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Research Article

Improvement for Construction of Concrete-Wall with Resistance to Gas-Explosion

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The research was initiated to investigate the performance of fiber-reinforced concrete for protecting people or assets in the building against the explosion or debris missiles. The fiber-reinforced concrete has the difficulty with being applied in the actual construction conditions with the normal ready-mixed concrete system. The fibers for the protection performance require high toughness to endure the huge energy from an explosion, but the large amount of the fiber is required. The required amount of fibers can result in decreased workability and insufficient dispersion of fibers. It has been difficult to apply fiber-reinforced concrete on field placing with the ready-mixed concrete system of plant mixing, delivering, and placing. This research carried out the investigation of properties of combined fiber of steel and polymeric fiber to improve workability and agitating in the mixer. Based on the preliminary experimental test results in a laboratory, combined fiber-reinforced concrete was applied on the actual field construction of chemical plant. According to the results from the laboratory tests and application in the real construction project, it is expected to introduce the combined fiber for desirable mechanical performance with less adverse effect on workability of the mixture.

1. Introduction

Against terrorism or warfare, structures or facilities with special purpose should have sufficient protecting performance for shock wave or debris missiles from bombing or explosion. In addition to the special purposed facilities, many people who work at the plants where handling explosive substances such as explosive gas or massive structures should be protected against explosion. Generally, to secure the enough protecting performance against these kinds of forces, the wall should be constructed thicken enough with normal strength-ranged reinforced concrete. For the lateral stress caused by earthquake or explosion, fiber-reinforced concrete (FRC) is known as a solution with its high energy absorption capacity and high tensile strength [1]. Comparing to the normal concrete without fiber reinforcement, FRC has high tensile strength and toughness. Generally, for FRC, the fiber content is a key of improving mechanical properties of the material [2].

On the contrary, addition of fiber in concrete mixture causes reduction of workability with increasing both viscosity and yield stress. Because of poor yield stress, FRC with increased fiber content has been reported a fiber ball effect during the mixing process and unfavorable consolidating performance. Therefore, as a method of achieving the maximum mechanical performance without workability issue, slurry infiltrated fiber concrete was introduced [3, 4]. Likewise, for FRC, the fiber content should be balanced between mechanical properties and workability.

The reinforcing fibers for improving the performance of cementitious materials have different roles or performances depending on their aspect ratios (length-to-diameter ratio), materials, or shapes (straight, bent, or hooked). Especially, regarding the materials, the reinforcing fiber can be categorized into metallic and polymeric fibers. First, metallic fiber, mainly steel fiber, increases the toughness of the mixture. The metallic fiber itself has a high tensile strength and elastic modulus; thus it provides increasing tensile strength and elastic modulus while it is pulled out from the cement matrix. Since the metallic fiber has a higher tensile strength than cement matrix, the fail behavior of metallic fiber is pulling out of the fibers, so there are various geometries of the metallic fibers such as hooked, bent, or various cross sections. Otherwise, polymeric fibers, such as polypropylene, polyethylene, or nylon fibers, have a relatively lower tensile strength and elastic modulus than metallic fiber. Hence, the polymeric fiber cannot improve the mechanical properties of the mixture as the metallic fiber does; however, because of the advantage of good dispersion inside of the fresh state cementitious materials, it contributes on improving mechanical properties of the mixture. Especially, the polymeric fiber can be produced with the high aspect ratio with thin diameter, and because of flexibility of the shape, it does not decrease the workability of the mixture rather than metallic fiber. The hybrid fiber or cocktailed fiber means the combined fibers of different types to achieve synergetic effect. For instance, Banthia et al. and Markovic et al. reported improved mechanical properties of FRC with two fibers with different materials [5, 6], and Peng et al. reported two different polymeric fibers with different aspect ratios and melting points for improved performance of preventing spalling damage of high-performance concrete mixture [7]. These studies were showing improvement in desired properties of FRC with combined fibers or hybrid fiber with decreased fiber content for the achievement of improved workability. Therefore, combining different types of fibers has been used as a solution of decreased workability by decreasing fiber content with equivalent performances [8].

Although various researches were reported using combined fiber for improving mechanical properties, the study based on sufficient workability by field placement is not reported enough. Especially, because of the issue of securing the quality of fiber dispersion and relatively low workability, it was difficult to apply the FRC on field placement using the ready-mixed concrete system including plant mixing, agitator truck delivering, and placing with pump. In this research, with the goal of providing protectable concrete against flying debris or missiles, combined fiber was applied for sufficient performance with favorable workability. Therefore, both the protecting performance against flying debris and the field applicability of fresh concrete placing were evaluated. Especially, for field applicability, the experiment was conducted for an actual plant construction. From the result of this research, it is expected to provide a technique of manufacturing high-performance fiber-reinforced cementitious composites (HPFRCCs) with favorable protecting performance and workability.

2. Experiment on Protecting Performance

2.1. Experimental Plan. To evaluate the protection performance of combined FRC, mixture conditions with the combination of three different fibers were prepared for the experimental test as shown in Table 1. The water-to-binder ratio (w/b) was fixed as 0.50 and the target concrete compressive strength was 24 MPa for the concrete wall. The water content was 220 kg/m^3 to satisfy 150 ± 20 mm of the target slump. According to the preliminary test, the sand-to-aggregate ratio (S/a) was designed as 0.55 for stable viscosity and the target air content was 4.5 ± 1.5%. For cementitious binder, ternary mix design was used with ASTM type I cement (OPC) including 20% of blast-furnace slag (BS) and 10% of fly ash (FA) by weight to expect the better workability [9]. Using steel fiber (SF) and polyaramid fiber (PF), three mix combinations were set up, and the fiber content was fixed to 1 percent of entire mixture volume which was determined by the preliminary test and the study of Yusof et al. [10]. The tests of the slump and air content were conducted to confirm the fresh concrete performance. For hardened concrete performance, fundamental mechanical properties were evaluated with compressive, flexural, and tensile strengths at 7 and 28 days of age, and protecting performance was evaluated with impacting high-velocity projectile.

Table 1: Experimental plan.

Mixing properties		Test items	
w/b	0.50	Fresh concrete	Slump Air content
Water content (kg/m^3)	220		
S/a	0.55	Hardened concrete	Compressive strength at 7 and 28 days Flexural strength at 7 and 28 days Tensile strength at 7 and 28 days Impact of high-velocity projectile
Target slump (mm)	150 ± 20		
Target air content (%)	4.5 ± 1.5		
Binder composition (by weight)	OPC : BS : FA = 7 : 2 : 1		
Fiber content (%)	1		
Fiber combination	SF only PF only SF + PF		

2.2. Materials and Sample Preparation. According to the information provided from the cement manufacturer, the specific gravity was 3.15 and Blaine was 3,650 cm^2/g. Blast-furnace slag was 2.88 of specific gravity and 4,469 cm^2/g of fineness. Fly ash was similar to the class F fly ash designated by ASTM C618; the specific gravity was 2.27, and fineness was 3,381 cm^2/g. The properties of admixture are shown in Table 2. For concrete mixture, coarse and fine aggregates were used with the use of manufactured aggregate and river sand, respectively, and the physical properties of those aggregates are shown in Table 3. As fiber reinforcement, two different types of fiber were used: steel and polyaramid fibers. The SF was bent, and the PF was twisted. The properties and shapes of fibers are provided in Table 4 and Figure 1, respectively.

Three different mixtures with different fiber conditions were prepared. Based on the single concrete mixture, SF, PF, and the binary fiber of SF and PF were added 1% of entire mixture volume. The mix proportions of three mixtures are shown in Table 5. For FRC mixing, a 60-liter pan-type mixer was used. The mixing protocol is shown in Figure 2. For the first step, cementitious binder and aggregate were introduced into the mixer and mixed with low speed (20 rpm) for 30 seconds. Next, mixing water was added and mixed with medium speed (30 rpm) for 60 seconds, and as the last

Table 2: Physical properties of admixture.

Classification	Form	Property	Color	pH	Density (g/cm^3)
SP agent	Liquid	Polycarbonate	Ivory white	6.5	1.06

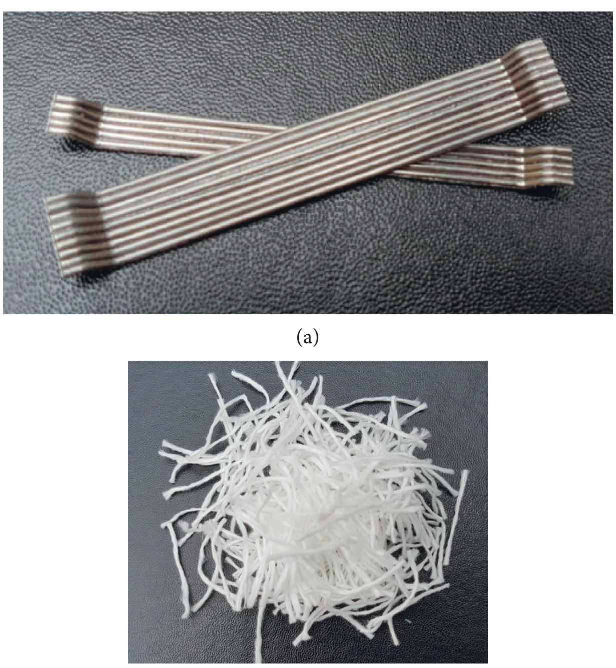
SP: superplasticizer.

Table 3: Physical properties of aggregates.

Aggregate	Density (g/cm^3)	Fineness modulus	Unit volume weight (kg/m^3)
Fine aggregate	2.57	2.57	2.84
Coarse aggregate	2.71	6.78	1.57

Table 4: Physical properties of fibers.

Fiber	Aspect ratio	Length (mm)	Diameter (mm)	Tensile strength (MPa)
SF	66	35	0.53	1,108
PF	61	30	0.49	623



(a)

(b)

Figure 1: Shape of the fibers. (a) Steel fiber (SF). (b) Polyaramid fiber (PF).

step, superplasticizer was added and the entire mixture was mixed with high speed (40 rpm) for 90 seconds during the fiber was spread into the mixer to prevent fiber ball production, which can be found in FRC [11].

2.3. Test Methods. For fresh state properties, slump and air content of the mixtures were measured as ASTM C143 and C138 standards, respectively. The mechanical properties of mixtures were inclusive of compressive, flexural, and tensile strengths at 7 and 28 days of ages. Each test was conducted following ASTM C39 and C78 for the compressive and flexural strength tests, and JSCE-E-531 [12] standard for the direct tensile test from Japan Society of Civil Engineering (JSCE) was used for tensile strength measurement. Each test was conducted with three specimens for a single averaged value. To evaluate the protecting performance against missiles resulted from explosion in building, the direct impact test was conducted by shooting 25 mm diameter of spherical iron projectiles to the concrete panel of height 200 mm, width 200 mm, and depth 50 mm. The projectile was shot by compressed gas, and the velocity of projectile at impact was 170 m/s. The evaluation of protecting performance was executed by observing both the front and back surfaces of the concrete panel after impact. The impact test was conducted with two samples for a single case's result.

3. Results and Discussion

3.1. Fresh Concrete Properties. To investigate the influence of different fiber combinations, slump of each mixture was measured, and the result is shown in Figure 2. Figure 2 shows that slump decreased for the mixture of only PF in concrete mixture. As the well-known theory, slump of concrete is related with yield stress of the mixture, and as the report of Tattersall et al. [13], adding fiber causes increasing yield stress with viscosity, especially, the yield stress is increased significantly [14]. Between the SF and PF, the biggest difference is rigidity of fiber. Therefore, it is considered that SF can be oriented and has relatively lower resistance of collapse of the mixture than PF because of its rigidity. Comparing with two mixtures with solely SF and PF, the concrete mixture with combined SF and PF showed a relatively favorable result of slump. Although the slump value of the mixture was slightly lower than the mixture with SF, still the slump value of the mixture with combined SF and PF showed a similar value to the slump value of the mixture with SF, and the value (130 mm) was higher than the average slump value (100 mm) of the mixture with single fiber.

The air contents of concrete mixtures were measured and are shown in Figure 3. Generally, all three cases satisfied the target air content range. As shown in the figure, the concrete mixture with SF showed the highest air content while the concrete mixture with PF showed the lowest air content. According to the research of Balaguru and Shah [15], the steel fiber contributes to the increase in air content while the polymeric fiber does not influence the air content. It is also considered as a result of different rigidity of fibers, and the test results agreed with the reference. For the concrete mixture with combined fibers of SF and PF, the air content was relatively close to the mixture with SF. From this result, it can be stated that SF influences more than PF on air content of the concrete mixture. Hence, the air content of the mixture with both SF and PF showed 9 % higher air content than the average air content of the mixtures with each SF and PF. Therefore, summarizing the fresh-state test results, combining SF and PF is having the properties of the dominated type of the fiber and it is mainly influenced by the rigidity of fiber. Furthermore, eventually, for slump and air

Table 5: Mix proportions.

Name	w/b	Fiber content (%)	S/a	SP (%/b)	Unit weight (kg/m^3)							
					W	C	FA	BS	S	G	SF	PF
SF					220	293	44	88	829	693	79	0
PF	0.50	1.0	0.55	0.7	220	293	44	88	829	693	0	11
SF + PF					220	293	44	88	829	693	39	5

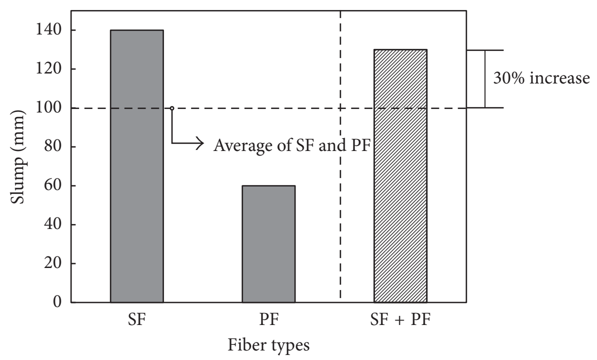


Figure 2: Influence of fiber combination on slump of concrete mixtures (the dotted line expresses the average value of SF and PF).

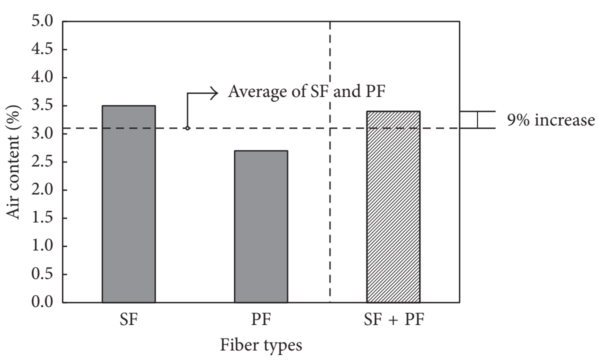


Figure 3: Influence of fiber combination on air content of concrete mixtures (the dotted line expresses the average value of SF and PF).

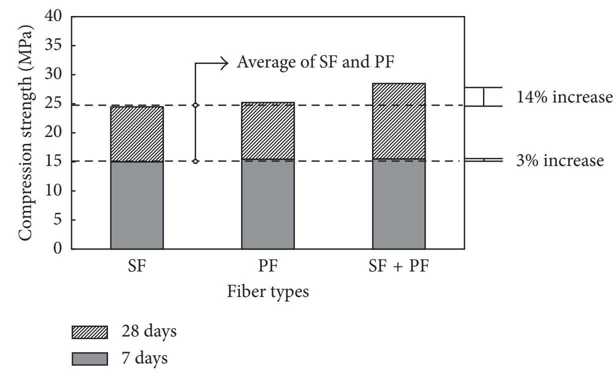


Figure 4: Influence of fiber combination on compressive strength of concrete mixtures (the dotted line expresses the average value of SF and PF).

content of concrete mixture, combining SF and PF shows favorable results on fresh-state concrete performances.

3.2. Mechanical Properties. To evaluate the mechanical properties of the concrete mixtures with various fiber conditions, compressive, flexural, and tensile strengths were measured. The compressive strength measurement results are shown in Figure 4. From the compressive strength results, it can be state that the different types of fiber do not influence on the compressive strength of the concrete mixture, in this research scope. However, when two types of fiber are combined, improved compressive strength can be obtained. At seven-day age, the average value of compressive strengths of the mixtures including each SF and PF was 15.3 MPa, and the compressive strength of the mixture with combined fiber of SF and PF was 15.8 MPa. Although there was no significant improvement at seven-day age, at 28-day age, the compressive strength of the mixture with combined fiber of SF and PF showed 28.7 MPa, approximately 14 % higher than the average value of each mixture. This improved compressive strength with combined fiber is considered as a result of synergetic effect of different types of fiber for controlling cracks and confining the sample, and at 28-day ages, the increasing compressive strength due to the fiber reinforcement was maximized with hardened cementitious matrix.

From the flexural strength test result, the synergetic effect of combined fiber was also shown. As shown in Figure 5, the concrete mixture with SF showed relatively higher flexural strength than the concrete mixture with PF at both seven-day and 28-day ages. In spite of this different performance of the mixtures with different fibers, the concrete mixture with combined fibers showed improved flexural strength values at both seven-day and 28-day ages. Also, similar to the compressive strength result, the improvement of flexural strength at 28-day age was higher than the improvement of it at seven-day age with approximately 29 and 19 %, respectively.

As shown in Figure 6, unlike compressive and flexural strength results, from the tensile strength test result, at seven-day age, the concrete mixture with PF was slightly higher than the concrete mixture with SF. Generally, steel fiber is difficult to be broken by tensile forces but pulled out, while polymeric fiber is easily broken by tensile forces. Therefore, at seven-day age, the concrete with SF experienced pulling out of the fiber rather than the breaking of fiber, and the improvement of tensile strength of the mixture with SF between seven days and 28 days was higher than that of the mixture with PF. Since the main factor of resistance against tensile forces was pulling rather than breaking of the fiber for concrete mixture with PF, there was less improvement between seven days and 28 days. In spite of this different trend of the concrete mixtures with single-type fiber, the concrete mixture with combined fiber showed similar trend with the compressive and flexural strengths'

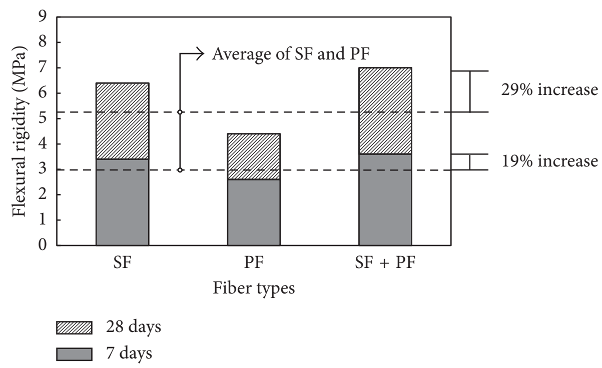


Figure 5: Influence of fiber combination on flexural strength of concrete mixtures (the dotted line expresses the average value of SF and PF).

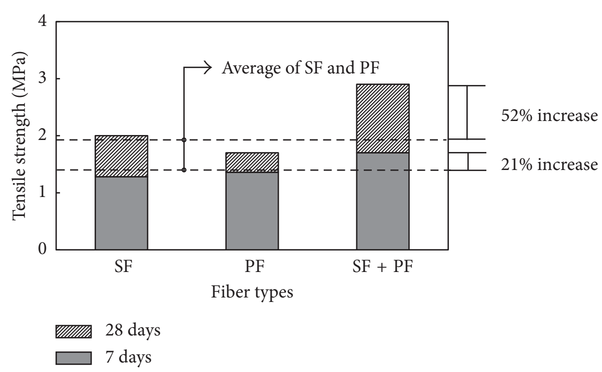


Figure 6: Influence of fiber combination on tensile strength of concrete mixtures (the dotted line expresses the average value of SF and PF).

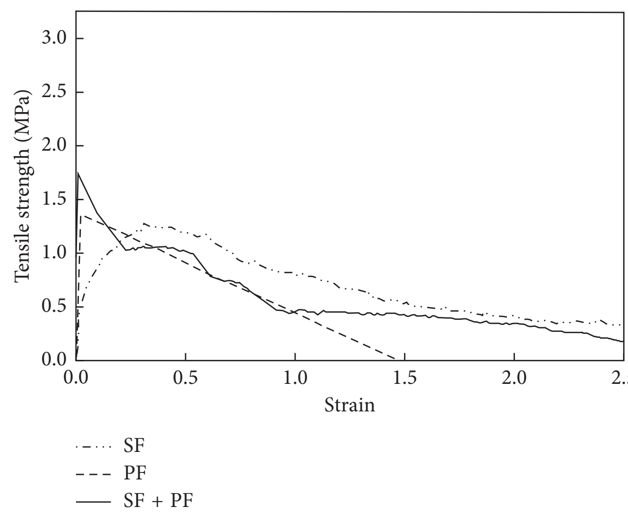


Figure 7: Influence of fiber combination on toughness of concrete mixture at seven-day age.

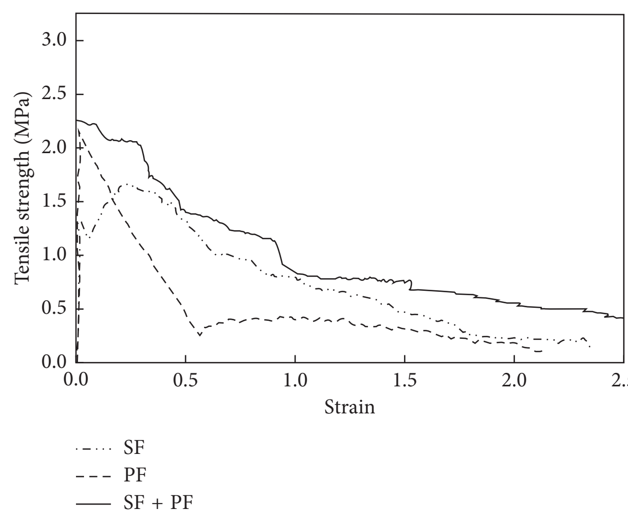


Figure 8: Influence of fiber combination on toughness of concrete mixture at 28-day age.

results of improving performance. At seven-day age, the tensile strength of the concrete mixture with combined fiber showed approximately 21 % higher than the average value of the mixtures with each SF and PF, and approximately 52 % higher than the average value of the mixtures with each SF and PF. Based on the tensile forces, strain-tensile strength relations were obtained and are shown in Figures 7 and 8 for seven-day and 28-day ages, respectively. From the results, generally, the concrete mixture with SF showed dropped tensile strength at very early stage, but after this, strain-hardening behavior was shown and continuously absorbed energy. On the contrary, in the case of the concrete mixture with PF, initially relatively higher strength was shown rather than the mixture with SF, but after the yield point, steep decrease of strength was observed. Hence, based on these results, it can be stated that some of SF could be pulled out at initial tensile forces, while the remaining fibers could be resisted and could absorb the energy while PF was hard to be pulled out by tensile forces, but it could be broken when the tensile forces were applied. Furthermore, at 28-day, the cementitious matrix became hardened and it grabbed the fibers hard to prevent pulling of fibers (by comparing tensile strength of all the cases in Figures 7 and 8). For the mixture with combined fiber, especially, synergetic effect was shown at both ages: high tensile strength at early age with PF and high toughness and energy absorption at later period with SF. Therefore, based on the mechanical properties of fiber-reinforced concrete mixtures, it is considered that the reinforcement with combined fibers has better performance than the reinforcement with single fiber. Furthermore, considering with fresh-state test results, it can be suggested that using combined fiber of different types can achieve improved mechanical properties with favorable workability of the concrete rather than using single type of fiber.

3.3. Protecting Performance. In this paper, steel fiber was applied into a concrete protection wall to ensure the safety of workers in the explosion of Freon gas used in cosmetic raw material companies. The gas tank used is located away from the wall as shown in the magnified area in Figure 9. It does not directly affect the workers by the gas explosion when the gas explosion occurs, but a lot of piping and equipment

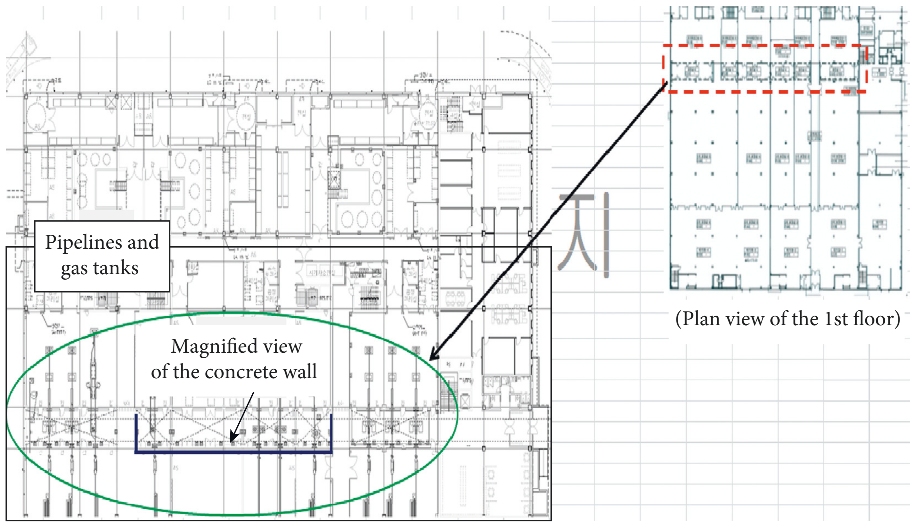


Figure 9: Plan view of the protection wall against flying debris due to explosion.

between the gas tank and the concrete wall are able to be affected at explosion due to gas explosion. Numerous debris from the explosion can impact the concrete, and scabbing or perforation on the other side of wall can damage workers on the other side of the concrete wall by an impact. As a result, the projectile test was performed to study the effect of debris damage for workers on the other side of wall.

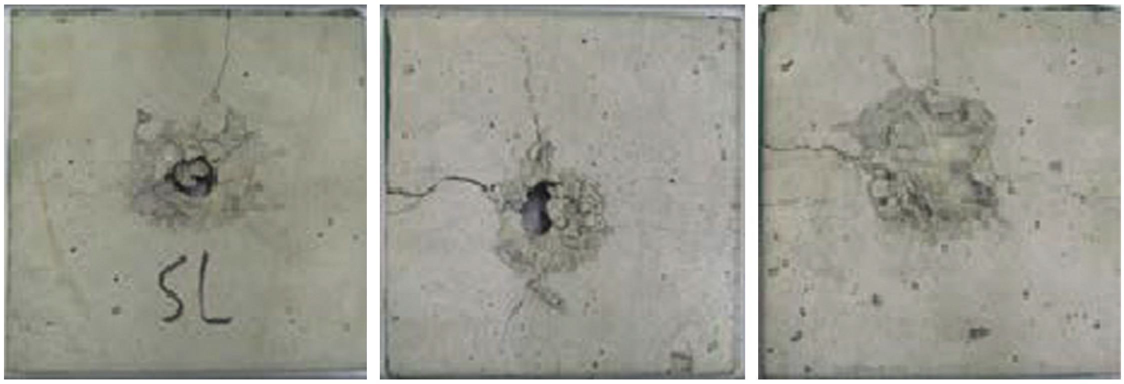
Using the high-velocity projectile, the influence of different fiber combination on the protection performance of concrete was evaluated. Since there was no standardized measurement method, the concrete panels after the impact test were observed on the impacted face and the back side. As shown in Figure 10, the concrete panels including a single fiber type showed penetrated damage. Comparing the impacted side, for both concrete panels with single-type fiber, the back side suffered spalling out of the concrete while the impacted surface has a hole with the size of projectile. However, in the case of the concrete panel with combined fibers, clearly improved protecting performance was shown rather than two concrete panels with SF and PF. In the case of the concrete panel with combined fiber, on the impacted side, relatively wide damage was shown instead of penetration. Since the penetration of projectile was prevented, cracking from the center of the panel was occurred without loss of concrete. Hence, it is considered that because of high pulling resistance and toughness by PF and SF, respectively, in the concrete panel with combined fiber, the impact resistance is improved and efficiently absorbed the impact energy. Summarizing the mechanical properties and protecting performance of the concrete samples with various fiber conditions, the combined fiber of SF and PF showed relatively improved mechanical properties and protecting performance with the synergetic effect from combined fiber.

4. Field Applications

4.1. Field Conditions for Site and Mixture. The target building was the chemical plant for manufacturing cosmetics. Because of the process of manufacturing the cosmetics, high-pressured gas should be injected, and the special area for this process should be protected against unexpected explosion or flying debris caused by the explosion. The main structure was reinforced concrete structure. In this research, the suggested HPFRCC was applied on the outer wall of the protected area as shown in Figure 11. The applied amount of HPFRCC was approximately 50 m^3 for 3 m depth of the protecting wall. The concrete mixture delivered by trucks with an agitator was placed using the ready-mixed concrete system from mixing at plant to placing by pump. The target concrete mixture was 25 MPa of target compressive strength (at 28 days), and 150 mm of target slump. Unlike the laboratory test, the field applied concrete mixture contained a maximum size 25 mm of coarse aggregate. For improving workability, combined fiber of SF to PF of 1 : 1 was replaced 1% of entire volume of the mixture. These levels of experimental tests were shown in Table 6.

The concrete mixture was mixed in the ready-mixed concrete plant with the central mix method. However, since the ready-mixed concrete plant should be used, the plant did not have the setting for fiber introduction, and thus, the fiber was introduced manually through the materials feeding entrance for the premeasured amount. The mixing time for HPFRCC was approximately one to two minutes instead of 30 to 40 seconds of normal concrete to provide sufficient workability and dispersion of fibers. Other processes of delivering and placing of concrete were conducted with agitator trucks and pump truck by following South Korean ready-mixed concrete standard of KSF 4009 [16]. For the ready-mixed concrete, cement with a density of 3.15 g/cm^3 was used. River and crushed sand were mixed in a proportion of 50 : 50 for fine aggregates, whereas coarse aggregates were a mixture of 5 to 10 mm and 10 to 25 mm aggregates in a proportion of 35 : 65.

4.2. Test Methods. To evaluate the properties of the mixtures for the actual field condition, slump and slump flow tests for workability, air content, and compressive strength for



SF PF SF + PF

(a)

SF PF SF + PF

(b)

Figure 10: Influence of fiber combination on protecting performance of the concrete panel against the impact test. (a) Impacted side (front). (b) Back side.

Figure 11: (a) Field application architecture perspective and (b) cross-sectional view.

Table 6: Field test plan.

Experimental items		Level of experiment
Mixture	Ready-mixed concrete specification	25-24-150
	Fiber mixing ratio (%)	1.0
	Combination of fibers	SF + PF

mechanical properties were measured. The testing samples were obtained from the first and third agitator trucks arrived in sites such as in Table 6 and tested samples were obtained before and after the pumping. Each test was conducted following ASTM C143, C1611, C231, and C39 methods for slump, slump flow, air content, and compressive strength, respectively. The compressive strength was tested at seven- and 28-day ages.

4.3. Result of Field Applications. First, from the slump and slump flow test results as shown in Table 7, respectively, the fluidity of the concrete mixture was increased after the pumping. Generally workability of concrete is decreased in slump or flow after the pumping. However, in this research with fiber-reinforced concrete, it is considered that the fibers in concrete mixture were oriented by the pressure of the pumping and it contributed to the improved fluidity of the fiber-reinforced concrete mixture. In spite of improved fluidity of the mixture, air content of concrete was decreased. It is similar trend of already reported results of studies.

Table 7: Experiment result of concrete.

Division		Slump (mm)	Slump flow (mm)	Air contents (%)	Compression strength (MPa)	
					7 days	28 days
First agitator truck arrived in site	Before pumping	130	225/220	4.0	20.9	30.9
	After pumping	170	240/300	3.6	23.8	32.7
Third agitator truck arrived in site	Before pumping	135	230/240	3.8	21.8	31.0
	After pumping	160	310/280	3.5	24.2	33.1

However, in general, the properties of fresh-state fiber-reinforced concrete mixture were acceptable to apply field construction, and there was no problem on placing process of the wall.

The field-processed HPFRCC's mechanical properties were evaluated with compressive strength. As shown in Table 7, all concrete samples showed over 30 MPa and it was higher than the target compressive strength of 25 MPa. For the concrete mixture obtained after the pumping, slightly increased compressive strength was observed. It can be stated that decreased air content and well-oriented fiber can contribute to the improved compressive strength. For more detail, although it is necessary to study the relation between pumping and performance of HPFRCC, in this research, the goal of the experiment was evaluating field applicability of HPFRCC, thus it is not discussed in this paper.

5. Conclusion

In this research with a goal of applying HPFRCC on field conditions, the workability, mechanical properties, and protecting performance of combined fiber-reinforced concrete mixtures were evaluated, and field application was conducted with a ready-mixed concrete system. According to a series of experiment, some conclusions can be obtained as follows:

(1) By using combined fiber of SF and PF, fresh-state properties of HPFRCC were improved rather than the case with the unfavorable result with a single fiber and showed better performances than the averaged value of each single-type fiber-reinforced mixture.

(2) For mechanical properties of compressive, flexural, and tensile strengths, the mixture with combined fiber showed improved values rather than any single-type fiber-reinforced mixtures.

(3) Regarding the protection performance against flying debris, the HPFRCC panel reinforced by combined fiber showed the most desirable performance of protecting the high-velocity projectile.

(4) The combined HPFRCC showed improved mechanical and protecting performances with favorable workability. Based on these improved features of combined fiber reinforcement, field application of combined HPFRCC was successful under the ready-mixed concrete system including agitators, delivering, and placing.

Conflicts of Interest

The author declares no conflicts of interest.

Acknowledgments

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