INVESTIGATION ON STRENGTH AND TOUGHNESS OF FRHPC AFTER EXPOSURE TO HIGH TEMPERATURE

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Abstract

The investigations on different fibre influences on the compressive strength, the flexural strength and ductility as well as failure pattern of fiber reinforced high-performance concrete (FRHPC) after exposure to various high temperature were carried out. The results indicated that the compressive strength of HPC without fibres declined strongly after high temperature at 900^{o}C, the residual compressive strength was only 10% compared to the original strength. However, both steel fiber (SF) and polypropylene (PP) fiber can reduce the negative effect of high temperature on the strength. The micro PP fiber can mitigate the surface spalling of HPC member significantly, but did not show clear effect on the flexural toughness of concrete matrix. In contrary, the HPC reinforced with macro steel fiber illustrated higher flexural toughness and ultimate load bearing capacity before and after high exposure temperatures. The mechanical properties of HPC reinforced with fibre cocktail (SF + PP) were better than that of HPC reinforced with mono-fibre. Besides, the failure mode of FRHPC beams changed from pull-out of steel fibers at lower temperature to tensile failure of steel fibers at higher temperature (900 ^{o}C).

Keywords: fiber reinforced high-performance concrete (FRHPC); high temperature; compressive strength; flexural toughness; failure pattern

1. INTRODUCTION

Dense microstructure of traditional high strength concrete (HSC) shows high strength and low permeability, which is important to achieve good durability. Despite some advantages, one of the major weaknesses of HSC is the high brittleness. The addition of steel fibres may compensate the inherently brittle property of HSC and change the traditional HSC to high performance concrete (HPC). In addition, the dense microstructure of HSC also brings more degradation than normal concrete, such as spalling under fire, and the buildup of high internal vapour pressure in the dense matrix has been suggested to be the major cause[1].

Steel fiber can be used to improve the toughness of concrete obviously[2-6]. Polypropylene (PP) fiber can reduce the spalling, however, minimal or even negative effects of PP fiber on the strength of HPC before or after exposure to high temperatures were also observed [6-8]. The combination of PP fiber and steel fiber have been used to reduce spalling and to enhance the residual compressive strengths[9-10]. Recently, numerous studies have been conducted on the physical, mechanical behaviors as well as fire properties of concrete and fiber reinforced concrete (FRC), and the studies are mainly concentrated on the fields of compressive strength loss, spalling behaviour and the microstructure after high temperature[11-15]. However, the investigations on the flexural toughness as well as the load bearing capacity of HPC reinforced with hybrid fibers (steel fiber + PP fiber) after the high-temperature exposures are rare, and the study on the connection among the microstructure, spalling and the flexural toughness are also restricted. In this study, the effects of fibers on the compressive strength, flexural strength and flexural toughness of HPC before and after the high-temperature exposures are investigated. In particular, the effects of high temperatures on the failure patterns of FRHPC beams in bending have been also analyzed.

2. EXPERIMENT

2.1 Materials

In this program, the mix design of FRHPC was as follows: cement CEM I 42.5 500 kg/m³, fly ash 100 kg/m³; natural medium coarse sand 1 – 4 mm, aggregate crushed limestone with particle size between 5 and 12 mm, Superplasticizer from1% to 1.5%, water/binder ratio 0.37. The matrix proportion was 1 : 0.2 : 1.53 : 1.53 for cement, fly ash, sand, and coarse aggregate, respectively. Generally, the investigated fibres can be divided into micro fibres (l < 3 cm) and macro fibres (l ≥ 3 cm). The micro PP fibres are mainly used to decrease the shrinkage cracks before heating and to reduce the spalling at the high temperature. The macro steel fibres are used for increasing the flexural toughness before heating and to enhance the load bearing capacity during and after the high temperature. Different fibre types and fibre contents have been added into the mixture as follows:

- PP-fibre B, (l = 15 mm, d=0.03 mm), density = 0.91 g/cm³; tensile strength 450 N/mm^2; Fibre content 1 - 3 kg/m³;
- Steel fibre C (l = 35 mm, d = 0.55 mm), density = 7.8 g/cm³; tensile strength 1200 N/mm^2; Steel fibre content 40 kg/m³ and 55 kg/m³;

The various fiber contents of different mixtures and the compressive strengths of different mixtures before heating are listed in Table 1.

Table 1: Fiber content, slump flow and compressive strength (kg/m^3)

Mixtures	HPC	PP1	SF40	SF55	HF403	HF552
PP fiber content		1	-	-	3	2
Steel fiber content			40	55	40	55
Slump flow (mm)	678	632	662	646	594	608
Compressive strength(28d) (MPa)	64	60	64	65	63	65

2.2 Specimens and test

The slump flow of various fresh mixtures with different fibre contents and fibre types is tested and listed in Table 1, all the values of the slump flow are close or larger than 60 cm. That means that all the mixtures show good flowability and fulfill the requirement for HPC. 24 specimens for each mixture, including 12 cubes (100×100×100 mm) and 12 beams (100×100×400 mm) are cast in steel molds. The specimens are cured in a water tank between 17 ^{o}C to 22 ^{o}C until 28 days. Three of the cubes and three of the beams in each mixture were tested immediately under the temperature of 20 ^{o}C, and the results have been referred to as unheated. The remaining nine cubes and nine beams were subjected to three different temperatures in an electrical furnace: three cubes and three beams to 300 ^{o}C, three cubes and three beams to 600 ^{o}C and three cubes and three beams to 900 ^{o}C. In the furnace, all the specimens are heated at a constant rate of 6 ^{o}C/min and the peak temperatures are maintained for 3 hours. After heating, the specimens are cooled to the room temperature, the tests of the residual compressive strength, the residual flexural load bearing capacity and the failure pattern are carried out.

All the beams are notched at midspan[16]. The width and depth of the notch were 3 mm and 15 mm, respectively, and the span length of the three point bending test beam is 300 mm. A close loop test machine is used and the deflection is measured using two linear variable displacement transducers (LVDT). The deformation rate of the midspan is 0.2 mm/min and the deflection is terminated up to 3.5mm. The load-deflection curves are used to evaluate the flexural strength and flexural toughness of FRHPC.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 RESIDUAL COMPRESSIVE STRENGTH

The compressive strengths of HPC with or without fibres before heating after 28 days are illustrated in Table 1. The compressive strengths of all samples exceed 60 N/mm^2. Therefore, the mixtures meet the strength requirement of HPC[4] . It can be seen that the PP fibers show lightly negative influence on the compressive strength for HPC. Generally, the addition of fibres aids in converting the brittle properties of concrete into a ductile material, but no significant trend of improving compressive strength was observed[2-4]. The compressive strength of all the samples exceeded 60 N/mm^2 after 28 days.

Fig. 1 shows the results of compression tests of all mixtures with different fibers before and after various high temperatures. It can be seen that HPC and FRHPC demonstrate the similar decreasing trend. In order to analyze the loss of compressive strength after heating, a concept of “relative residual compressive strength $f_{cu,T}/f_{cu}$” is introduced[8], where $f_{cu,T}$ is the compressive strength after different high temperatures, and f_{cu} is the compressive strength before heating.

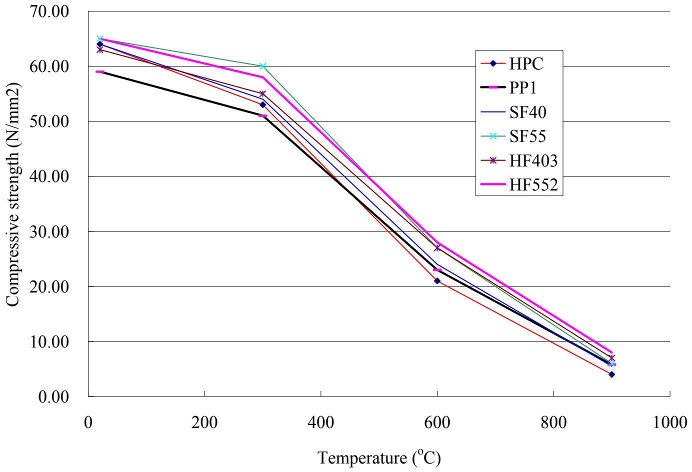

Fig. 1 Development of compressive strength of FRHPC after various heating temperatures

Table 2 illustrates the relative residual compressive strength of HPC and FRHPC with different fibre types and fibre contents. The various high temperatures induce the loss of strength for HPC and FRHPC. For HPC without fiber, it showed the strongest loss in strength after exposure to high temperatures. For the exposure temperatures of 300 °C, 600 °C and 900 °C, the residual compressive strengths were 83%, 32.8% and 6.3% of its original strength before heating, respectively. The fast loss in compressive strength for HPC is partly due to its dense microstructure, which restricts the ability of releasing the vapor pressure from the pore and leads to the buildup of high internal pressure during heating.

Table 2 Relative residual compressive strength of HPC and FRHPC

fcu,T/fcu (%)	20°C	300 °C	600 °C	900 °C
HPC	1	82.81%	32.81%	6.25%
PP1	1	86.44%	38.98%	9.83%
SF40	1	84.38%	37.50%	8.59%
SF55	1	92.31%	41.54%	9.23%
HF403	1	87.30%	42.86%	11.11%
HF552	1	89.23%	43.08%	12.31%

For FRHPC with PP fiber, their properties are improved significantly after exposure to high temperatures. As shown in Fig.1, when the maximum exposure temperature achieved 900 °C, the residual compressive strength was 9.83% of the original strength for PP1. In some studies[5, 8-9], PP fiber shows positive effect on the residual strength of concrete after the high-temperature exposures. The reason may be that PP fibers melt and vaporize due to the lower melting point (160-180°C) during the rapid temperature increasing process, which makes micro-channels in matrix. The strong tension stress in capillaries and compression stress in concrete matrix can be reduced.

Steel fibers can compensate the inherently brittle behaviour of high strength concrete, bridge and resist cracking in the matrix, mitigate expansion of concrete due to the rapid change of environmental temperature and the large temperature gradient, and then restrict the development of crack in HPC [2-12]. When the temperature reached up to 300 °C, 600 °C and 900°C, the relative residual compressive strengths of SF40 were 84.4%, 37.5% and 8.6% of the original value, the SF55 were 92.3%, 41.5% and 9.2%, and the SF70 were 91.1%, 42.5% and 9.3%[5, 8], from which the HPC with higher steel fiber content has higher residual compressive strength than that with lower one.

Generally under the heating process of this work, for maximum exposure temperatures below 300 °C, the loss in compressive strength was relatively low, more than 83% of the original compressive strength of all the mixtures can be maintained after firing. Significant further reductions in compressive strength are observed, as maximum exposure temperature increases to 600 °C, HPC samples start to suffer a greater compressive strength loss than fibre reinforced HPC (FRHPC), the residual compressive strengths of all hybrid fibre reinforced HPC samples (HF403 and HF502) and SF55 maintained more than 41% of the original strength of unheated samples. At maximum exposure temperatures of 900 °C, the strengths of all mixtures reached the minimum values; the HPC samples without fibre reinforcement kept only 6% of the original compressive strength; however, the residual compressive strengths of all hybrid fibre reinforced HPC samples (HF403 and HF502) maintained more than 11% of the original strength of unheated samples due to the positive hybrid effect between steel fibres and PP fibres.

3.2 FLEXURAL TOUGHNESS

The energy adsorption capacity of concrete in bending is defined as the area under the load-deflection curve calculated up to specified deflection values. In this study, RILEM TC 162-TDF[16] is used as references to evaluate the flexural toughness of HPC and FRHPC before and after exposure to different temperatures.

Fig. 2 – Fig.3 show the examples of load-deflection curves of different mixtures with or without fiber reinforcement in three-point bending test after exposure to the temperatures of 20, 300, 600 and 900 °C[5, 8]. Table 3 illustrates the calculated results of the flexural strength, ultimate load, energy absorption and equivalent flexural strength[16], where the values were averages of three specimens. It can be seen that the post-peak load bearing capacity of HPC without fibres drops faster than that of FRHPC. The FRHPC can absorb much more energy over the entire deflection zone than that of HPC without fibres. The ductility of beams becomes stronger with the increasing of steel fiber content of SFHPC. Furthermore, FRHPC with hybrid fibers exhibit superior flexural toughness compared to the mono fiber-reinforced HPC beams.

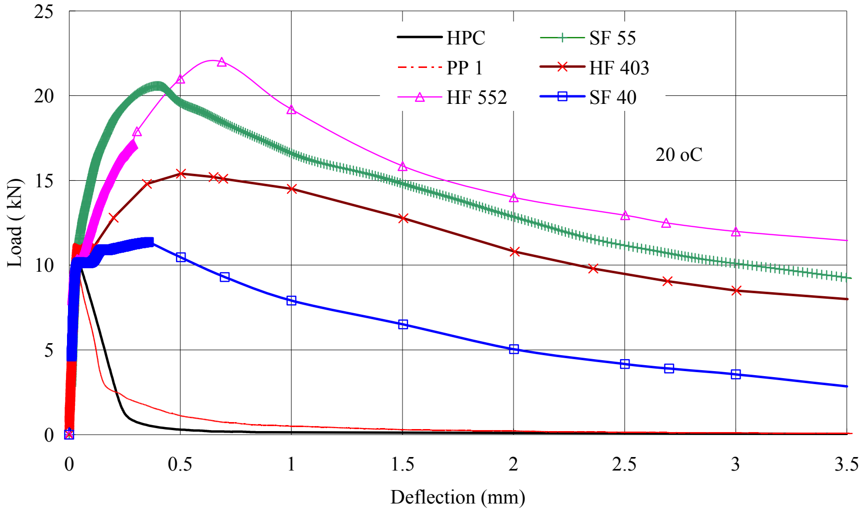

Fig.2: Comparison of load-deflection curves of FRHPC with different fibres before heating

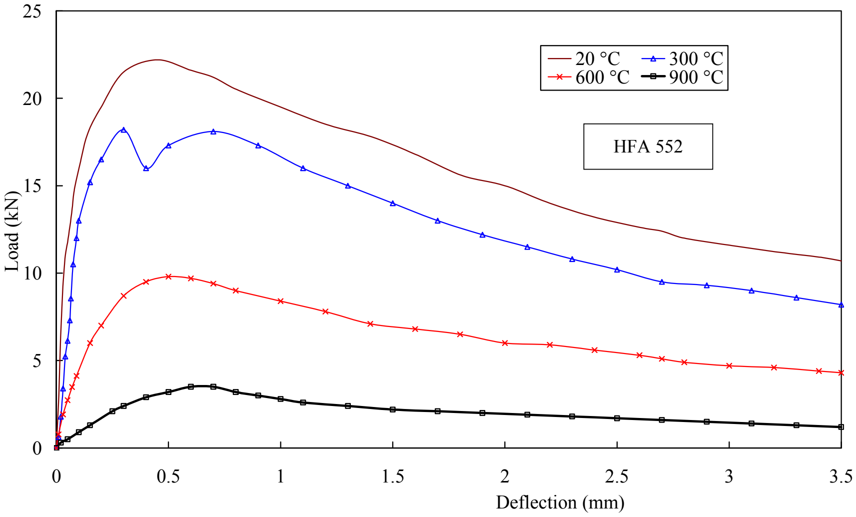

Fig.3: Comparison of load-deflection curves of hybrid fibre reinforced HPC samples under deferent temperatures.

At the room temperature before heating, HPC with 1kg/m^3 PP fibres indicates the similar flexural behaviour like HPC without fibres. HF552 shows the strongest ultimate load bearing capacity after cracking. After heating to different high temperatures, the flexural strength and flexural toughness of all mixes drop clearly with the increasing of the temperatures, and the higher the maximum exposure temperature is, the lower the flexural toughness is. In Table 3, it can be seen that $f_{fct,L}$, $D^f_{BZ,2}$, $f_{eq,2}$, $D^f_{BZ,3}$ and $f_{eq,3}$ decrease with the increasing of temperature, however, the values of toughness parameters with hybrid fibers are higher than that with mono fiber reinforced HPC.

Table 3 Flexural strength, ultimate load, energy absorption and equivalent strength of different mixes subjected to high temperatures

Specimens		F_L [kN]	$f_{fct,L}$ [Mpa]	F_u [kN]	D^b_{BZ} [Nmm]	$D^f_{BZ,2}$ [Nmm]	$f_{eq,2}$ [Mpa]	$D^f_{BZ,3}$ [Nmm]	$f_{eq,3}$ [Mpa]
20 °C	HPC	10.23	2.53	10.23	1790	1790	-	1790	-
	PP1	10.20	2.52	11.16	1785	3164	1.72	4544	0.69
	SF40	10.18	2.51	11.25	1781	7166	6.71	19402	4.39
	SF55	11.87	2.93	20.58	2077	12566	13.07	40723	9.63
	HF403	9.50	2.35	14.10	1663	8657	8.71	26577	6.21
	HF552	11.79	2.91	22.2	2063	13616	14.39	46359	11.04
300 °C	HPC	8.50	2.10	8.5	1368	1368	-	1368	-
	PP1	9.82	2.42	9.82	1625	2384	0.95	3332	0.43
	SF40	8.75	2.16	9.51	1531	5997	5.56	16692	3.78
	SF55	6.13	1.51	16.51	1072	9796	10.87	35275	8.52
	HF403	6.00	1.48	11.8	1050	7040	7.46	21035	4.98
	HF552	6.18	1.52	18.1	1081	10784	12.09	37544	9.08
600 °C	HPC	2.20	0.54	3.14	385	385	-	385	-
	PP1	2.61	0.64	3.90	460	1575	1.39	2149	0.42
	SF40	2.73	0.67	5.50	477	3223	3.42	9418	2.23
	SF55	2.67	0.66	8.40	467	4676	5.24	16866	4.09
	HF403	2.90	0.72	7.50	508	4310	4.74	14615	3.51
	HF552	2.73	0.67	9.80	478	5434	6.17	19124	4.65
900 °C	HPC	0.16	0.04	0.38	28	28	-	28	-
	PP1	0.23	0.06	0.48	41	586	0.68	536	0.12
	SF40	0.30	0.07	1.66	53	867	1.01	3251	0.80
	SF55	0.40	0.10	3.20	70	1456	1.73	5521	1.36
	HF403	0.50	0.12	2.60	88	1211	1.40	5146	1.26
	HF552	0.50	0.12	3.50	88	1643	1.94	6088	1.49

Where
F_u is the ultimate load; $f_{fct,L}$ is the flexural strength corresponding to F_L; D^b_{BZ} is the energy absorption capacity of concrete matrix alone; $D^f_{BZ,2}$ and $D^f_{BZ,3}$ are the energy absorption capacity of fiber reinforced concrete at the deflections of (δ_L + 0.65mm) and (δ_L + 2.65mm), respectively; $f_{eq,2}$ and $f_{eq,3}$ are the equivalent flexural strengths at the specified deflections of (δ_L + 0.65mm) and (δ_L + 2.65mm), respectively.

3.3 FAILURE PATTERN OF FRHPC

It is important to explain that PP fibers can mitigate the spalling of HPC and steel fibre can enhance the residual load bearing capacity of concrete under fire or at high temperatures, and that may be the precondition for using fibre cocktail in HPC.

3.3.1 STEEL FIBRE REINFORCED MATRIX

Fig.4 demonstrates the clear spalling damage of FRHPC beam with 40 kg/m^3 steel fibres after the maximum exposure temperature at 600 ^{o}C. Fig.5 shows the SEM analysis of steel fibres in the matrix of the same FRHPC beam after 3 hours heating at 600 ^{o}C. The interface cracks between steel fibres and matrix can be observed clearly.

Fig.4: Spalling of SF40 after 600 ^{o}C.

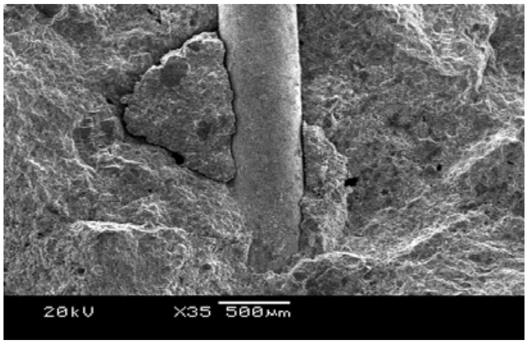

Fig.5: Steel fibre in the matrix after 600 ^{o}C.

The flexural toughness of SF40 beam after 600 ^{o}C is much stronger than that of PP1 (see Table 3). In addition, if the maximum exposure temperature is not exceeding 600 ^{o}C, the steel fibers are mainly pulled out from the matrix after the first crack[8]. The failure mode of FRHPC beams were mainly ductile. After maximum exposure temperature of 900 ^{o}C, the steel fibers are oxidized, which damaged the mechanic behaviour of steel fibres seriously, both bending beams and fibres are broken down very quickly and indicate strong brittle failure.

3.3.2 PP FIBRE REINFORCED MATRIX

Fig.6 demonstrates the HPC beam with 1 kg/m^3 PP fibre (PP1) after the maximum exposure temperature at 600 ^{o}C. Fig.7 shows the SEM analysis of the HPC matrix of beam PP1 after 3 hours heating at 600 ^{o}C. The traces caused by melted PP fibres in the HPC matrix can be observed clearly, which may provide the channels to release the water vapor pressure in the matrix pores for mitigating the explosive spalling (Fig. 7). Therefore, there is no visible spalling on the surface of PP1 beam (Fig. 6); even so, the post crack behaviour of mono PP fibre reinforced HPC beam after high temperatures are much lower than that of SF40.

Fig.6: No spalling of beam PP 1 after 600 °C

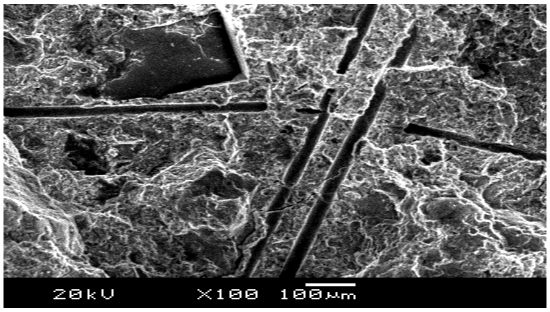

Fig.7: Micro channels due to melting of PP fibres after 600 °C

4. CONCLUSIONS

In this paper, the influences of various fibers on the residual strength, flexural toughness and failure pattern of HPC before and after the high temperature exposures have been investigated. The following conclusions can be drawn from the results:

- Fibers, especially hybrid fibers, can improve the relative residual compressive strength of FRHPC subjected to different high temperatures.
- Toughness parameters $D^f_{BZ,2}$, $D^f_{BZ,3}$, $f_{eq,2}$ and $f_{eq,3}$ of FRHPC are very sensitive to the steel fiber content and fiber types. For SFHPC, those factors increase with the increasing of steel fiber content, and hybrid fibers could result in superior flexural ductility compared to the mono fibre reinforced HPC after heating.
- After exposure to high temperature, the flexural strength and flexural toughness of all samples are dropped, and the higher the maximum exposure temperature, the lower the flexural toughness. Besides, the influences of fibre contents and fibre types on the flexural toughness of FRHPC at normal condition are similar to that after exposure to high temperature.
- For maximum exposure temperature of 900 °C, the steel fibers are oxidized strongly, the failure model of steel fiber changes from pull-out at lower temperature to tensile failure (broken down). The failure pattern of FRHPC beam changes from ductile pattern into brittle one.
- PP fibre can reduce the spalling, but it is not able to enhance the ductility of HPC. Steel fibre can enhance the ductility of HPC, but it is not able to mitigate the spalling damage of HPC during the heating. This observation supports the use of fibre cocktail in HPC as fire resistant materials.

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