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Spalling Properties of High Strength Concrete Mixed with Various Mineral Admixtures Subjected to Fire

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Abstract: This study investigates the spalling properties of high strength concrete designed with various types of mineral admixture and diverse content ratios of polypropylene (PP) fiber. Experimental factors considered in series I are four pozzolan types of mineral admixture and series II consists of three shrinkage reducing types of mineral admixture. PP fiber was added 0.05, 0.10 and 0.15vol. % in each mixture of series I and series II, so that totally 27 specimens including control concretes in each series were prepared. Test results showed that the increase of fiber content decreased the slump flow of fresh concrete and increased or decreased the air content depending on the declining ratio of slump flow. For the properties of compressive strength, all specimens were indicated at around 50 MPa, which is high strength range; especially all specimens in series II were 60 MPa. Fire test was conducted in standard heating curve of ISO 834 with Ø100 × 200 mm size of cylinder moulds for 1 hour. The specimens incorporating silica fume exhibited severe spalling and most specimens without the silica fume could be protected from the spalling occurrence in only 0.05vol % of PP fiber content. This fire test results demonstrated that the spalling occurrence in high strength concrete was not only affected by concrete strength related to the porosity of microstructure but also, even more influenced by micro pore structure induced by the mineral admixtures.

Keywords: high strength concrete, spalling, polypropylene fiber, mineral admixture.

1. Introduction

High strength concrete has been widely used in field constructions with excellent strength development, which can be used to build ultra high-rise structures and to use the space of the buildings effectively.

However, unlike normal strength concrete, the high strength concrete has dense internal system of pore structures which causes spalling under fire (Fig. 1)[1-4].

The influences of environmental and material factors on spalling resistance of HSC have been carried out such as rate of heating, maximum temperature, types of aggregates, types of mineral admixtures, and saturation level of the concrete.[3-5]

Kodur[6] demonstrated that the extent of spalling in HSC was very significant with high silica fume content (about 15%) and the higher silica fume and associated compressive strength increases the extent of spalling due to the fact that the addition of silica fume appears to reduce the permeability of the concrete, restricting the loss of moisture during curing, drying and the fire test. Studies showed that carbonate aggregate provides higher fire resistance and better spalling resistance in concrete than siliceous aggregate does due to superior heat capacity of carbonated aggregate.

Some solutions as to incorporation of PP fiber to discharge vapor pressure from concrete matrix have been proposed to avoid spalling occurrence.[7,8]

The authors have investigated fire tests for 60 MPa class of high strength concrete (HSC) made with various influential factors.[8-13]

This study is to investigates the fundamental properties of fresh concrete using pozzolan types and shrinkage reducing types of mineral admixture with fiber content, and then examines the 1 hour unloading fire test. Consequently it is intended to find out the spalling properties of the concrete incorporated mineral admixtures among the other influential factors.

2. Experimental design and methods

2.1 Experimental design

Table 1 shows the experimental details of this study. Water to binder ratio (W/B) is fixed at 0.25. In series I, plain concrete made of 100% ordinary Portland cement (OPC) is used, and four types of concrete mixed with such mineral admixtures as fly ash (FA) 30%, silica fume (SF) 30%, blast furnace slag (BS) 30% and the combination of FA 20%+SF 10% are prepared as for the experimental factors. In this series, polypropylene (PP) fiber is added at ratios of 0.05vol.%, 0.10vol.% and 0.15vol.% in order to evaluate the occurrence of spalling clearly. Thus, a total of fifteen specimens are prepared.

In addition, it has been recently reported that concrete can be influenced by expansive agent (EA) or shrinkage reducing agent

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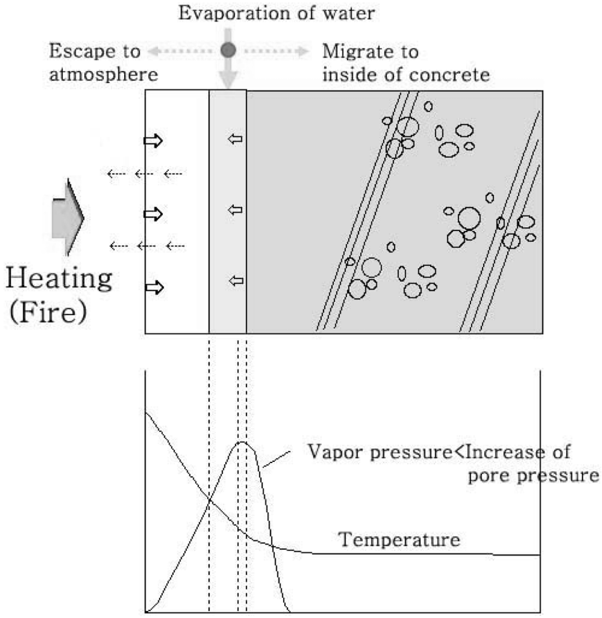


Fig. 1 Diagram of spalling occurrence.

(SRA), applying for protecting the cracks, resulted from self-desiccation of high strength concrete.[14] The experimental series II considers these influences on concrete. Namely, due to the contribution of high strength gain, the mixture of FA+SF specimen concerns as to high self-desiccation is arisen. Thus, it was set as the control concrete. Two types of specimens incorporating EA 5% and SRA 1% and one type of specimen incorporating the combination of EA 5% and SRA 1% are prepared for the control concrete. PP fiber is added in the same ratio as in series I. Additional 12 specimens in series II are examined.

Target slump flows of the plain concrete (OPC) in series I and the control concrete in series II are set at 700 ± 100 mm, which is rather in the range of high fluidity range, and the air content was set at 3.0 ± 1.0%. Other specimens are prepared with these settings. Experimental items of the fresh and hardened concrete are summarized in Table 1, and the mix proportions are given in Table 2.

2.2 Materials

Ordinary Portland cement (density: 3.15 g/cm^3, blaine: 3,302 cm^2/g) produced in Korea was used for the test specimens in all experimental series. Crushed sand and river sand was used as the fine aggregate. This blended aggregate was intended to satisfy the target fineness modulus (FM) of 2.7. Accordingly, in series I, the blended aggregate was mixed with the proportion of 6 (crushed) to 4 (sand) sand volume ratios in concrete. The aggregate had 2.6 g/cm^3 of density and 2.81 of FM. In series II, it was mixed with 5 (crushed) to 5 (sand) ratio of the fine aggregate, resulting in 2.61 g/cm^3 of density and 2.7 of FM. Crushed coarse aggregate of 20 mm grain size was used. The coarse aggregate of series I had 2.61 g/cm^3 of density and 6.56 of FM, and the coarse aggregate of series II had 2.66 g/cm^3 of density and 6.56 of FM. In addition, FA (density: 2.21 g/cm^3, blaine: 4,061 cm^2/g), SF (density: 2.20 g/cm^3, blaine: 200,000 cm^2/g) from Norway and BS (density: 2.90 g/cm^3, blaine: 4,580 cm^2/g) in Gwangyang were used for the mineral admixtures in experimental series I. Calcium sulfur aluminate (CSA) based EA (density: 2.98 g/cm^3, blaine: 3,117 cm^2/g) produced in Japan and glycol based SRA (density: 1.02 g/cm^3, dry solid: 31%) produced in Germany were used for the mineral admixtures in experimental series II. Moreover, some materials, a polycarboxylate type of superplasticizer, air entrainment (AE) agent and polypropylene fiber, were used equally in each series.

2.3 Experimental methods

In this study, concrete was mixed in a forced fan type mixer. Slump flow tests were carried out according to ASTM C 1611. Air content was measured according to ASTM C 138.

As for the compressive strength test of hardened concrete, Ø100 × 200 cylinder molds were cast pursuant to ASTM C 39 for designed age. Fire test was performed for one hour in accordance with the standard heating curve specification of ISO 834, as

Table 1 Experimental design.

Mixture		Mineral admixture (%)	Mineral admixture (%)	W/B (%)	Target air content (%)	Target slump flow (mm)	PP fiber content (%)	Parameters measured	
								Fresh concrete	Hardened concrete
Series I	OPC[1] (Plain)	-	-						Compressive strength
Series I	FA[2] SF[3] BS[4] FA+SF	FA 30 SF 30 BS 30 FA20+SF10	-						Fire test (1 hour) Spalling appearance
Series II	Control	FA20+SF10	-	25	3.0 ± 1.0	700 ± 100	0.05 0.1 0.15	Slump flow Air content	Spalling degree
Series II	EA[5] SRA[6] EA+ SRA	FA20+SF10	EA 5 SRA 1 EA 5+SRA 1						Weight loss ratio Residual compressive strength ratio

1) Ordinary Portland cement 2) Fly ash 3) Slica fume 4) Blast furnace slag
5) Expansive agent 6) Shrinkage reducing agent

Table 2 Mix proportion of concrete.

Mix.		W/B (%)	Water content (kg/m^3)	S/a (%)	AE agent (%)	SP agent (%)	Weight mixture (kg/m^3)							
							C	FA	SF	BS	EA	SRA	S	G
Series I	OPC	25	160	45	0.04	1.3	640	-	-	-	-	-	692	850
	FA						448	192	-	-	-	-	662	812
	SF						448	-	192	-	-	-	662	812
	BS						448	-	-	192	-	-	686	842
	FA+SF						448	128	64	-	-	-	660	810
Series II	Control	25	160	45	0.07	2.2	448	128	64	-	-	-	663	826
	EA						416	128	64	-	32	-	662	824
	SRA						442	128	64	-	-	6.4	658	819
	EA+SRA						410	128	64	-	32	6.4	657	818

shown in Fig. 2. After the fire test was completed, the occurrence of spalling was examined by visual inspection, and the degree of spalling was evaluated as seen in Table 3, based on the weight loss ratio given by Eq. (1). The residual compressive strength ratio of specimens, having only class 1 of spalling degree, was accomplished as a percentage of the concrete strength before and after the fire test.

$$Weight\ loss\ ratio(\%) = \frac{W_L}{W_C} \times 100 \qquad (1)$$

Where, W_L: Specimen's weight before the fire test
W_C: Specimen's weight after the fire test

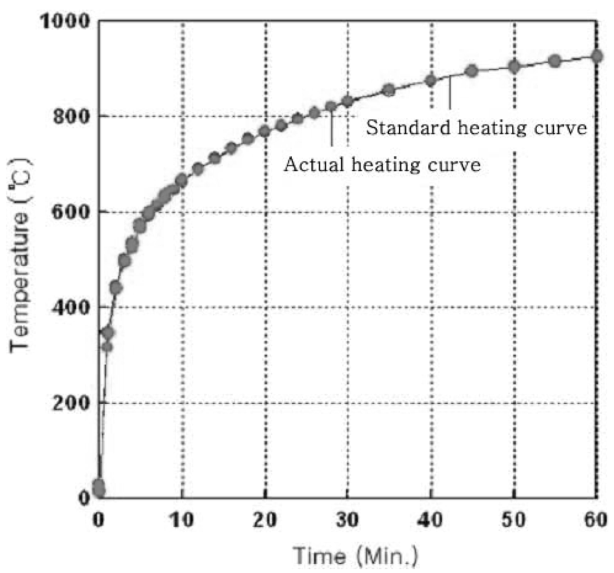


Fig. 2 Standard and actual heating curve.

Table 3 Spalling grade.

Grade	Criterion
Class 1	Weight loss ratio 0 to 25%
Class 2	Weight loss ratio 25 to 50%
Class 3	Weight loss ratio 50 to 75%
Class 4	Weight loss ratio 75 to 100%

3. Results and discussion

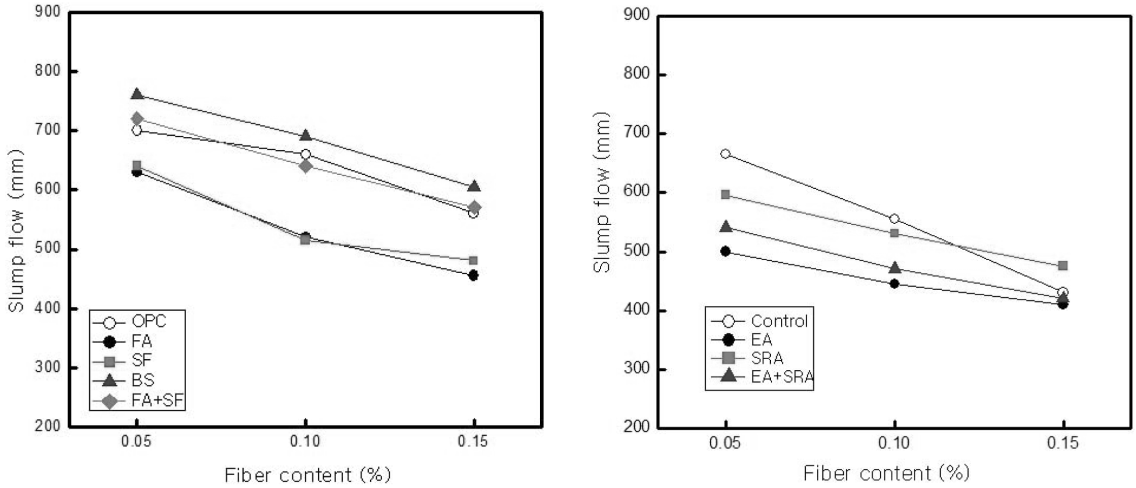
3.1 Properties of fresh concrete

Fig. 3 shows results of the slump flow test with experimental variables of mineral admixture types and fiber content. Overall, the increase in fiber content significantly decreased the slump flow. Fig. 3(a) shows that the specimens incorporating BS improved the slump flow by 6% compared to that of OPC, while the addition of SF or FA decreased the slump flow. However, using both FA and SF simultaneously exhibited similar tendency to OPC. Additionally, Fig. 3(b) indicates that the control concrete, which incorporates the same mixture as the FA + SF specimen in series I, decreased the slump flow drastically with the increase in fiber content as expected. Nevertheless, other specimens incorporating mineral admixtures decreased the slump flow gradually. The slump flow value of specimens using 1% SRA ranged from 500 mm to 600 mm favorably, but using 5% EA exhibited the lowest slump flow value of 410 mm. Incorporating both EA and SRA also lowered the fluidity of fresh concrete than that of SRA due to the EA usage.

Fig. 4 shows the results of air content measurement for the test specimens with experimental variables of mineral admixture types and fiber content. All specimens incorporating SF exhibited more than 5% air content, while the air content of other specimens favorably measured between 2 and 4%. With respect to this point, those specimens exhibiting significantly decreased ratio of fluidity increased the air content with the increase in fiber content as shown in Fig. 4(a). In the same context, other specimens exhibiting smaller decrease in the fluidity ratio decreased the air content only slightly with the increase in fiber content as shown in Fig. 4(b) excluding the control specimen. The reason for these properties can be found when the complex reaction of both fluidity and air content is considered at the same time. In other words, when the slump flow decreased significantly at first with the increase in fiber content, the air content increased due to the influence of flow decrement. Conversely, when the slump flow showed a gradual decrease, the air content decreased due to the influence of the fiber itself.

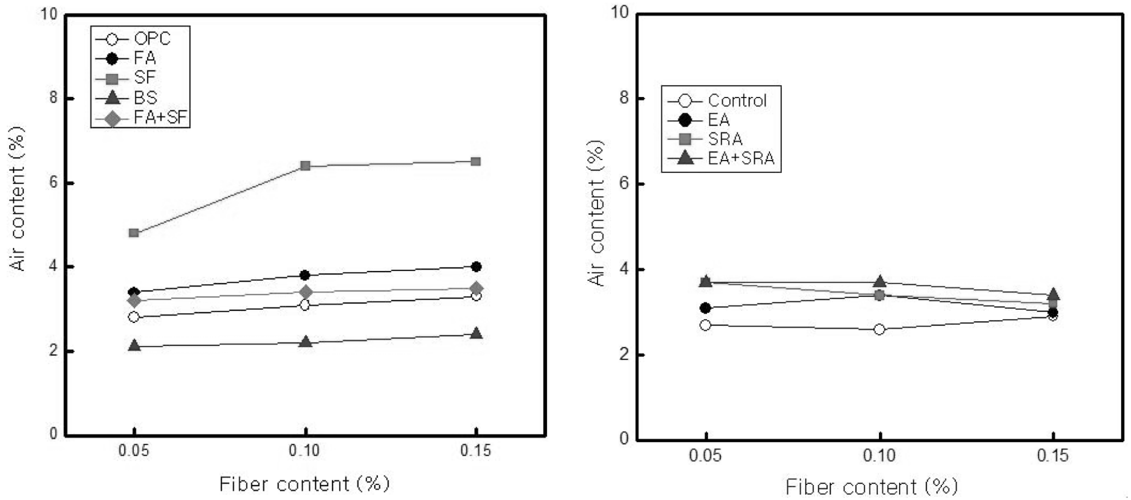
3.2 Properties of hardened concrete

Fig. 5 shows the results of compressive strength test at 28 days with the experimental variables of mineral admixture types and fiber content.



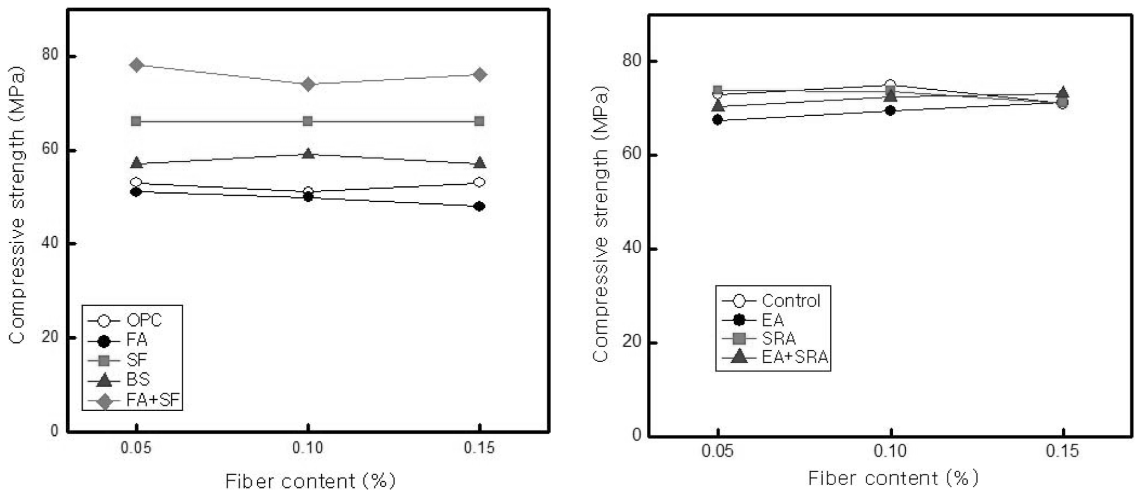
(a) Series I (b) Series II

Fig. 3 Slump flow of fresh concrete.



(a) Series I (b) Series II

Fig. 4 Air content of fresh concrete.



(a) Series I (b) Series II

Fig. 5 Compressive strength of hardened concrete.

As seen in Fig. 5(a), the compressive strength of OPC of series I measured at about 55 MPa, while the specimens incorporating SF and BS had higher compressive strengths, but FA specimen exhibited the lowest strength of 48 MPa. More importantly, using the combination of FA and SF simultaneously in concrete resulted in the highest strength of this series as measured at 78 MPa due to the most favorable mix proportion. In addition, specimens in series II exhibited compressive strengths more than 70 MPa because of the incorporated FA+SF as seen in Fig. 5(b). This tendency for higher compressive strength slightly declined with the incorporation of shrinkage reducing admixture. However, the compressive strength values of all specimens with fiber content of 0.15vol.% were similar.

3.3 Spalling properties

Fig. 6 depicts the spalling appearance and the degree of spalling with various mineral admixture types and fiber content after a fire test for one hour.

OPC of series I was protected from spalling occurrence with PP fiber content of 0.05vol.% only, indicating the best (the first) class

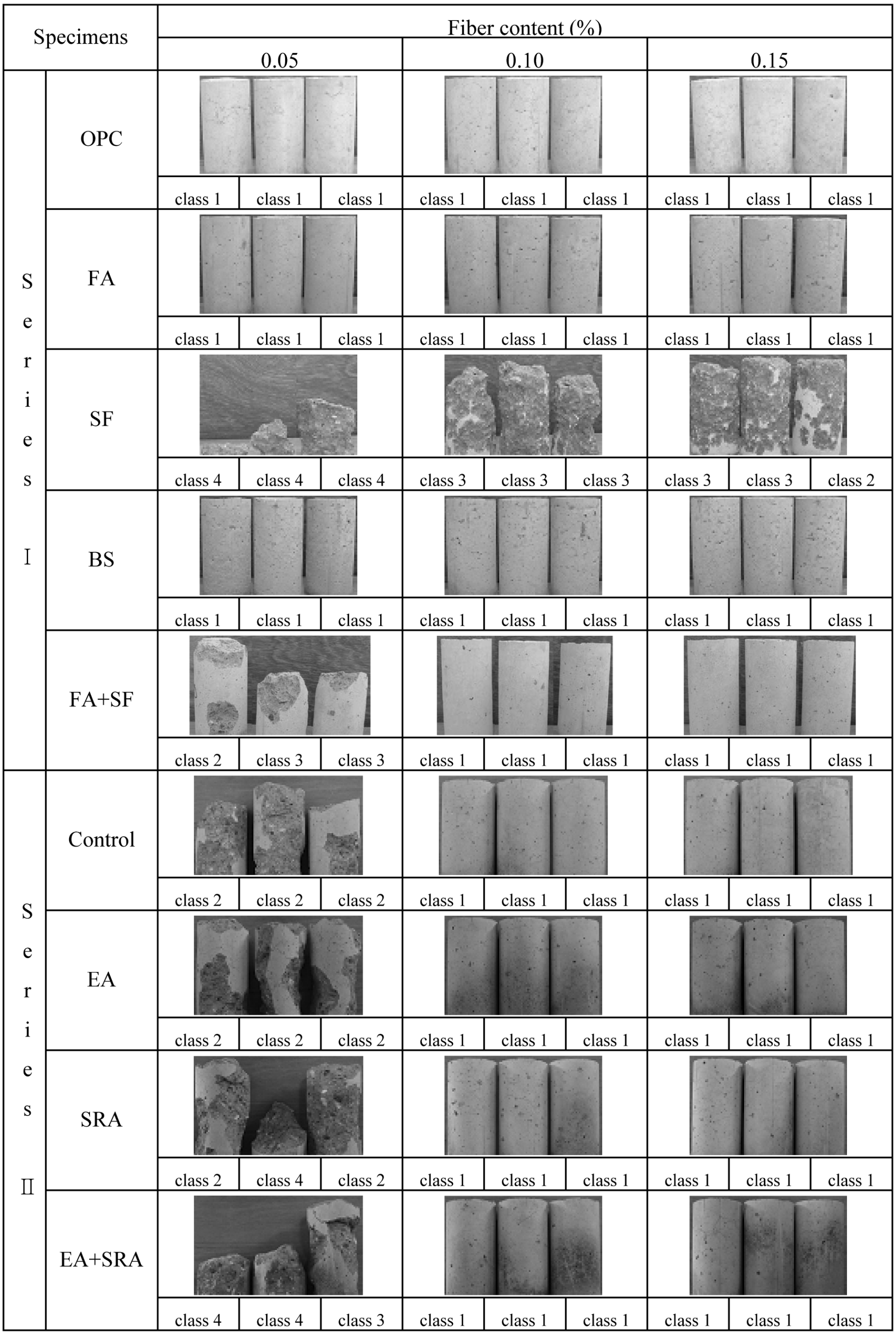


Fig. 6 Spalling appearance of specimens.

spalling appearance (cf. Table 3 for the explanation of the degree of spalling classified into four classes of grading). This spalling tendency was similarly shown in all specimens, which do not have incorporated SF admixture. Meanwhile, the specimens with FA and SF exhibited the occurrence of spalling with PP fiber content of 0.05vol.%, but spalling was not observed with PP fiber content of more than 0.10vol.%. Interestingly, although the specimens incorporating 30% of SF had three times the PP fiber content than the specimen aforementioned above, its degree of spalling was still class 2 to 3, indicating severe spalling occurrence.

These phenomena are related to the micro structure of concrete using different mineral admixture. As seen in Fig. 7, Rosa Maria Espinosa[15] diagramed the details of pore system of a cement structure in hydration process. One single particle of hydrated cement consists of numerous C-S-H gels, and the gels are surrounded by gel pores. Moreover, the spaces between the cement particles have many capillary pores. The SF used in this test has ultra micro particles having very high blaine values, 200,000 cm^2/g. The properties of this material are 60 to 70 times higher the blaine values of 4,601 cm^2/g, 4,580 cm^2/g, and 3,302 cm^2/g for the specimens with FA, BS, and cement, respectively. Thus, the specimen with SF builds dense pore systems inside the concrete, which means it significantly blocks floating vapor at elevated temperature to cause more severe spalling occurrence eventually. In addition, it is assumed that these spalling phenomena are related to the strength properties of concrete. As it was explained above, the specimens with OPC, FA and BS did not exhibit spalling due to absence of SF. However, they still gained 48 to 59 MPa of compressive strength, which is high strength value. However, previous study[16] reported that some specimens with SF, which had only 50 MPa range of compressive strength, could not be protected from the spalling occurrence. Therefore it is demonstrated that spalling is not only affected by the strength improvement with SF usage but also is more related to the alteration of pore structure system of concrete induced by mineral admixture like SF, which has fine blaine value.

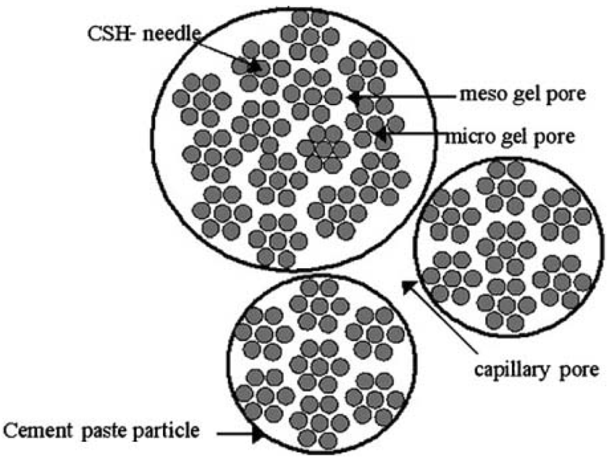


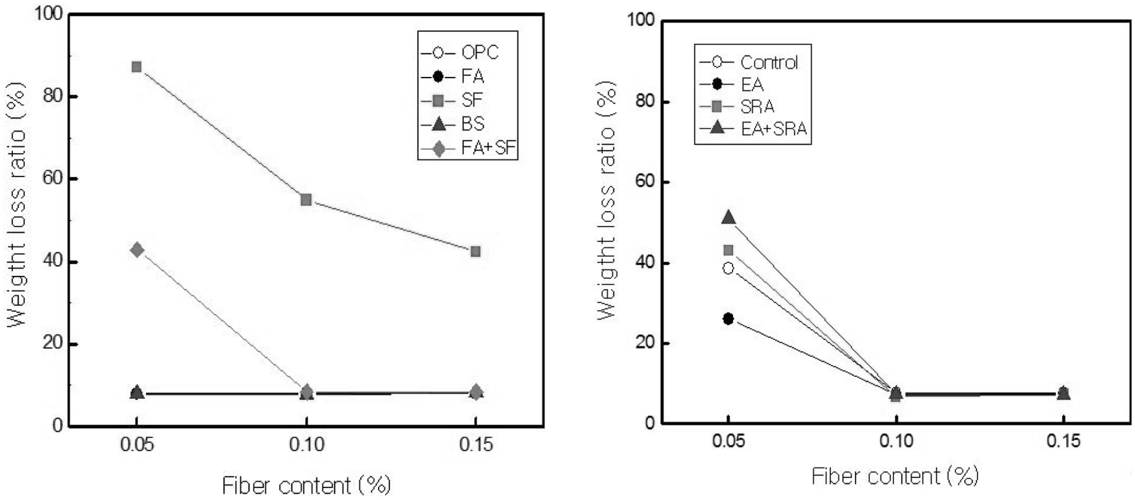
Fig. 7 Diagram of pore systems in hardened cement paste.[15]

As expected, control concrete of experimental series II exhibited similar tendency to OPC of experimental series I. The degrees of spalling for EA, SRA, and EA+SRA specimens with fiber content of 0.05vol.% were indicated at class 2 to 4, but these specimens were protected from spalling when the fiber content increased to more than 0.10vol.% as it was similarly shown in control concrete. Therefore it is clear that incorporating shrinkage reducing admixture does not significantly affect the protection from spalling.

Fig. 8 shows the weight loss ratio of high strength concrete with experimental variables of mineral admixture types and fiber content after the fire test.

As the spalling degree was examined in Photo 1, the specimens incorporating SF and containing 0.05vol.% of PP fiber resulted in 87% reduction of its original weight as shown in Fig. 8(a), while other specimens without SF admixture showed 7 to 8% of weight loss ratio. Even though spalling was not observed in some specimens, the reason for these weight loss ratios of less than 10% is attributed to the vaporization of free water and water content in the concrete itself. In addition, for the properties of concrete with EA and SRA as shown in Fig. 8(b), the EA+SRA specimen with PP fiber content of 0.05vol.% indicated a 51% reduction of its original weight, which was the highest weight loss. The lowest one was seen in EA specimen, exhibiting only 25% weight loss.

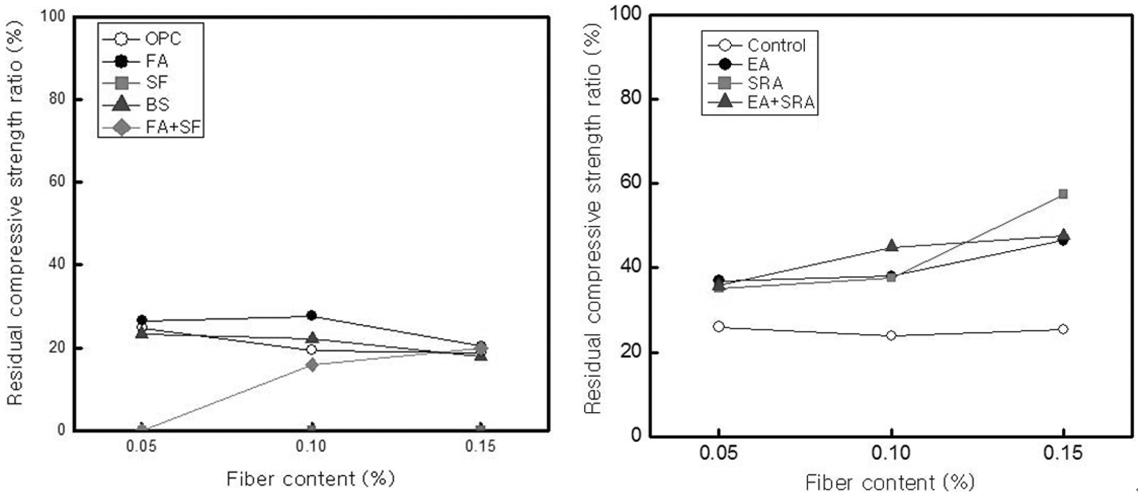
However, the specimens with fiber content of more than 0.10vol.% showed rather small weight loss ratios of 7 to 8%.



(a) Series I

(b) Series II

Fig. 8 Weight loss ratio of specimens after the fire test.



(a) Series I (b) Series II

Fig. 9 Residual compressive strength of specimens after the fire test.

These ratios were exhibited in all specimens, for which the spalling was protected.

Fig. 9 shows the residual compressive strength ratio of high strength concrete after the fire test for one hour.

The residual compressive strength ratios of FA+SF specimens in series I could be measured when PP fiber content of more than 0.10vol.% was added as shown in Fig. 9(a). The ratios were less than 15%, indicating significantly reduced residual compressive strength. These values were not improved even in spalling-protected specimens as their residual compressive strength ratios were mostly measured at less than 25%. The residual compressive strength ratios for the specimens with SF admixture could not be measured due to the lower spalling degree of 3rd to 4th class. In addition, most specimens in Fig. 9(b) exhibited less than 50% of the residual strength ratio, also. This large percentage of strength loss is because of the small size of specimens, allowing the abrupt high heat from outside getting through deep inside the cylinder mould to cause the thermal expansion of concrete components and cracking. However, these values of residual compressive strength of the concrete can have favorable results if the size of the specimens is large enough due to the effect of cutting-off the heat conduction to the inside of concrete.[16] Thus, although the small size of specimens results in very low values of residual compressive strength, it should be pointed out that the issue of whether spalling occurs or not is a very important factor itself in finding a fire resistance method in the future.

4. Conclusions

This study investigated the fundamental and spalling properties of high strength concrete designed with various mineral admixtures and fiber content. The results of this study are summarized in the following.

1) As for the properties of fresh concrete, incorporating SF and FA in the test specimens decreased the (slump flow). Adding higher fiber content also decreased the (slump flow) in all specimens. Interestingly, air content was affected by the complex reaction of both (slump flow) and fiber content. Thus it is found that adding fiber itself in fresh concrete obviously decreases the air content as the increase in air content is prohibited by the decrease in the slump flow only.

2) As for the properties of hardened concrete, the compressive strength of FA+SF specimens of experimental series I at 28 days was measured at 78 MPa, which was the highest value, and that of other specimens without SF decreased the value from 20 to 40%. In addition, most of specimens of experimental series II exhibited excellent development of the strength as measured at more than 70 MPa.

3) The specimens with 30% SF exhibited severe spalling occurrence even with three times higher fiber content than other specimens. FA+SF specimens with fiber content of more than 0.10vol.% were protected from the spalling, while specimens with OPC, BS and FA did not exhibit spalling occurrence even with the fiber content of only 0.05vol.%. These spalling properties are significantly related to the usage of mineral admixtures. Thus spalling occurrence not only is affected by strength improvement but also is more influenced by the alteration of pore structures inside the concrete mixed with certain mineral admixtures.

4) The results of residual compressive strength tests after the one-hour fire test showed that most specimens even including those protected from spalling exhibited residual compressive strength ratios of only 20 to 50% of their original strengths, which are rather small values. Addition of EA, SRA or EA+SRA to the specimens did not badly affect the experimental results of the residual compressive strength tests.

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