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Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement

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Abstract

This paper presents an experimental study on the spalling resistance of high performance concrete with polypropylene (PP) fibers and fabric or sheet material for lateral confinement subjected to fire. According to the test results, spalling occurred on all specimens that did not contain PP fiber in the concrete mixture. However, spalling did not occur on specimens containing PP fibers above 0.05% by volume. A metal fabric showed beneficial effect on spalling resistance, but glass or carbon fiber fabrics do not show the same effect on the spalling resistance due to reduction of bond strength at high temperatures. Spalling did not occur on all specimens in which PP fibers and metal fabric were applied at the same time, and hence spalling resistance performance was significantly improved. The residual compressive strength was maintained at about 90% of its original strength, and this can be considered as an improved performance against fire damage.

Keywords: High performance concrete; Spalling resistance; Polypropylene fiber; Lateral confinement; Metal fabric

1. Introduction

It is important that concrete structures endure fire conditions for a specified time and are structurally safe from the point of view of saving life and protecting property. Spalling is defined as damage where concrete surface scales and falls off from the concrete along with explosion at a high temperature [1–3]. It is well known that its occurrence in concrete is facilitated as w/c is low, the strength is high and the matrix is dense like in the case of high strength concrete and high performance concrete [4–6]. Since most of the concrete structures have been constructed with normal strength concrete the concern about spalling has been neglected and the investigation related to spalling has not been fully investigated. However, nowadays as many concrete structures tend to be high-rise buildings, high strength and high performance concrete have been used extensively. Though the prevention of spalling becomes a major concern, investigation in this area is scarce.

Therefore, this study is intended to investigate the spalling resistance of high performance concrete by use of polypropylene (PP) fiber contents, which is known to be effective for the spalling resistance, and lateral confinement materials such as metal lath, glass fiber and carbon fiber. Performance of the spalling resistance and residual strength, are tested after fire resistance evaluation.

2. Design and method of experiment

2.1. Design of experiment

The experimental details of this study are shown in Table 1. Water/binder ratios (w/b) used were 0.3 and 0.4, while varying PP fiber mixing ratio of 0%, 0.05% and 0.10% (by

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Table 1
Design of experiment

Factors considered				Parameters measured	
w/b (%)	FA[a] (%)	PP fiber (% by volume)	Lateral confinement material (thickness)	Fresh concrete	Hardened concrete
30 40	20	0 0.05 0.10	• Plain • Metal fabric – M_1(0.6mm) – M_2(1.6mm) • Glass fiber (0.38 mm) • Carbon fiber (0.27 mm)	• Slump • Slump-flow • Air content • Unit weight	• Compressive strength • Fire resistance test • Residual compressive strength • Weight reduction ratio

[a] Fly ash.

Table 2
Mixture of concrete

w/b (%)	Water content (kg/m^3)	PP fiber (% by volume)	s/a (%)	sp/c (%)	Absolute volume mix (ℓ/m^3)					Weight mix (kg/m^3)				
					Cement	FA	Sand	Coarse aggregate	PP fiber	Cement	FA	Sand	Coarse aggregate	PP fiber
30	175	0/0.05/0.10	48	1.5	148	53	278	211	0/0.5/1.0	467	117	715	555	0/0.45/0.90
40			51	1.05	111	39	321	216	0/0.5/1.0	350	88	825	568	0/0.45/0.90

s/a: Sand/aggregate ratio, sp/c: Superplasticizer/cement ratio.

Table 3
Physical properties of cement

Specific gravity	Blaine fineness (cm^2/g)	Stability (%)	Setting time (min)		Compressive strength (MPa)		
			Initial setting	Final setting	3 days	7 days	28 days
3.15	3522	0.16	207	353	21.4	30.5	39.2

volume) were used. Lateral confinement materials varied from metal fabrics of 0.6 mm (M_1) and 1.6 mm (M_2) thick, glass fiber and carbon fiber sheets of 0.38 mm and 0.27 mm in thickness, respectively. The mixture proportions of concrete were determined to satisfy air contents of 4.5±1.5% and target slump-flow of 60±5 cm. The parameters of fresh concrete and hardened concrete investigated, and mixture proportions of concrete are shown in Tables 1 and 2, respectively.

2.2. Materials

The cement used in this experiment is a Portland cement produced in Korea, and the river sand produced in Chongwon region, Korea is used as fine aggregates. The crushed granite stone with a maximum size of 20 mm is used as coarse aggregate. The main component of the Superplasticizer (sp) used is polycarbonic acid. PP fiber made by S Co. Inc., Korea is used and metal fabrics, glass and carbon fiber fabrics are used as lateral confinement materials. The physical properties of each material are presented in Tables 3–8.

2.3. Test method

Concrete was mixed in a forced circulating pan mixer. In order to facilitate dispersion of fibers, dry mixing was carried out after distributing PP fibers manually. Slump test was carried out according to KS F 2401 and slump-flow was measured through averaging the maximum diameter and diameter at right angles, after slump test. Air content and unit weight were measured according to KS F 2421 and 2409, respectively.

Specimens were made in accordance with KS F 2403 after setting up lateral confinement materials in Φ10×20 cm moulds. Lap joint lengths of lateral confinement material were determined as 40 times the thickness of each material.

Table 4
Physical properties of aggregates used

Type	Specific gravity	FM[a]	Absorption ratio (%)	Unit weight (kg/m^3)	Passing 80 μm sieve (%)
Fine aggregate	2.57	2.7	1.83	1470	1.8
Coarse aggregate	2.63	6.9	0.62	1577	0.3

[a] FM: Fineness modulus.

Table 5
Physical properties of admixture

Type	Main composition	Form	Color	Specific gravity at 20 °C
Superplasticizer	Polycarbonic acid	Liquid	Light yellow	1.05±0.02

Table 6
Physical properties of PP fiber

Type	Specific gravity	Length (mm)	Diameter (mm)	Melting point (°C)	Tensile strength (MPa)
Homopolymer polypropylene	0.9	19	0.07	162 °C	560

Table 7
Standard size of metal fabric

Type	SW (mm)	LW (mm)	T (mm)
M_1	6.6	13.3	0.6
M_2	24	48	1.6

As for the test of hardened concrete, compressive strength test were carried out according to KS F 2405. Specimens were cured in water of 20±3 °C for 27 days and then, kept in air for 1 day. After that, each specimen was heated in a furnace at Korea Institute of Construction Technology (KICT), in accordance with standard heating curve of KS F 2257(see Fig. 1), and heated for 40 min. After the fire resistance test, spalling was examined with the naked eye, and the weight reduction ratio was calculated by measuring the weight of specimens before and after the fire resistance test.

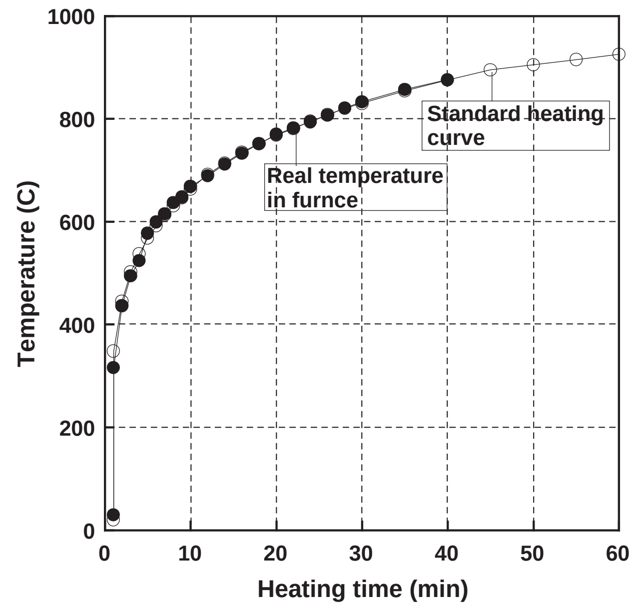

Fig. 1. Standard heating curve and real temperature curve of heating furnace.

3. Results and discussions

3.1. Properties of fresh concrete

Fig. 2 shows slump, slump-flow, air content and unit weight with the variation of PP fiber content. Slump-flow satisfies the range of 60±5 cm, and air content was in the range of 4.5±1.5%. As the PP fiber content increased, fluidity decreased slightly. Air content and unit weight were similar when compared to the mixture without any PP fibers.

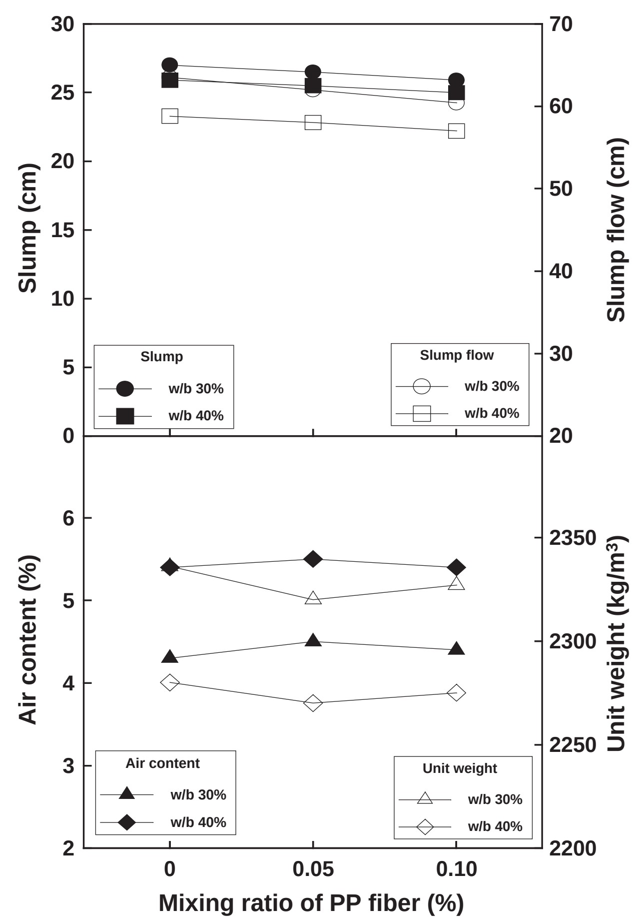

Fig. 2. Slump, slump-flow, air content and unit weight with PP fiber contents.

3.2. Properties of hardened concrete

Fig. 3 shows compressive strength ratio of concrete with w/b, lateral confinement material and the PP fiber contents, considering compressive strength of plain concrete as the reference. As the PP fiber content increases, compressive strength increases slightly. This is due to the fact that toughness is improved due to an increase in crack arresting

Table 8
Physical properties of lateral confinement materials

Type	Tensile strength (MPa)	Tensile elastic modulus (MPa)	Specific gravity
Metal fabric	439	–	7.85
Glass fiber fabric	3480	86,000	2.53
Carbon fiber fabric	3800	245,000	1.80

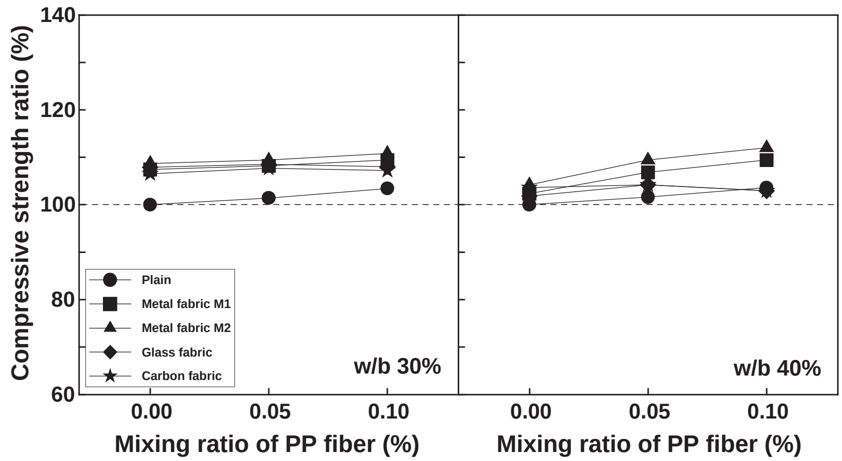

Fig. 3. Compressive strength ratio with PP fiber contents.

ability by the presence of increased number of PP fibers. Compressive strength of concrete, which is confined with lateral confinement materials, increases due to the increase of lateral confinement stress compared to that of plain concrete. In the case of metal fabric, the increase of compressive strength is higher than that of glass fiber and carbon fiber. It is higher in the case of metal fabric M_2 due to higher thickness of M_2 than in the case of metal fabric M_1 as expected.

When PP fiber is mixed, compressive strength ratio increases slightly by 1–3% which is marginal. In the case of specimens confined by glass and carbon fibers, compressive strength ratio increases by 7–8% and 3–4% at w/b of 0.3 and 0.4, respectively. Compressive strength increase is higher in mixes with w/b of 0.3 than with w/b of 0.4. In the case of metal fabric, compressive strength ratio shows about 10% for w/b of both 0.3 and 0.4, and is higher than in the case of glass fiber and carbon fiber.

3.3. Properties of spalling

Table 9 shows whether spalling of specimen occurs or not with variation of the PP fiber contents and lateral confinement materials after fire resistance test, and Fig. 4 shows spalling of specimens. As for the properties of spalling with PP fiber contents, severe spalling failure occurs with a decrease of w/b in the case of plain concrete (with no PP fibers and no lateral confinement). However, when PP fiber percentage was more than 0.05%, spalling did not occur in any of the specimens. This confirms that PP fiber can prevent spalling effectively. In the case of plain concrete, which does not contain PP fibers but is confined laterally with metal fabric, spalling resistance is favorable because lateral confinement force is stronger than spalling energy by internal vapor pressure. On the other hand, lateral confinement by glass fiber or carbon fiber mat on the surface of concrete is not effective for spalling resistance and behaved similar to plain concrete since fibers are worn or stripped by spalling due to reduction of bond strength by high temperature. Carbon also has almost zero co-efficient of thermal expansion where as concrete expands. This resulted in spalling failure of cylinders.

Also, when the mixture contained PP fiber and lateral confinement, which was provided by metal fabric, glass fiber and carbon fiber, spalling was prevented in most of the specimens. As presented in Figs. 5 and 6, and discussed by Kalifa et al. [7], there are two reasons; one is that as PP fiber in concrete melts at the high temperature (at about 165 °C), and vapor pressure is relieved. The other reason is that lateral confinement pressure provided by confining material is higher than the pressure induced by the internal vapor pressure.

Table 9
Results of spalling test with polypropylene fibers after exposure to high temperature

w/b (%)	PP fiber (%)	Plain			Lateral confinement material											
					Metal fabric M_1			Metal fabric M_2			Glass fiber fabric			Carbon fiber fabric		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
30	0	×	×	×	△	×	△	△	△	△	△	×	×	×	×	△
	0.05	○	○	○	△	○	△	○	○	○	○	○	○	○	○	○
	0.10	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
40	0	×	×	×	△	△	△	○	△	△	×	×	×	×	×	×
	0.05	○	○	○	○	△	○	○	○	○	○	○	○	○	○	○
	0.10	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

×: Spalling failure, ;△: scaling of surface, ○: no spalling.

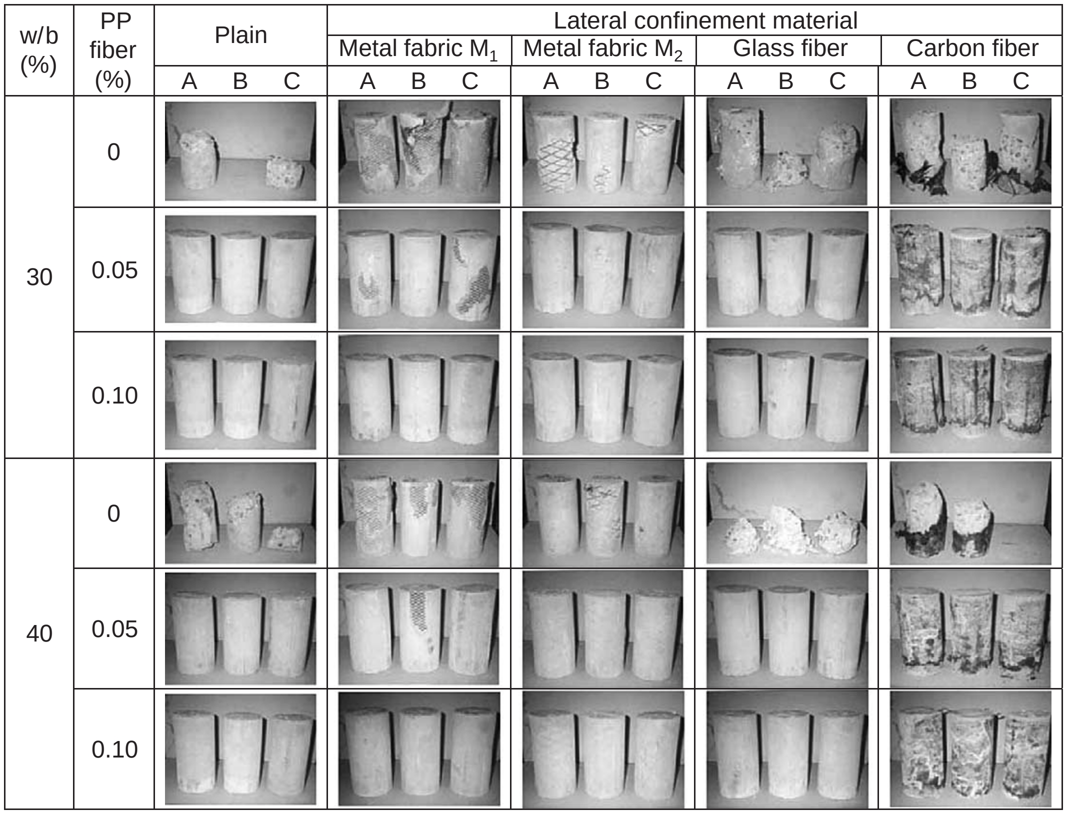

Fig. 4. Spalling shape of specimens after fire resistance test.

Fig. 7 shows the residual compressive strength ratio with the PP fiber contents and lateral confinement materials. In the case of plain concrete, the residual compressive strength is impossible to measure because of spalling failure of all specimens although other researches have made some measurement. In the case of concrete which is confined laterally only by metal fabric, the residual compressive strength ratio shows 50–60% and 80–90% for M_1 and M_2, respectively, so the residual compressive strength is dependent on thickness of metal fabric. In the case of concrete which is confined laterally by glass fiber or carbon fiber, the residual compressive strength is impossible to measure (similar to plain concrete), but the residual compressive strength ratio shows about 30% in some specimens which can be measured at the w/b of 0.3. As the PP fiber contents increases, the residual compressive strength ratio also shows a slight increase. When the mixture of PP fiber and lateral confinement by metal fabric are applied together, it shows about 90%, which is the highest, due to spalling resistance by the mixture of PP fiber and lateral confinement force by metal lath. When only PP fiber is mixed, it shows about 70%. When the mixture of PP fiber and lateral confinement by glass fiber or carbon fiber are

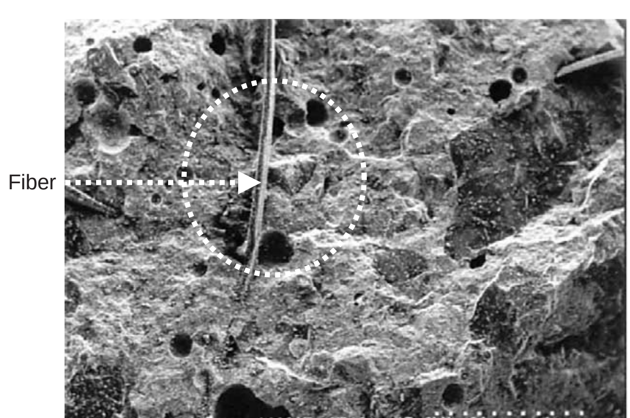

Fig. 5. Shape of PP fiber in concrete before fire resistance test.

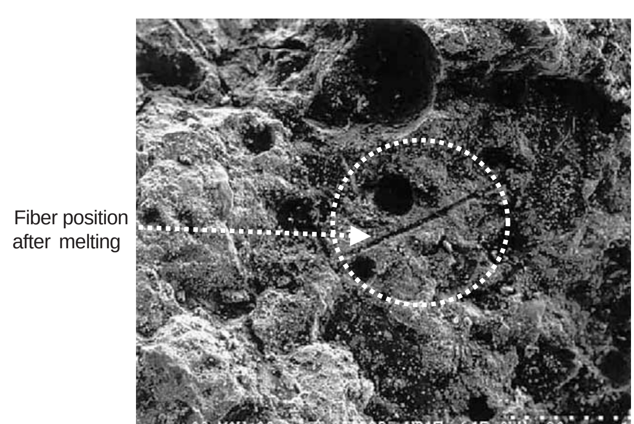

Fig. 6. Melting shape of PP fiber in concrete.

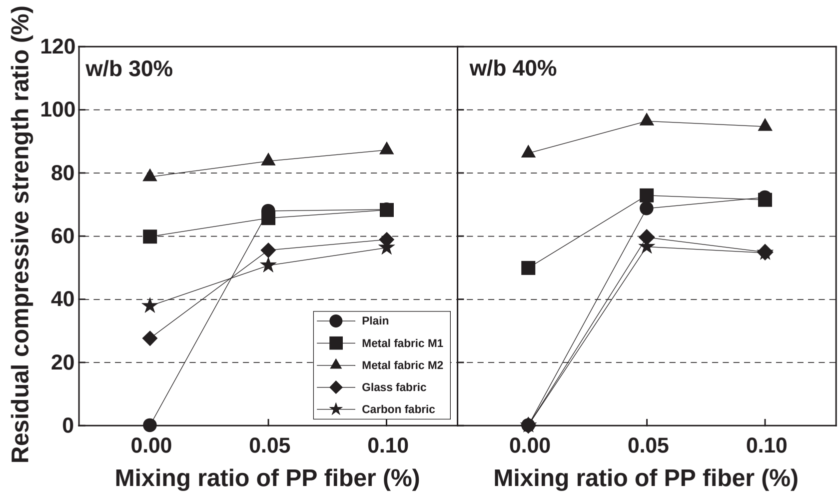

Fig. 7. Residual compressive strength with PP fiber contents.

applied, it shows 50–60% of the original strength, i.e. it decreases a little [8]. This is because the lateral confinement force is reduced due to a decrease of bond strength of glass fiber or carbon fiber for these configurations. However, if glass fiber or carbon fiber fabrics are bonded to the surface by an adhesive or embedded in concrete with sufficient cover they can provide lateral confinement. In particular, carbon fiber fabric can provide satisfactory confinement, but it is expensive when compared with steel fabric.

Fig. 8 shows the weight reduction ratio after fire resistance test with the PP fiber contents and lateral confining materials. In the case of the mixture with no PP fiber or lateral confinement by glass or carbon fiber, the weight reduction ratio increases significantly by up to 60%. In the case of lateral confinement by metal fabric, it shows a small increase of 10–20% due to high spalling resistance. When PP fiber is mixed in quantities more than 0.05% by volume, or a combination of PP fiber and lateral confinement are applied at the same time, the weight reduction is below 10%.

4. Conclusions

The following conclusions were drawn:

1) As for the properties of spalling after fire test, a serious spalling failure occurs in the case of plain concrete which does not contain PP fiber. However, when PP fiber is mixed in quantities more than 0.05% by volume (more than 0.45 kg/m^3), spalling is prevented in all specimens because melting of PP fiber in concrete at the high temperature plays a role in releasing the high internal vapor pressure.
2) When concrete is confined laterally by metal fabric, spalling resistance is very favorable, which is caused by lateral confinement pressure, is higher than that of the internal vapor pressure. The higher the thickness of metal fabric is, the better the spalling resistance is. On the other hand, lateral confinement by glass fiber or carbon fiber mat as used in the above configurations is not effective for spalling resistance and behaved like plain concrete.

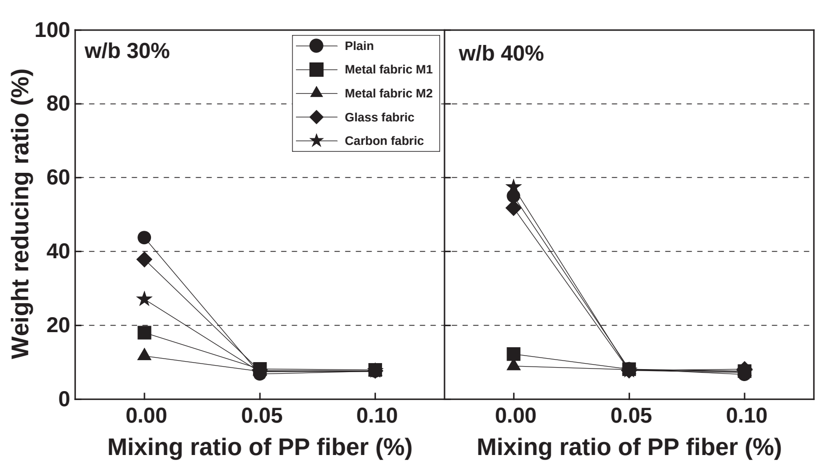

Fig. 8. Weight reduction ratio after fire resistance test.

3) When the mixture contains PP fiber above 0.05% by volume and lateral confinement are applied at the same time, no spalling occurs, so that spalling resistance is significantly improved.
4) When the mixture contains PP fiber and lateral confinement by metal fabric is applied together, the residual compressive strength ratio is about 90%. On the other hand, when lateral confinement by glass fiber or carbon fiber is applied, it shows 50–60%, so it decreases slightly.

Based on the above results, when the concrete mixture contains PP fiber and lateral confinement by a metal fabric are applied at the same time, spalling resistance is very favorable and the residual compressive strength ratio is also improved significantly, so that this method can be considered as a possible measure for safety in high performance concrete subjected to fire.

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