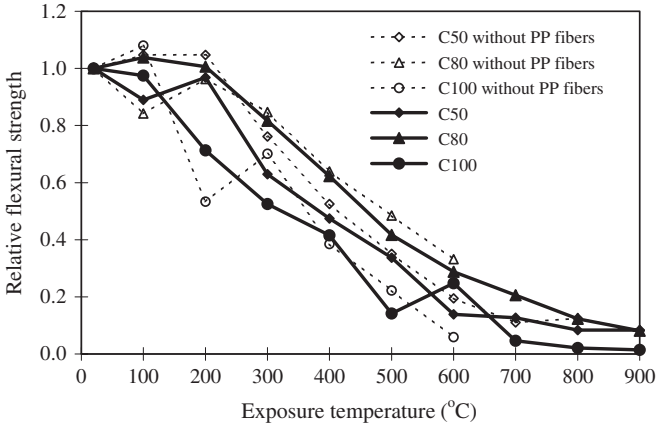

Fig. 7. Comparisons of the residual flexural strength of HPC.

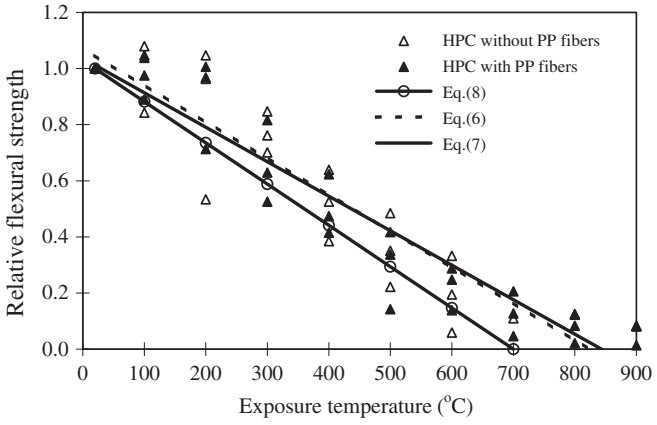

Fig. 8. Regression for the residual flexural strength of HPC.

was non-uniform within cross-sections when the temperature was beyond 500 °C. Generally speaking, the concrete in the centre within a ruptured section was darker than that on the border. In brief, PP fibres had only nominal effects on the colour change within a cross-section for specimens being subjected to elevated temperatures ranging from 100 to 900 °C.

5.3. Discussion on residual flexural strength

The relationship between the relative flexural strength (i.e., the ratio of residual flexural strength at elevated temperature to the initial flexural strength at ambient temperature) and the exposed temperature is presented in Fig. 7. It shows that: (1) the residual flexural strength of HPCs after exposure to high temperatures decreases approximately linearly with the increase of exposure temperature; (2) the influence of PP fibres on the residual flexural strength for each grade of HPCs after exposure to high temperature is insignificant; and (3) the blast furnace slag enhances the residual flexural strength of HPCs after exposure to high temperature, whereas the silica fume causes a reduction.

5.4. Relationship between residual flexural strength and exposure temperature

If the different effects of blast furnace slag and silica fume are not considered, one can classify all the data (including C50, C80 and C100) into two categories, i.e., with PP fibres and without PP fibres. By adopting a linear fitting formula to obtain a regression equation for the relative residual flexural strength of HPCs after exposure to high temperature, we obtained the following two formulae (as shown in Fig. 8).

Without PP fibres:

$$f_f^T/f_f^{20} = 1.0732 - 0.0013\,T\ (R = 0.92). \quad (6)$$

With PP fibres:

$$f_f^T/f_f^{20} = 1.0366 - 0.0012\,T\ (R = 0.95), \quad (7)$$

where T represents exposure temperature (°C), f_f^T represents the residual flexural strength of HPC at T, f_f^{20} is the flexural strength of HPC at 20 °C and R is correlation coefficient.

For simplicity, Eq. (8) is recommended to estimate the residual flexural strength of HPCs with or without PP

fibres. This associated curve to Eq. (8) is also plotted in Fig. 8 for comparison:

$$f_f^T/f_f^{20} = 1.0 - (T - 20)/680. \quad (8)$$

6. Conclusions

This study presents a series of experiments to investigate the residual strength of HPCs after exposure to elevated temperatures. It was found that:

(1) When mixed with polypropylene (PP) fibres, the mass loss of the heated HPC is slightly higher. In general, the mass loss for HPC can be classified into three categories, regardless of the presence of PP fibres. Below 100 °C, the mass loss is relatively small, while it becomes significant when temperature rises from 100 to 300 °C. Beyond 300 °C, the rate of mass loss slows down. Eqs. (1) and (2) are proposed to predict the mass loss of HPC with and without PP fibres, respectively.
(2) Regardless of the presence of PP fibres, there is an obvious falling point in terms of the residual compressive strength of HPCs at 400 °C. PP fibres increase the relative residual compressive strength of HPCs. Eqs. (3) and (4) are proposed to predict the residual compressive strength of HPC without and with PP fibres, respectively. For simplicity, Eq. (5a) and (5b) is recommended to cater for HPCs either with or without PP fibres.
(3) Unlike the residual compressive strength, the residual flexural strength of HPCs without and with PP fibres always drops continuously under rising temperatures. The residual flexural strength of HPC without and with PP fibres can be calculated by the proposed Eqs. (6) and (7), respectively. Similarly, Eq. (8) is recommended for HPCs either with or without PP fibres.
(4) The blast furnace slag is beneficial to the residual compressive and flexural strengths of HPCs with and without PP fibres after fire exposure, compared to silica fume.

Briefly, these tests show that except for the mass loss, the addition of PP fibres in HPCs has no negative effects on the residual compressive and flexural strengths of HPCs after exposure to high temperatures. However, the influences of higher content of PP fibres on the residual mechanical behaviour are still unclear. This deserves a further investigation.

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