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Compressive Properties of Amorphous Metal Fiber Reinforced Concrete Exposed to high Temperature

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Abstract

Compressive property of high strength concrete with amorphous metal fibers subject to high temperature has been investigated. The measure of this investigation includes explosive spalling, weight loss, residual compressive strength, strain at peak stress, elastic modulus, and residual energy absorption capacity after exposure to 400℃, 600℃and 800℃. In addition to the amorphous metal fiber, two other types of fibers (polypropylene fiber and hooked-end steel fiber) were also included in this investigation for comparison. The experimental program was conducted with high strength concrete using several combinations of the fiber types. The testing result shows that the concrete with amorphous metal fibers plus polypropylene fibers shows a superior behavior than those using other combination or single fiber type ingredient.

Keywords : amorphous metal fiber, fiber reinforced concrete, explosive spalling, compressive material properties

1. Introduction

High strength concrete (HSC) is superior to normal strength one in terms of its mechanical strength, stiffness and also durability due to its intrinsic characteristic of microstructure, dense matrix with low volume of disconnected voids. However, this beneficial microstructure causes a critical problem, explosive spalling, when the material undergoes high temperature for a certain period of time. Under a high temperature condition, internal vapor pressure developed in isolated voids cannot be discharged through the dense structure hence initiates micro cracks and finally spalls abruptly [1].

In order to solve the explosive spalling problem, many researchers utilizes synthetic polymer, steel, or both fibers as an essential ingredient of high strength concrete. These types of fibers play different roles under high temperature environment. The synthetic fibers are melted at a certain level of temperature below the "spalling temperature" and provide some paths for the vapors. The discharged vapors through the paths reduce the internal vapor pressure and prevent the abrupt spalling. Although the synthetic fibers prevent the abrupt spalling, they cannot improve the residual strength due to the additional voids, the paths [2]. On the other hand, steel fibers confine the concrete matrix and improve the tensile strength of the composite hence show a good residual strength. However, in many cases, the steel fiber composite shows the spalling when exposed to high temperature [3]. The remedy of the weakness of each fiber composite is the use of both fibers in concrete, i.e. synthetic fibers

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prevent the spalling and steel fibers strengthen the composite material [4].

Although the steel fibers provides a good performance in the residual strength, mechanical properties of steel are dramatically degraded at high temperatures hence the benefit of the steel fiber in concrete is not as good as in room temperature. In this sense, if one finds a better performing metallic fiber in high temperatures, one may produce a better performing concrete. In other words, a fabric metal material showing less degradation in mechanical properties at high temperatures may enhance the overall performance of HSC under high temperature and also in the residual performance. One of the candidates for the replacement of the steel fiber could be amorphous metal fibers (AMF).

Usual metals including steel have highly ordered atomic-scale structure which means they are highly crystalline. The crystalline of metal limits the gain of mechanical properties due to the intrinsic defects such as dislocations. In contrast to this, an amorphous metal has disordered non-crystalline atomic-scale structure hence it is literally free from the defects and shows much better mechanical properties such as high strength, high elastic moduli, high resistance to wear and corrosion, etc. With this benefit, some researchers tried to replace steel fibers with amorphous metal fibers (AMF) for a room temperature application and showed the superior performance than steel fiber reinforced concretes [5].

It is reported, under a high temperature condition, some proportion of amorphous metal experiences phase changes and turns into a crystalline structure but some other proportion of the material still remains in non-crystalline structure[6], hence we expect the benefit of amorphous metal even in a higher temperature condition. Therefore, in addition to room temperature applications, we may also expect a better performance of HSC with AMF under high temperature since the fabric material (AMF) will show less degradation than normal steel fibers.

This study is intended to assess the compressive material behavior of HSC with AMF under high temperature condition to establish basic data with which evaluate the residual strength of a structure in a fire. The compressive behavior evaluated in this study includes the residual compressive strength, elastic modulus, and residual energy absorption capability.

2. Experimental program

2.1 Design of experiment

Although the main interest of the study is the performance of HPC with AMF under high temperature condition, we also included several concrete materials with various fiber mixture conditions into the experimental program in order to compare the performance with each other.

The details of experimental program are shown in Table 1. The experimental program designed for one plain concrete (HPC), three single fiber FRCs (PHPC, SHPC and AHPC), and two hybrid fiber FRCs (PSHPC and PAHPC).

The mixture proportion of the plain concrete is shown in Table 2. The plain concrete was designed to achieve a 28-day compressive strength of about 60MPa. The concrete mixture was prepared at a water-to-binder ratio of 0.26. The mixture proportions of concrete were determined to satisfy air content of 3.5±1.0% and target slump-flow of 550±150mm.

The fiber contents used were 0.91kg/m^3(0.1% by volume) for the polypropylene fibers, 7.85kg/m^3 (1.0% by volume) for the steel fibers and 3.7kg/m^3 (0.5% by volume) for the amorphous metal fibers.

The hybrid mixes included the polypropylene fibers were the combination of 50% of the previous contents for respective fiber types, i.e., 0.45kg/㎥ of polypropylene fibers plus 3.9kg/㎥ of steel fibers and 0.45kg/㎥ of polypropylene fibers plus 1.8kg/㎥ of amorphous metal fibers.

Table 1. Experimental design of fiber reinforced concrete materials

Type	W/B (%)	Air content (%)	Admixture (%)	Slump flow (mm)	Fiber (vol.%)		
					PPF	SF	AMF
HPC	26	3.5±1.0	10	550 ±150	0	0	0
PHPC					0.10	0	0
SHPC					0	1.0	0
AHPC					0	0	0.50
PSHPC					0.05	0.5	0
PAHPC					0.05	0	0.25

NOTE: Admixture=silica fume PPF=polypropylene fibers, SF=steel fiber, AMF=amorphous metal fiber

Table 2. Mixture proportion for plain concrete

W/B (%)	S/a (%)	SP (%)	Unit weight(kg/㎥)			
			Binder		S	G
			OPC	Silica fume		
26	42	1.0	597	59	702	961

NOTE: W/B= water to binder ratio, S/a=sand to coarse aggregate ratio, SP=superplasticizer, OPC=ordinary Portland cement, S=Sand, G=Gravel

2.2 Materials

The cementitious materials used in this study were ordinary Portland cement (OPC) equivalent to KS L 1201 Type I and silica fume with a grain size of 0.15㎛. A usual river sand and crushed granite stone with maximum size of 13mm was used as fine and coarse aggregates, respectively. A superplasticizer based on polycarbonic acid was used at a dosage from 1.0%~1.5% of binder contents in order to maintain slump of mixtures. Figure 1 shows the shape of each fiber used in this study. The polypropylene fibers have a length of 19mm with aspect ratio of 475. The steel fibers were hooked-end fibers with a length of 50mm and aspect ratio of 71. The amorphous metal fibers were amorphous Fe-base metals with a length of 30 mm and thickness of 0.026 mm. The physical properties of each fiber are presented in Table 3 through Table 5.

Table 3. Properties of polypropylene fiber

Type	Melting Temp.	Diameter (mm)	Length (mm)	Aspect ratio	Density (g/㎥)	Tensile strength (MPa)
Straight	165	0.04	19	475	0.91	550

Table 4. Properties of steel fiber

Type	Diameter (mm)	Length (mm)	Aspect ratio	Density (g/㎥)	Tensile strength (MPa)
Bundle (Hooked end)	0.7	50	71	7.85	1,100

Table 5. Properties of amorphous metal fiber

Type	Specific gravity (g/㎥)	Thickness (mm)	Width (mm)	Length (mm)	Tensile strength (MPa)
Straight	7.4	0.026	0.2	30	1,700


(a) (b) (c)

Figure 1. Shape of fibers; (a) Polypropylene fiber, (b) Steel fiber (c) Amorphous metal fiber

2.3 Specimen preparation and test

A pan mixer was used for mixing concrete. As for the fresh concrete properties, the value of slump-flow was measured after slump test carried out according to ASTM C143 [7], and also air contents of all mixtures were measured according to ASTM 231 [8].

For each mixture, a total of twelve 100 mm (diameter) × 200 mm (height) cylinders were cast in steel moulds. Specimens were cured in a temperature controlled water bathe at 20±3℃until the age of 27 days, and then kept in air for 1 day.

Compressive strength test was carried out according to ASTM C39 with three specimens [9]. The axial deformations were measured using two LVDTs mounted on opposite sides of the specimen with a gage length of 50 mm, according to JSCE-SF5 [10]. Figure 2 shows the test setup for measuring deformation.

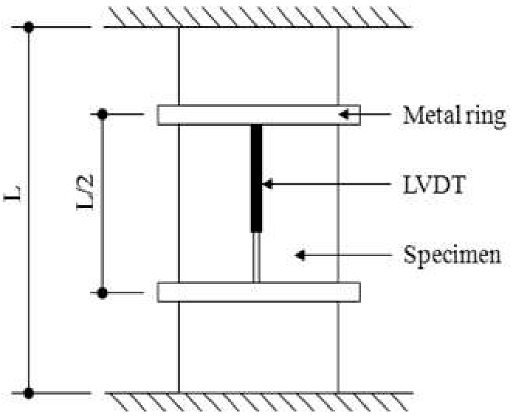


Figure 2. Test setup for measuring deformation

The remaining nine specimens were subjected to three temperature exposure conditions in an electric furnace. Three were heated to 400℃, other three to 600℃, and the other three to 800℃. This study did not include the heating temperature of 200℃ since it has been shown in the previous studies that heating to temperature of 200℃ does not have significant effects on compressive strength of concrete [11,12,13].

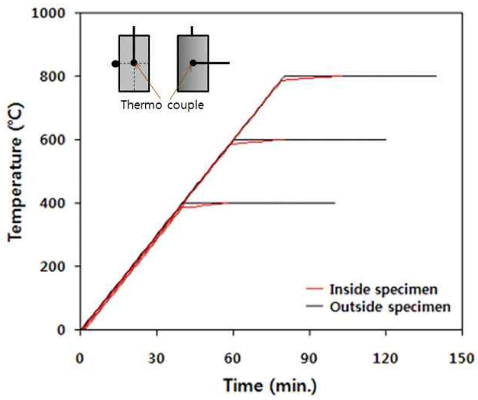


Figure 3. Temperature curve of specimen

Specimens were heated in an electric furnace at the rate of 10℃/min until reaching target temperature. The target temperature was maintained for 1hr. The duration of 1hr was based a preliminary investigation which showed temperature at the center of a specimen rose gradually to the target temperature from the first 20 minutes during the 1 hr period for maintaining temperature. After the 1 hr duration, the specimens were left in the furnace for 40 minutes until electric heating was turned off. Figure 3 shows the temperature curve of a specimen. After exposure to the high temperatures, the uniaxial compressive test was conducted as the same way to the unheated concrete specimens. The weight loss of each specimen was also measured.

3. Experimental Result

3.1 Characteristics of fresh concrete

Table 6 shows the characteristics of fresh concrete according to the type of mixed fiber. The air content and slump flow satisfy the target values, but they vary according to the fiber types within the target range. The slump flow was lowest in the concrete mixed with amorphous metal fiber (AHPC and PAHPC). It seems that the amorphous metal fiber reduces the fluidity of concrete because its specific area is larger than those of PP fiber and steel fiber.

Table 6. Properties of fresh concrete

Type	Air contents (%)	Slump flow (mm)
HPC	4.2	690
PHPC	4.3	640
SHPC	4.1	570
AHPC	3.9	440
PSHPC	4.0	520
PAHPC	3.8	440

3.2 Characteristics of hardened concrete at room temperature

Figure 4 shows the compressive stress-strain curve of the hardened concrete at room temperature according to the type of the mixed fiber. Based on these stress-strain curves, several mechanical properties are extracted including compress strength, strain at peak stress, area under stress-strain curve, specific toughness ratio. Table 7 shows these properties according to the fiber type.

3.2.1 Strain at peak stress

The concrete mixed with fiber had 0.01-0.04% higher strain values than the concrete with which no fiber was mixed. This seems to have been because of the fine cracks and the confinement effect of the reinforcement fiber on the concrete under the compressive stress, as in the results of previous studies [14]. The strain at maximum compressive stress was largest when the concrete was mixed with PP fiber and steel fiber (PSHPC). When the fibers were hybridized, the strain under maximum stress was 0.02-0.03% higher than when only one fiber was mixed.

Table 7. Test results for unheated concrete

Type	Compressive strength (MPa)	Strain at peak stress (%)	Area under stress-strain curve (MPa×10^{-2})	Specific toughness ratio (%)
HPC	75.83	0.25	18.15	0.24
PHPC	59.73	0.26	22.72	0.38
SHPC	76.44	0.26	36.49	0.48
AHPC	65.95	0.27	32.45	0.49
PSHPC	67.48	0.29	28.76	0.43
PAHPC	71.73	0.28	31.79	0.44

3.2.2 Compressive strength

Figure 5 shows the compressive strength of hardened concrete at the age of 3, 7 and 28 days. All the test specimens other than SHPC showed lower compressive strength compared to the control mixture regardless the material age. The compressive strength of PHPC showed the largest decrease (21.2%) from that of control mixture. The compressive strength of AHPC is decreased by 13.0% from the control mixture. On the other hand, SHPC showed 0.8% strength increase. The compressive strength of PSHPC showed a decrease of 11.0% from the control mixture, which was larger than SHPC. The compressive strength of PAHPC showed a decrease of 5.4% from control mixture, which was smaller than PHPC.

3.2.3 Compressive toughness ratio

Figure 6 shows the definition of the compressive toughness ratio of the fiber-reinforced concrete. The compressive toughness is defined as the area below the stress-strain curve (A) at the reference strain. The toughness ratio is calculated by dividing A by the maximum compressive strength [15]. In this study, with the strain of 0.75% that had been used in JSCE-SF5 and previous studies of Nataraja [16] and C.S. Poon[4] as the reference, the area below the stress-strain curve was calculated to evaluate the compressive toughness ratio.

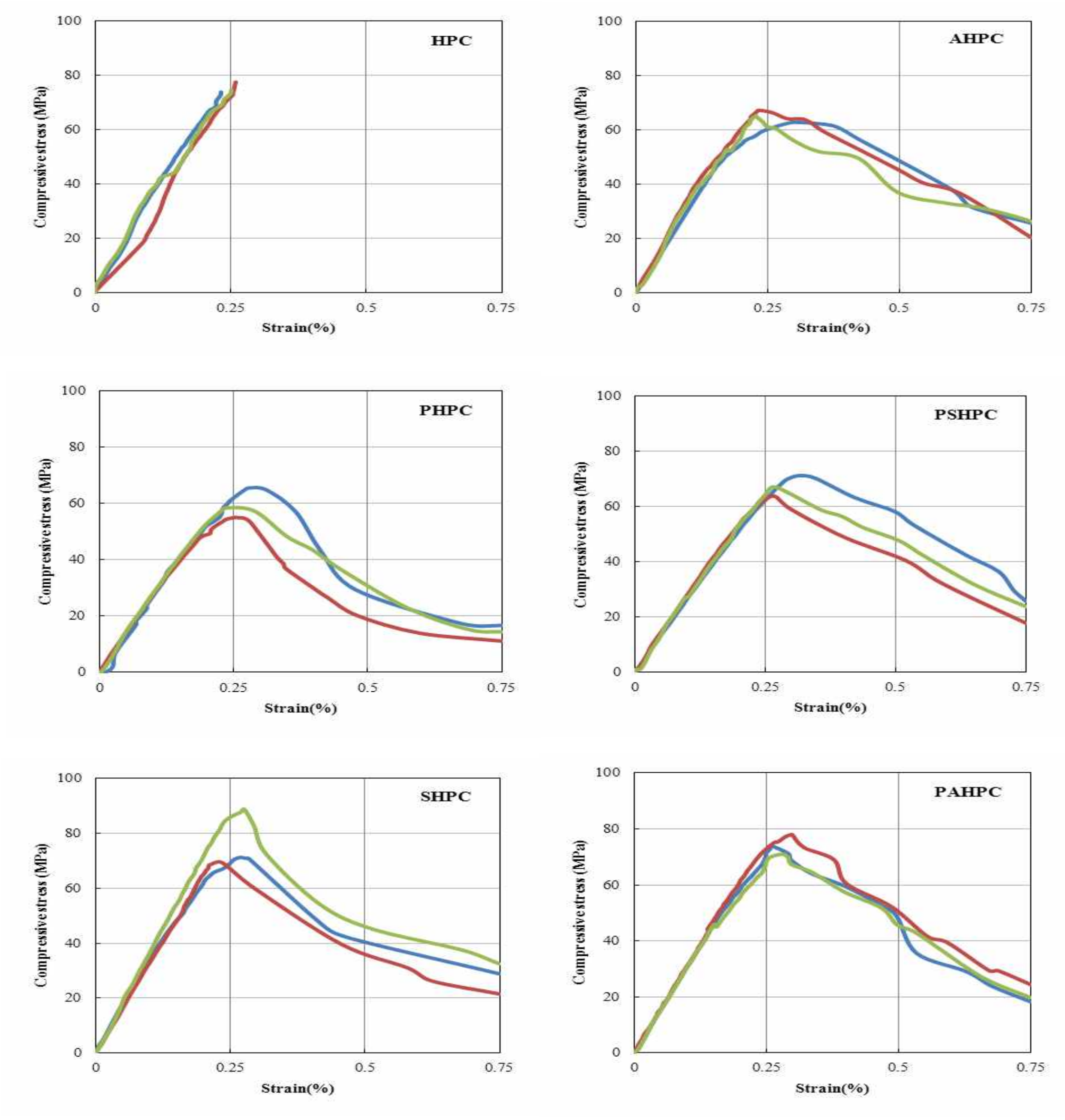


Figure 4. Stress-strain curves for unheated concrete materials

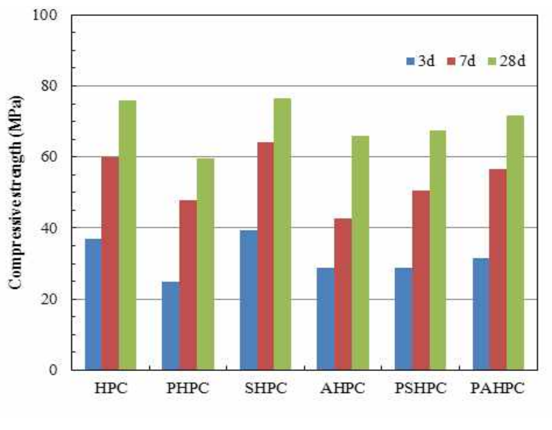


Figure 5. Compressive strength of unheated concrete

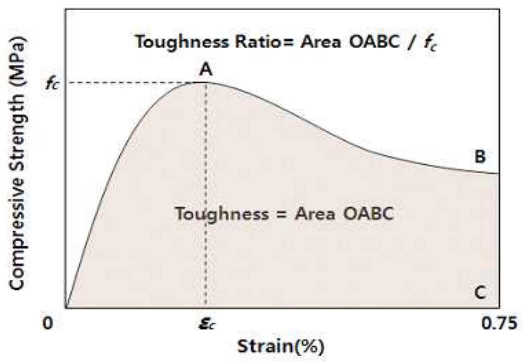


Figure 6. Definition of compressive toughness

Figure 7. Occurrence of explosive spalling

Type	HPC	PHPC	SHPC	AHPC	PSHPC	PAHPC
400°C						
600°C	N/A		N/A	N/A		
800°C	N/A		N/A	N/A		

Table 7 shows the evaluation results. The results showed that the compressive toughness of the fiber-mixed concrete was substantially higher than that of the concrete to which no fiber was mixed. The compressive toughness of SHPC and AHPC was especially high as 0.49% and 0.48% respectively. The compressive toughness of PHPC was lowest as 0.38%. The concrete mixed with hybrid fibers (PSHPC and PAHPC) shows about 0.05% lower value compared to those with single metal fiber ingredient (SHPC and APHPC).

3.3 Behavior of concrete after exposure to high temperature

3.3.1 Explosive spalling

Figure 7 shows the result of explosive spalling. After exposure to 400℃, HPC, SHPC and AHPC suffered significant spalling. On the other hand, concretes using polypropylene fibers (PHPC, PSHPC and PAHPC) behaved quite well until 800℃.

3.3.2 Weight reduction

Figure 8 shows the relative weight of specimens after exposure to high temperature. The relative weight was defined as the weight of specimen after heating to that at room temperature. Note that the figure shows only for the non-spalled mixtures (PHPC, PSHPC, PAHPC).

There was no significant difference in the weight loss among the different fiber types. The PAHPC shows slightly higher weight reduction at higher temperatures (600℃, 800℃) compared to PHPC or PAHPC. On an average, the weight reduction rate was 6.5% at 400℃, 7.8% at 600℃, and 8.8% at 800℃.

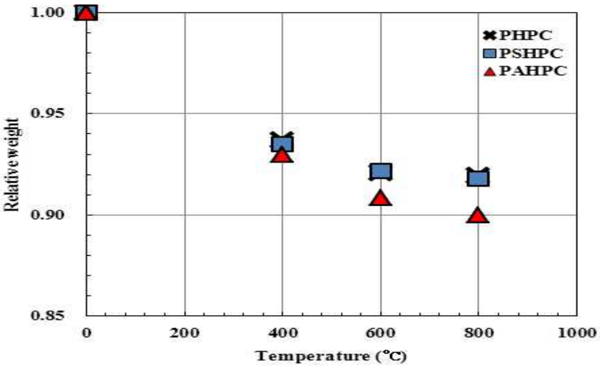


Figure 8. Relative weight

Table 8. Test results for heated concrete

Temperature (°C)	Type	Compressive strength (MPa)	Strain at peak stress (%)	Area under stress -strain curve (MPa×10^{-2})
400	PHPC	44.90	0.31	18.64
	PSHPC	45.79	0.35	20.08
	PAHPC	61.35	0.35	25.29
600	PHPC	24.65	0.44	10.62
	PSHPC	26.22	0.56	11.68
	PAHPC	39.39	0.54	17.15
800	PHPC	13.28	0.62	5.85
	PSHPC	22.51	0.71	7.11
	PAHPC	27.29	0.68	8.59

3.3.2 Residual compressive strength

Figure 9 shows the compressive stress–strain curve of the hardened concrete after exposure to high temperature according to the type of the mixed fiber. Note that the curves are only for the non-spalled mixtures (PHPC, PSHPC, PAHPC). Based on these stress–strain curves, several mechanical properties are extracted including compress strength, strain at peak stress, area under stress–strain curve, specific toughness ratio. Table 8 shows these properties according to the fiber type.

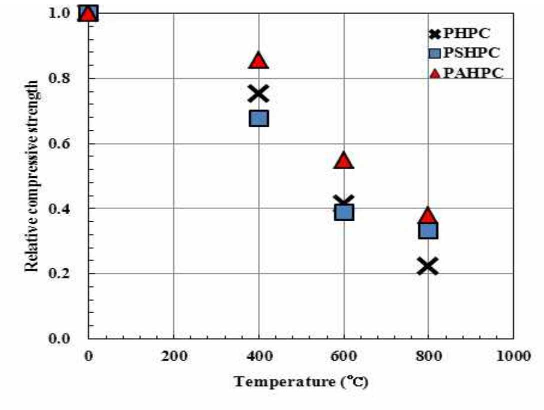


Figure 9. Relative compressive strength with regard to temperature

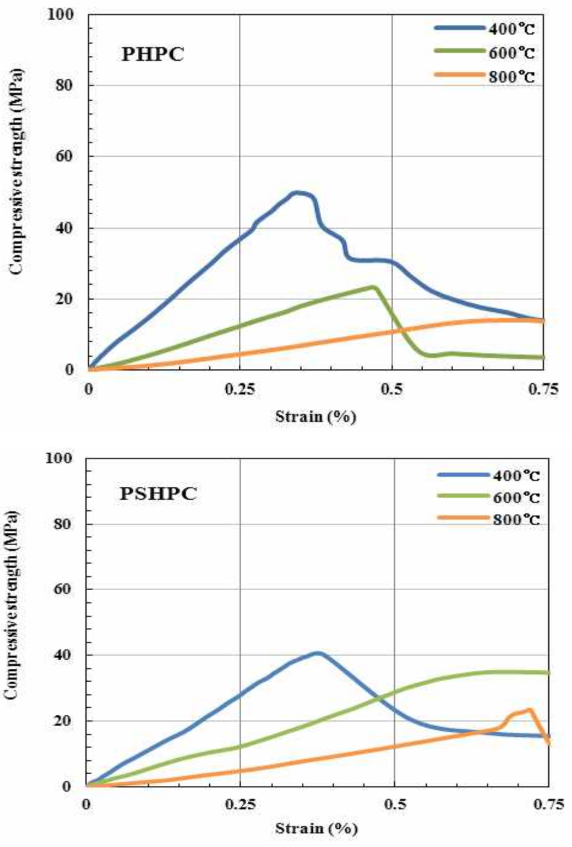
Figure 10 shows the relative residual strength for the non-spalled mixtures. The relative residual strength was defined as the ratio of the compressive strength of specimen after heating to that at room temperature. As seen in the figure, the ratio of PAHPC was highest among the fiber mixture. PAHPC shows 15% higher value in residual compressive strength rate than PSHPC at 400℃ and 600℃. When exposed to 800℃, the rate of PAHPC shows less significant performance (9% higher than PSHPC) compared to the lower temperature exposure.

3.3.3 Elastic modulus

Figure 11 shows the relative elastic modulus of the test specimens after exposure to high temperature. The relative elastic modulus was defined as the ratio of the elastic modulus of specimen after heating to that at room temperature. The elastic modulus was calculated using the closest measurement value within the range of 1/3 of the peak stress.

The relative elastic modulus of each fiber mixture was decreased to 56% at 400℃, 21% at 600℃, and 8% at 800℃. The elastic modulus abruptly decreased within the temperature range of 400–600℃, and slowly decreased within the temperature range of 600–800℃.

There were no significant differences in the elastic modulus according to the fiber type at given temperatures. PAHPC showed slightly higher values in the elastic modulus compared to the others two mixtures (PHPC or PSHPC): 5~7% higher values than others at 400℃, 3~4% higher values at 600℃, and almost the same at 800℃.



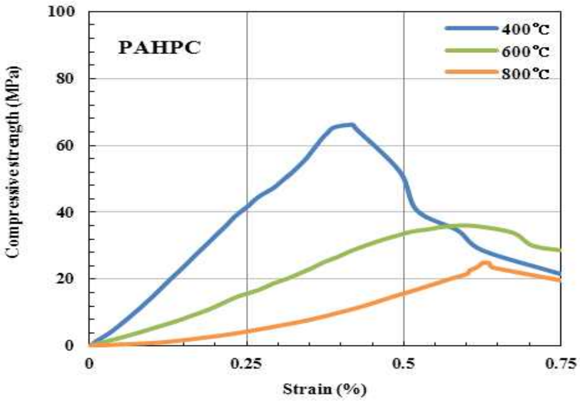


Figure 10. Stress-strain curves for heated concrete

3.3.3 Strain at peak stress

Figure 12 shows the relative peak strain according to temperature. The relative peak strain was defined as the ratio of the strain at peak stress of specimen after heating to that at room temperature.

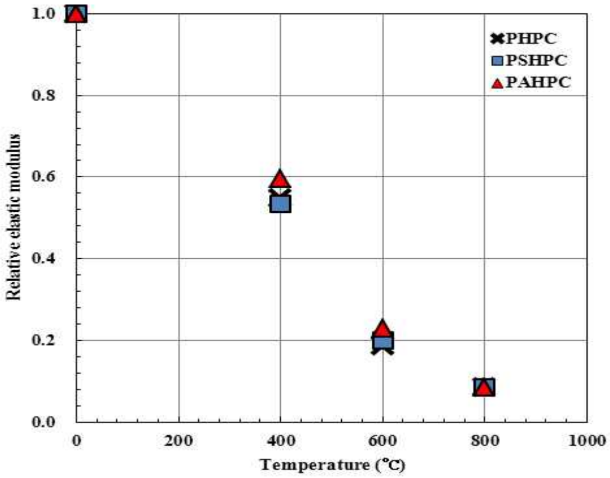


Figure 11. Relative elastic modulus

The relative peak strain increased with the increase of temperature, and no significant differences among the fiber types. They were 1.2 times higher at 400℃, 1.9 times higher at 600℃, and 2.4 times higher at 800℃ than those of the unheated concrete.

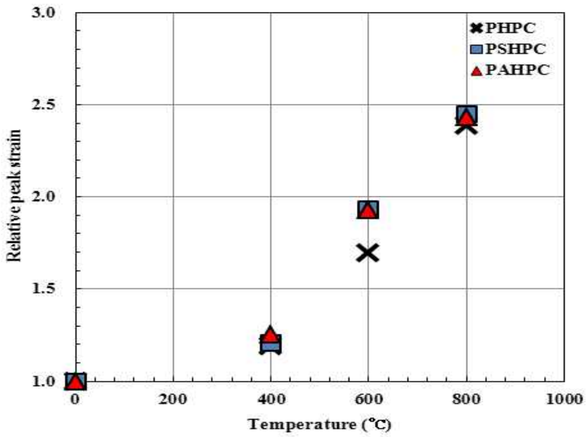


Figure 12. Relative peak strain

3.3.4 Residual energy absorption capability

Figure 13 shows the relative residual energy absorption capability of the test specimens after exposure to high temperature. The relative residual energy absorption was defined as the area under the stress–strain curve up to the strain value of 0.75% after heating to that at room temperature. After exposure to high temperature, the overall average relative energy absorption capability was 77% at 400℃, 47% at 600℃, and 26% at 800℃. This trend was similar to that of the residual compressive strength rate.

The residual energy absorption capability by mixed fiber was highest at 82% PHPC at 400℃; and at 53% when PAHPC at 600℃. At the temperature of 800℃, the residual energy absorption capability was highest PAHPC.

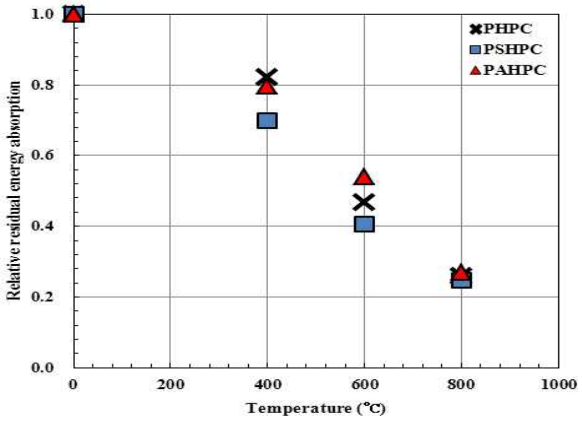


Figure 13. Relative residual energy absorption

4. Discussion

4.1 Explosive spalling resistance

As explosive explosive spalling is governed by a vapor-pressure mechanism, it is reasonable to consider that the use of PP fibers can prevent the concrete from explosive explosive spalling, due to the fact that polypropylene fibers are melted under temperature around 165 ° C and moisture in concrete can escape through inter-connected pores to outside of concrete. However, from the result of SHPC and AHPC, the use of metal fiber alone cannot prevent the explosive spalling due to the fact that the melting points of steel fibers and amorphous metal fibers are much higher than the temperature occurred spalling.

4.2 Material properties after high temperature exposure

The mechanical properties are degenerated with the increase of temperature. By comparing the test result of two similar fiber ingredient mixtures, PSHPC and PAHPC, we can observe several interesting facts. PAHPC showed a better anti-firing resistance than PSHPC through the temperature range examined in this investigation. However, the outperformance of PAHPC compared to PSHPC at higher temperature (800℃) is not as significant as those at lower temperature. We could observe this tendency in the residual strength, in strain at peak stress, and also in residual energy absorption. This relatively lower performance of PAHPC at higher temperature seems to be due to the structural change of AMF. The amorphous structure changes into crystalline one due to high temperature hence it loose the benefit of amorphous structure [5].

5. Conclusion

The investigation revealed the outperformance of the AMF high strength concrete in high temperature. The fireproof characteristic was most pronounced in the concrete mixed with AMF+ PPF in terms of the residual compressive strength, residual elastic modulus, peak strain, and residual energy absorption capability.

The investigation also re-confirmed the usefulness of polymer type fiber under high temperature condition, i.e. PPFs were melted and made paths for the vapor pressure discharge hence the concrete using PPF (PPF alone, PPF+SF, PPF +AMF) were free from the explosive spalling. However, the plain concrete and the concrete with metal fiber ingredient (SF mixture and AMF mixture) showed explosive spalling since they could not form a network for a vapor pressure discharge.

Acknowledgements

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