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Communication

Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures

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Abstract

Residual strengths of high-strength concrete (HSC) and hybrid-fiber-reinforced high-strength concrete (HFRHSC) after exposure to high temperatures were investigated in the paper. The results showed that normal HSC is prone to spalling after exposure to high temperatures, and its first spalling occurs when the temperature approaches 400 °C. For HSC reinforced by high melting point fibers, the first spalling occurs when the temperature reaches to approximately 800 °C, while there is no spalling during exposing to high temperatures for HSC reinforced by polypropylene (PP) fiber with a low melting point. Mixing high melting point fiber (i.e., carbon or steel fiber) with low melting point fiber (i.e., PP fiber) HSC greatly improves the properties of HSC after exposure to high temperatures.

Keywords: HSC; High temperatures; Hybrid fiber; Residual strength

1. Introduction

Fire remains one of the serious potential risks to most buildings and structures. Since concrete is widely used in construction, research on fire resistance of concrete becomes more and more important. Many researchers all over the world have done some researches on this subject and made some progresses since Lea and Stradling's research [1,2] in 1920. With the increase of the application of high-strength concrete (HSC), more and more attentions are paid on the research on its fire resistance properties [3–5]. HSC has been found to be prone to spalling under high temperature. For the time being, there are two main explanations about the mechanism of spalling of HSC: one is thermal stress mechanism, i.e., spalling results from the thermal stresses due to rapid change of environmental temperature and large temperature gradient; the other is vapor pressure mechanism, i.e., the buildup of the high vapor pressure is due to inner moisture of concrete under high temperature [6,7]. Some possible methods to improve fireproof property of HSC have been developed correspondingly. Adding steel fiber in HSC, though limitedly reported, has been proved to be effective. Adding polypropylene (PP) fiber in HSC was good for decreasing possibility of spalling, but this has an adverse effect on strength. In this study, hybrid fibers were added in HSC and their compressive strength and split tensile strength under different high temperatures were investigated.

2. Materials and experimental study

2.1. Materials and mix proportions

Ordinary Portland cement in accordance with ASTM type 1 standard, river sand with a fineness modulus of 2.85, crushed limestone with particle size between 5 and 20 mm, superplasticizer, silica fume, and fly ash were used in this study. The chemical compositions of the cementitious materials, as provided by the suppliers, are shown in Table 1, where OPC, SF, and FA represent ordinary Portland cement, silica fume, and fly ash, respectively. Three types of fibers were used and their properties are listed in Table 2. Mix proportions of different series for concrete specimens are shown in Table 3, where, C, S, and P represent carbon, steel, and PP fiber, respectively. For concretes containing fibers, the

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Table 1
Chemical compositions of cementitious materials

	OPC	SF	FA
Chemical composition (%)			
Silicon dioxide (SiO_2)	21.6	92.4	50.66
Aluminum oxide (Al_2O_3)	4.13	0.80	35.58
Ferric oxide (Fe_2O_3)	4.57	0.50	5.11
Calcium oxide (CaO)	64.44	0.91	1.94
Magnesium oxide (MgO)	1.06	0.27	1.09
Sodium oxide (Na_2O)	0.11	–	0.40
Potassium oxide (K_2O)	0.56	–	0.34
Sulfur trioxide (SO_3)	1.74	–	0.37
Loss on ignition	0.76	2.0	4.07

Table 2
Properties of fibers

	Carbon	Steel	PP
Length (mm)	5	25	15
Diameter (um)	7	500	100
Shape	Straight, round	Crimped	Straight, round
Density (g/cm^2)	1.6	7.8	0.9
Modulus (GPa)	240	200	8
Elongation at break (%)	1.4	3.2	8.1
Tensile strength (MPa)	2500	1500	800

dosages of superplasticizer were increased properly to maintain the slump around 160 mm.

2.2. Casting, curing, and testing of specimens

For each concrete mix, 100 × 100 × 100-mm cubes were cast and wet cured for 24 h. Then, the specimens were demoulded and cured in the water with the temperature ranged from 15 to 25 °C. After 28 days of curing, the fully saturated specimens with average moisture content of 3.7% were taken out and dried to saturated and surface dry status with average moisture content of 3.5%. Then specimens were heated in an electric oven to peak temperatures of 20, 200, 400, 600, and 800 °C at the heating rate of 10 °C/min, respectively. The peak temperature was maintained for 3 h. After the specimens had been allowed to cool naturally to room temperature, the residual compressive strength and splitting tensile strength of the test specimens were determined.

3. Experimental results and analysis

3.1. Testing phenomena

When the temperature increased at the rate of 10 °C/min within 200 °C, only free water inside the specimens was evaporated. When the temperature reached to 400 °C, a lot of moisture began to evaporate, which resulted from dehydrations of C-S-H and AFt. White water mist emitted from the mouth of the oven and became thicker when maintaining peak temperature. After temperature exceeded 400 °C, the higher the temperature, the thicker the water mists. When maintaining peak temperature for 50 min after the temperature reached to 600 °C, water mists around the mouth of the oven almost disappeared, which indicated that the dehydrations of C-S-H and AFt were completed.

During the testing, different HSCs showed different phenomena. For normal HSC, the first explosive spalling occurred when temperature increased to 400 °C and then maintained it for 40 min. With the increase of time to maintain peak temperature, several explosive spalling occurred sequently. In addition, the higher the temperature, the severer the explosion. When temperature increased to 600 °C during the process of increasing temperature, the explosive spalling occurred in succession in normal HSC specimens. Significant rupture could be seen on the surface of specimens with splashing fragments. When temperature was up to 800 °C, most of specimens completely exploded and only a few concrete specimens could be used for strength tests. The fracture surfaces of explosive pieces were irregular and no damage along the coarse aggregate-matrix interface was detected.

In the oven for concrete with carbon fibers or steel fibers, the first explosive spalling occurred at the peak temperature maintaining stage of 800 °C; while for concrete with PP fiber, there was no explosive spalling during the whole process. Neither were concretes with hybrid fibers. It can be seen that adding fibers in HSC delays the time when spalling occurs or eliminates the spalling under high temperature.

3.2. Residual strength

Generally, exposure to high temperature resulted in loss of strength for HSC and fiber-reinforced HSC. Fig. 1

Table 3
Mix design for HSC and fiber reinforced HSC (kg/m^3)

Series	Cement	Water	Sand	Crushed limestone	Silica fume	Fly ash	Fiber volume fraction (%)			Strength at 28 days (MPa)
							Carbon	Steel	PP	
HSC	500	165	540	1158	50	50	–	–	–	82.1
HSC-C	500	165	540	1158	50	50	0.6	–	–	93.5
HSC-S	500	165	540	1158	50	50	–	0.6	–	88.5
HSC-P	500	165	540	1158	50	50	–	–	0.6	80.2
HSC-C-S	500	165	540	1158	50	50	0.3	0.3	–	107.8
HSC-C-P	500	165	540	1158	50	50	0.3	–	0.3	105.2
HSC-S-P	500	165	540	1158	50	50	–	0.3	0.3	86.3

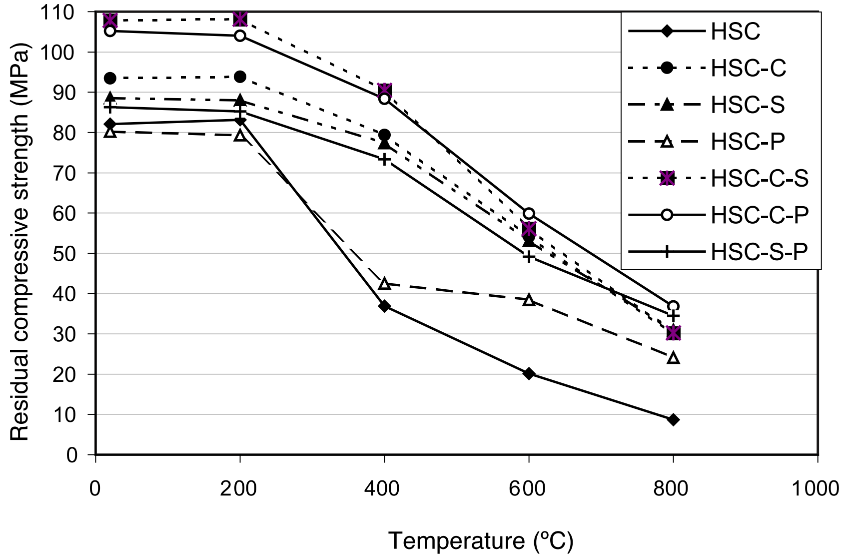

Fig. 1. Residual compressive strengths of HSC mixes after exposure to various peak temperatures.

illustrated residual compressive strengths of HSC mixes after exposure to different high temperatures. Within 200 °C, the changes of residual compressive strength values with the temperature for all types of HSC were consistent with those for HSC without exposure to high temperature, similar to that reported previously [8–10]. However, when temperature was higher than 200 °C, their strength values were different from the results for those without exposure to high temperature. For normal HSC, the strength values decreased significantly. When temperature reached to 800 °C, its residual strength was only 10% of original strength.

Because high elastic modulus fibers such as steel and carbon fibers bridge and resist cracking inside the concrete, they can control the volume change of concrete due to rapid change of environmental temperature and large temperature gradient and then mitigate the initiation and expansion of inner microdefects of concrete. It is also can be seen from Fig. 1. Adding carbon or steel fibers to HSC, the significant decrease of strength occurred after 400 °C. In addition, when temperature reached to 800 °C, the residual strengths were 32% and 38% of original values, respectively. For concrete with PP fibers, when temperature ranged at 400–600 °C, the loss of strength was not significant; however, after 600 °C, it was. When temperature reached to 800 °C, its residual strength was still 30% of original value. Therefore, adding fibers to HSC, to some degree, mitigated the deterioration of HSC after exposure to high temperatures.

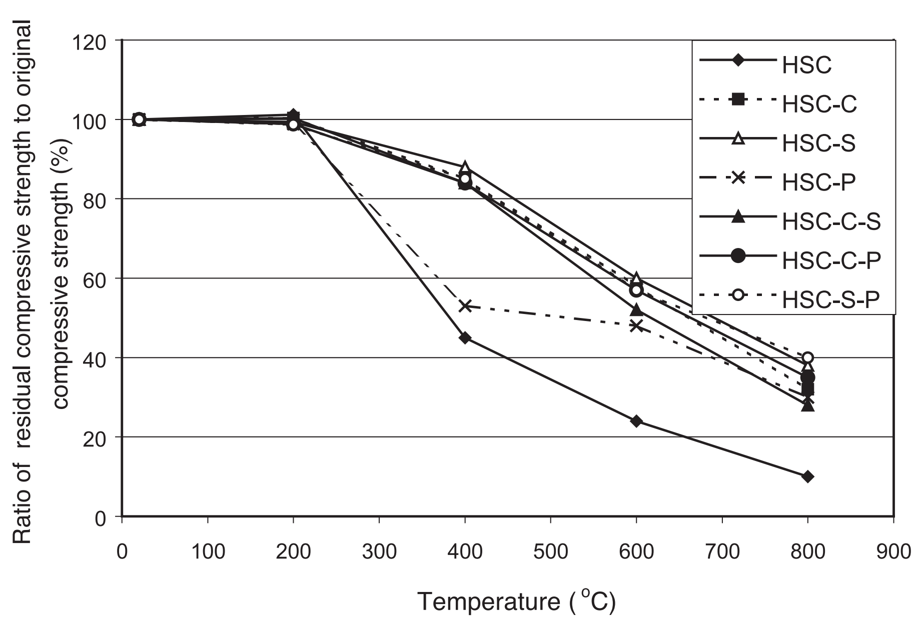

Fig. 2. Ratio of residual compressive strength of HSC mixes subjected to different peak temperatures to original compressive strength at 20 °C.

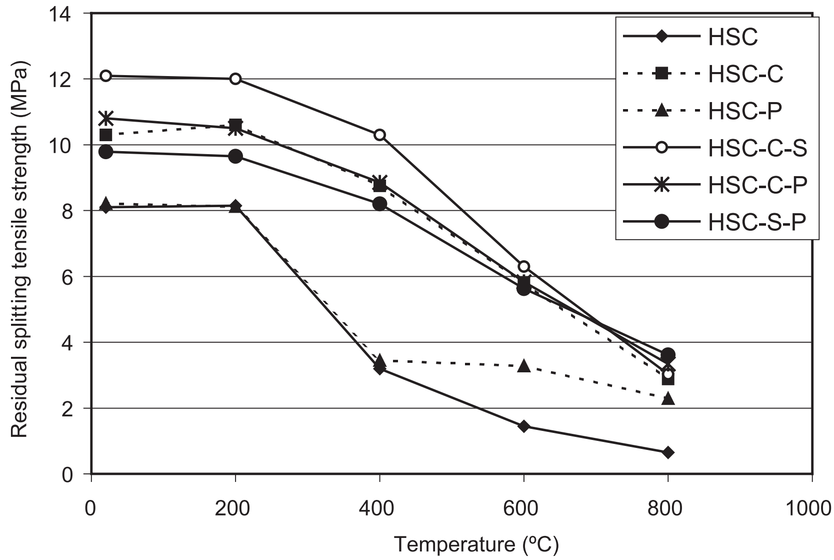

Fig. 3. Residual splitting tensile strength of HSC mixes after exposure to different peak temperatures.

For concretes with hybrid fibers, especially mixing with PP fiber, their properties exposure to high temperature improved significantly. As shown in Fig. 2, their residual strengths were around 36% of original strength, when the temperature was up to 800 °C. It may be because during the rapid temperature-increasing process, PP fibers melt and vaporize due to the lower melting point, which result in microchannels in the concrete. Thus, greater vapor tension in capillaries can be alleviated and released, which maybe the reason why there was no explosive spalling in HSC with PP fibers. In addition, carbon or steel fibers can to some degree, restrict the initiation and expansion of cracking in the concrete due to their tensile resistance, which maintain higher residual strengths of concretes after exposure to high temperature. However, the durability of concretes will deteriorate due to the change of pore structure in the concretes. In the study, HSC-C-S showed larger strength loss than HSC-S-P and HSC-C-P after exposure to high temperature. It may because that for HSC-C-S, the high vapor pressure due to inner moisture of concrete under high temperature cannot be released by microchannels, which results in more damage and cracking occurring in the concretes and then larger strength loss.

The residual split tensile strengths of HSC after exposure to high temperature with the temperature were shown in Fig. 3. The residual split tensile strengths showed the similar trends with the temperature as compressive strengths did. However, compared to fiber-reinforced HSC and normal HSC, adding fibers greatly improved the residual split tensile strengths, as shown in Fig. 4.

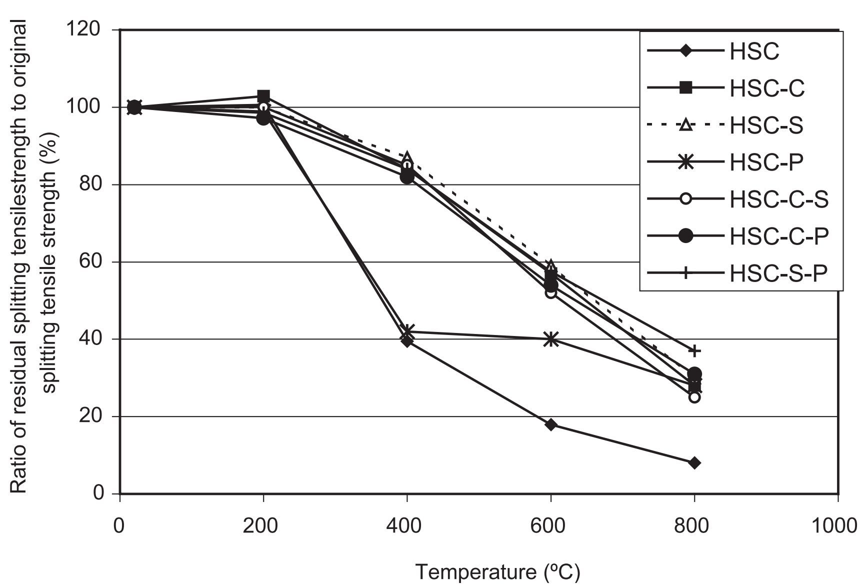

Fig. 4. Ratio of residual splitting tensile strength of HSC mixes subjected to different peak temperatures to the original splitting strength at 20 °C.

After temperature reached up to 800 °C, the residual split tensile strength of HSC with hybrid fibers (i.e., mixing steel and PP fibers) was around 40% higher than that of normal HSC.

4. Conclusion

Residual strengths of HSC and hybrid-fiber-reinforced high-strength concrete (HFRHSC) after exposure to high temperatures were investigated in the paper. Based on the scope of this study, the following conclusions are made:

1. There is explosive spalling for normal HSC when exposure to high temperatures. The higher the temperature, the severer the explosion. Adding carbon and steel fibers in HSC can delay the time when spalling occurs, while adding PP fibers can eliminate the spalling under high temperatures.
2. That higher residual compressive strengths and splitting tensile strengths of fiber-reinforced HSC than those of normal HSC indicates that adding fibers in HSC can alleviate the deterioration of mechanical properties of HSC exposure to high temperatures.
3. For concretes with hybrid fibers, especially mixing with PP fiber, their properties exposure to high temperatures improve significantly because the high vapor pressure due to inner moisture of concrete is released by microchannels due to melting of PP fiber under high temperatures.

In this study, all specimens are in saturated and surface dry status before exposed to high temperature. Since the moisture content of the specimen is one of the crucial environmental factors affecting the mechanical properties of HSC subjected to high temperatures [7], the effect of different degree of moisture saturation on the spalling occurrence should be addressed in further research.

References

[1] F.C. Lea, The effect of temperature on some of the properties of materials, Engineering 110 (1920) 293–298.
[2] F.C. Lea, R. Stradling, The resistance to fire of concrete and reinforced concrete, Engineering 114 (1922) 341–344.
[3] C. Castillo, A.J. Durrani, Effect of transient high temperature on high-strength concrete, ACI Mater. J. 87 (1) (1990) 47–53.
[4] Y.N. Chan, G.F. Peng, M. Anson, Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures, Cem. Concr. Compos. 21 (1999) 23–27.
[5] Y. Xu, Y.L. Wong, C.S. Poon, M. Anson, Impact of high temperature on PFA concrete, Cem. Concr. Res. 31 (2001) 1065–1073.
[6] G. Sanjayan, L.J. Stocks, Spalling of high-strength silica fume concrete in fire, ACI Mater. J. 90 (2) (1993) 170–173.
[7] Y.N. Chan, X. Luo, W. Sun, Compressive strength and pore structure of high-performance concrete after exposure to high temperature up to 800 °C, Cem. Concr. Res. 30 (2000) 247–251.
[8] H.L. Malhotra, Effect of temperature on the compressive strength of concrete, Mag. Concr. Res. 8 (1956) 85–94.
[9] U. Schneider, Concrete at high temperatures—A general review, Fire Saf. J. 13 (1988) 55–68.
[10] Y.N. Chan, G.F. Peng, K.W. Chan, Comparison between high strength concrete and normal strength concrete subjected to high temperature, Mat. Struct. 29 (1996) 616–619.