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RESEARCH

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Evaluation on Protection Performance and On-Site Applicability of Hybrid Fiber-Reinforced Concrete

Dongyeop Han[1], Yong-Jun Park[2], Min-Cheol Han[3] and Seong-Tae Yi[4*]

Abstract

The aim of this research is to evaluate the protecting performance of hybrid fiber-reinforced concrete against lateral forces such as explosives or flying objects. The objective of this research is to better prepare this concrete for use in the ready-mix concrete industry. Even though the fiber addition gives it strong mechanical properties, it also decreases workability due to the inefficient dispersion of fibers. Therefore, it has been difficult to apply to the ready-mix concrete plant's mixing, delivery and on-site placement. The authors have developed a combined steel and polyaramid fiber that gives the favorable protection needed against high-impact forces and provides a suitable workability for the ready-mix concrete system. To evaluate the required performance, the hybrid fiber-reinforced concrete specimen was subjected to high-speed projectiles and had its workability and performance tested on a construction site of an established ready-mix concrete company. The hybrid fiber-reinforced concrete successfully provided the protection capabilities sought for the finished product and provided a workable-ready mix applicability.

Keywords: hybrid fibers, fiber-reinforced concrete, blast resistant concrete, field application, ready-mix concrete system

1 Introduction

When subjected to terrorism or warfare, everyone wants protection, which is why structures or facilities in areas that suffer from these attacks need to provide occupants with sufficient protection from shock waves or flying debris from bombs or other types of explosives. Plants that handle or manufacture explosive substances in highly populated areas also need to be housed in structures that can provide protection. For the lateral stress caused by an earthquake or explosion, fiber-reinforced concrete (FRC) is known as a solution because of its high energy absorption capacity and high tensile strength (Li and Leung 1992; Yazıcı et al. 2007; Hsie et al. 2008). Compared to normal concrete without fiber reinforcement, FRC, developed to control cracking, has a high tensile strength and toughness. Generally, for FRC, the fiber content is the key to improving mechanical properties of the FRC mixture (Balaguru and Shah 1992).

On the other hand, the addition of fiber in a concrete mixture causes reduction of workability while increasing both viscosity and yield stress (Tattersall and Banfill 1983). It means FRC is still not suitable for on-site placement with a general ready-mix concrete system. Thus, for FRC, the fiber content should be balanced between mechanical properties and workability. The reinforcing fibers used to improve 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 (Balaguru and Shah 1992; Bentur and Mindess 2006). First, metallic fiber, mainly steel fiber, increases the mechanical properties such as tensile strength and toughness of the mixture. The metallic fiber itself has a high tensile strength and elastic

*Correspondence: yist@inhatc.ac.kr
[4] Department of Civil and Environmental Engineering, Inha Technical College, Incheon, South Korea
Full list of author information is available at the end of the article
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modulus; thus, it increases tensile strength and elastic modulus until it is pulled out from the cement matrix. Since the metallic fiber has a higher tensile strength than cement matrix, the failure behavior of metallic FRC is mainly due to fiber pull-out or debonding, so there are various geometries designed to keep this from happening. Otherwise, generally, polymeric fiber has been known as a fiber with lower tensile strength and elastic modulus than metallic fiber, although some polymeric fibers has a higher tensile strength than some metallic fibers. Hence, the polymeric fiber cannot improve the mechanical properties of the mixture like the metallic fiber does; however, because of the advantage of good dispersion inside of fresh state cementitious materials, it helps control cracking of the concrete (Ferrara et al. 2007).

The hybrid fibers or cocktailed fibers mean the combined fibers of different types of fiber are needed to achieve the synergetic effect. For instance, Yao et al. (2003), Hsie et al. (2008), Banthia and Gupta (2004), Park et al. (2012), and Markovic et al. (2003) reported improved mechanical properties of FRC with two fibers with different materials, and Lee et al. (2012) reported two different polymeric fibers with different aspect ratios and melting points for improved performance in preventing spalling damage of high performance concrete mixtures. As shown in these studies, using hybrid fibers in concrete mixture can achieve a broad range of performance depending on the different conditions of the reinforced fiber. Therefore, using hybrid fibers can solve some drawbacks of the single-fiber reinforcing concrete such as decreased workability with an increased single-fiber content. The problem is that workability is needed to secure the sufficient protection performance.

Although many researchers have used hybrid fibers for improving mechanical properties, the study on achieving both workability and mechanical properties has not been reported sufficiently. Especially, due to the decreased workability of FRC, it has been difficult to apply FRC on-site using the ready mix concrete system with plant mixing and mobile concrete agitator truck delivery. The objective of this research was to provide both sufficient concrete protection performance and acceptable workability for ready mix concrete systems by using the suggested hybrid fibers. To evaluate the field applicability of fresh properties, a sufficient workability was evaluated with an appropriate range of slump and air content, and to evaluate the protection performance, the impact test using a high velocity projectile was executed. Additionally, to evaluate the applicability of FRC for a ready-mix concrete system and on-site placing, regarding the actual construction project, the determined mixture with hybrid fibers was applied to the ready-mixed concrete system. Hybrid fibers made success possible in this research. Furthermore, an actual example of applying FRC to a ready-mix concrete system is provided.

2 Lab-Based Experiment

2.1 Experimental Plan

In the lab-based experiment, the goal was to provide mixture conditions with hybrid fibers reinforcement to satisfy the two requirements of field applicability and protection performance. To evaluate the objectives, three mixtures were prepared under different conditions with a single mix design and three different fiber conditions. As shown in Table 1, the water-to-binder ratio was fixed at 0.50 or half of the normal strength range. The unit water content was 220 kg/m^3 to satisfy 150 ± 20 mm of the target slump

Table 1 Experimental plan.

Mixture conditions		Test items	
w/cm[a]	0.50	Fresh state	Slump Air content
Unit water content (kg/m^3)	220		
S/a[b]	0.55	Hardened state	Compressive strength (@ 7, 28 days) Flexural strength (@ 7, 28 days) Tensile strength (@ 7, 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 (%)[c]	1		
Fiber combination	SF only PF only SF + PF		

OPC ordinary Portland cement, *BS* blast furnace slag, *FA* fly ash, *SF* steel fiber, *PF* polyaramid fiber.

[a] Water-to-cementitious materials ratio.

[b] Sand-to-aggregate ratio.

[c] Fiber content to entire mixture volume.

for the steel fiber reinforced concrete mixture. According to the preliminary test, the sand-to-aggregate ratio was designed with a 0.55 stable viscosity, and the target air content was 4.5 ± 1.5%. For the cementitious binder, a ternary binder was used with ordinary Portland cement (OPC), then blast furnace slag (BS), and then fly ash (FA) of 7 to 2 to 1 by weight. Although the fiber combinations were prepared with two single strands, one steel fiber (SF) and one polyaramid (Nylon) fiber (PF), along with one hybrid fibers of SF and PF with a 50/50 weight. The fiber content was fixed to 1% of the entire mixture by volume, which was determined in a preliminary test. The fiber was replaced with a fine aggregate. To evaluate the field applicability of the FRC, the slump and air content were evaluated in fresh properties. Specifically, for the mixture slump, to assess the possibility of applying FRC for ready mix concrete, a target slump value of 150 ± 20 mm was used as the slump value from KS F 4009 (KS F 4009 2011). For hardened concrete performance, fundamental mechanical properties were evaluated with compressive, flexural, and tensile strengths at 7 and 28 days of age, and protection performance was evaluated by impacting a high-velocity projectile.

2.2 Materials and Sample Preparation

As a cementitious binder, the ordinary Portland concrete (OPC), blast furnace slag (BS), and fly ash (FA) used were commercially available products from the South Korean market. The OPC used had properties similar to Type I cement as designated by ASTM C150 (2012). Based on the information provided from cement manufacturer, the specific gravity was 3.15, and Blaine fineness was 3650 cm^2/g. The BS used was 2.88 of specific gravity and 4469 cm^2/g of fineness. The FA used was similar to the class F fly ash designated by ASTM C618 (2013), and the specific gravity was 2.27 with a fineness of 3381 cm^2/g. For mixing water, tap water was used and a polycarboxylate-based superplasticizer was added as a chemical admixture. The polycarboxylate-based superplasticizer used was a general product from the South Korean market. For concrete mixture, coarse and fine aggregates were used with manufactured aggregate and river sand, respectively. The aggregate physical properties are shown in Table 2. As a fiber reinforcement, two different types of fiber were used: steel and polyaramid fibers. The steel fiber (SF) was the hooked type and the polyaramid fiber (PF) was the twisted type fiber. Each fiber's properties and shapes are provided in Table 3 and Fig. 1, respectively.

There were three different mixtures with different fiber condition. Based on the single concrete mixture, SF, PF, and the binary fiber of SF and PF were added as 1% of the entire mixture volume. The mix design of the three mixtures is shown in Table 4. For FRC mixing, a pan-type mixer with 60 L capacity was used. The mixing protocol was shown in Fig. 2. For the first step, a cementitious binder and aggregate were introduced into the mixer and mixed at low speed (20 rpm) for 30 s. Next, mixing water was added and mixed at a medium speed (30 rpm) for 60 s. For the last step, a superplasticizer was added and the entire mixture was mixed at a high speed of 40 rpm for 90 s during which the fibers were spread into the mixer to prevent fiber balling.

2.3 Test Methods

For fresh properties, slump and air content of the mixtures were measured as ASTM C143 (2012), and C138 (2013) standards, respectively. The mechanical properties of mixtures were evaluated based on compressive, flexural, and tensile strengths at 7 and 28 days of age. Each test was conducted following ASTM C39 (2012), and C78 (2010) for compressive and flexural strength tests as well as the JSCE-E-531 standard (Japan Society of Civil Engineers 2010). The direct tensile test from the Japan Society of Civil Engineers was used for tensile strength measurement. Each test was conducted with three specimens for a single averaged value. To evaluate the protection performance against flying debris, the direct impact test was conducted by shooting a 25 mm diameter spherical iron projectile to a concrete panel with a height of 200 mm, a width of 200 mm, and a depth of 50 mm. The projectile was shot by compressed gas, and the velocity of the projectile at impact was 170 m/s (see brief drawing of the impact test setup in Fig. 3). The evaluation of the protection performance was executed by observing both front and back surfaces of the concrete panel after impact. The impact test was conducted with two samples for a single case result.

Table 2 Physical properties of aggregates.

Aggregate	Specific gravity	Fineness modulus (FM)	Unit volume weight (kg/m^3)
Fine aggregate	2.57	2.57	1840
Coarse aggregate	2.71	6.78	1570

Table 3 Physical properties of fibers.

Fiber	Aspect ratio	Length (mm)	Diameter (mm)	Tensile strength (MPa)
Steel fiber (SF)	66	35	0.53	1108
Polyaramid fiber (PF)	61	30	0.49	623

Fig. 1 Shape of the fibers; **a** steel fiber (SF) and **b** polyaramid fiber (PF).

Table 4 Mix proportions.

Mixture[a]	w/b[b]	Fiber content (%)	S/a[c]	SP[d] (%/B)	Unit weight (kg/m^3)							
					W	*C*	*FA*	*BS*	*S*	*G*	*SF*	*PF*
SF	0.50	1	0.55	0.7	220	293	44	88	829	693	79	0
PF					220	293	44	88	829	693	0	11
SF + PF					220	293	44	88	829	693	39	5

W water, *C* cement, *FA* fly ash, *BS* blast furnace slag, *S* sand (fine aggregate), *G* gravel (coarse aggregate).

[a] The name of mixtures were determined based on the types of reinforced fiber: *SF* (steel fiber), *PF* (polyaramid fiber).

[b] Water-to-binder ratio.

[c] Sand-to-aggregate ratio.

[d] Superplasticizer (polycarboxylate-based).

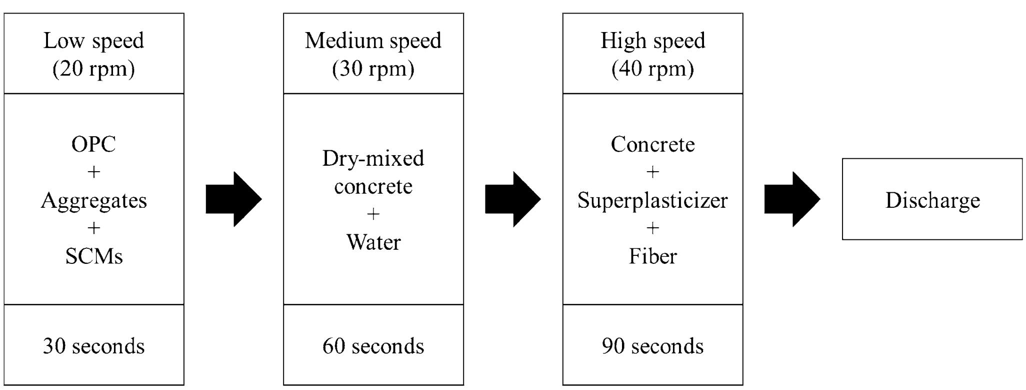

Fig. 2 Mixing protocol for FRC.

3 Results of Lab-Based Experiment and Discussion

3.1 Fresh Properties

To assess the influence of different fiber combinations, the slump of each mixture was measured and the result is shown in Fig. 4. The concrete mixture including SF and PF caused a decreased slump. Since the slump of concrete is related to yield stress of the mixture (Schowalter and Christensen 1998; Saak et al. 2004; Roussel 2006), and as Tattersall and Banfill (1983) reported, adding fiber causes increasing yield stress and viscosity. The yield stress increases significantly. Since the mixtures were in the normal strength range of water-to-binder ratio (w/cm)

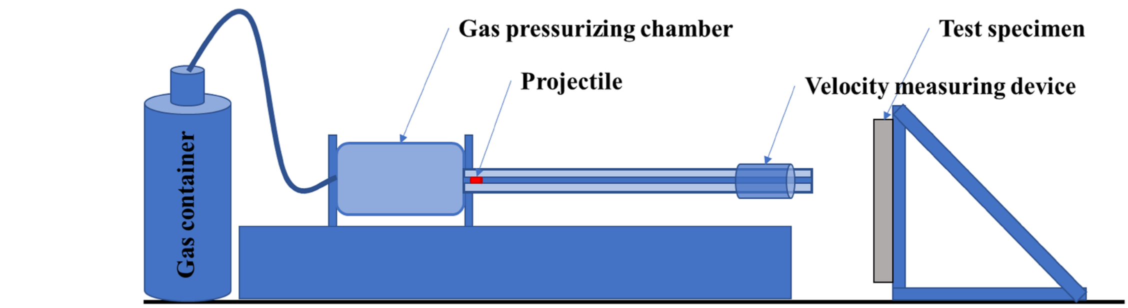

Fig. 3 Brief setup of impact test setup.

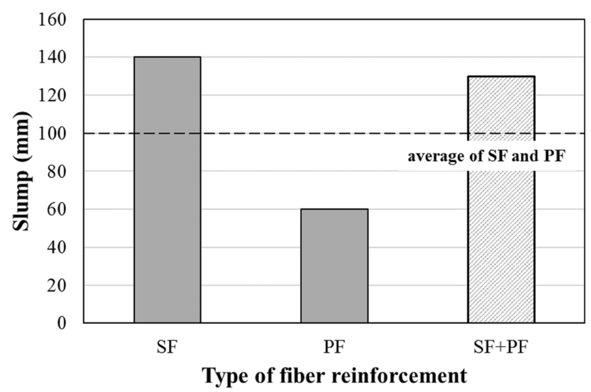

Fig. 4 Influence of fiber combination on slump of concrete mixtures (the dot line expresses average value of SF and PF).

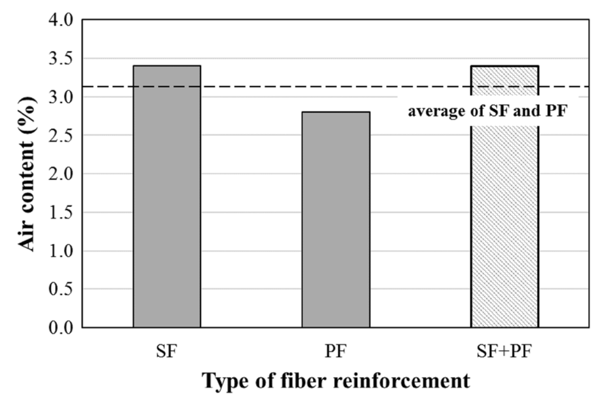

Fig. 5 Influence of fiber combination on air content of concrete mixtures (the dot line expresses average value of SF and PF).

0.50, the mixture should be deformed rather than flowed. Regarding the influence of the fibers tested, comparing SF and PF, the clearest difference is rigidity of fiber. SF can be oriented and has a relatively lower resistance to slumping or deforming the mixture than the PF because of its rigidity. Comparing the two mixtures based solely on the SF and PF, the concrete mixture with hybrid SF and PF showed a relatively favorable slump: although the slump mixture was slightly lower than the mixture with SF; still, the slump value of the mixture with hybrid SF and PF was similar to the slump value of the SF mixture, and the value (130 mm) was higher than average slump value (100 mm) of the single fiber mixture.

The air content of the concrete mixtures was measured as shown in Fig. 5. Generally, all three cases satisfied the target air content range. Figure 5 shows the concrete mixture with SF having the highest air content while the concrete mixture with PF had the lowest air content. According to Balaguru and Shah (1992), the steel fiber contributes to increasing air content while polymeric fiber has no influence on air content. It is also due to a different rigidity of fibers, and the test results agreed with the reference. For the concrete mixture with hybrid fibers of SF and PF, the air content was relatively close to the SF mixture. From this result, it can be stated that SF influences air content of the concrete mixture more than PF. Hence the air content of the mixture with both SF and PF showed 9% higher air content than the average air content of the SF and PF mixtures independently. Therefore, summarizing the fresh state test results, combining SF and PF yields the properties of a dominant fiber type, which is mainly determined by fiber rigidity. Furthermore, the slump and air content of the concrete mixture, combining SF and PF shows favorable results on fresh state concrete performance.

From the assessment of the fresh properties of FRC, the mixture with hybrid fibers generally showed a favorable performance compared with the PF mixture. In the case of workability, the SF mixture showed the highest workability. On the other hand, when the mixture contained the hybrid fibers, the workability of the mixture maintained an acceptable degree of workability although the PF was contained. Therefore, it can be considered that if PF is necessary for protection performance, its role is to secure the acceptable workability for a ready-mix concrete system using hybrid fibers.

3.2 Mechanical Properties

To evaluate the mechanical properties of the concrete mixtures with various fiber conditions, compressive, flexural, and tensile strengths were measured. Compressive strength measurement results are shown in Fig. 6. From the compressive strength results, it can be stated that the different types of fiber do not influence the compressive strength of the concrete mixture in this research scope. However, when two types of fiber are hybrid, improved compressive strength can be obtained. After 7 days, the average compressive strength value of the mixtures including each SF and PF was 15.3 MPa and the compressive strength of the mixture with the hybrid fibers of SF and PF was 15.8 MPa. Although there was no significant improvement at the 7-day age, at the 28-day age, the compressive strength of the mixture with hybrid SF and PF fibers showed 28.7 MPa, which is approximately 14% higher than average value of each mixture. This improved compressive strength with hybrid fibers is considered a result of the synergetic effect of different types of fiber for controlling cracks and confining the concrete by PF, and SF, respectively. 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 hybrid fibers was also shown. Figure 7 shows the concrete mixture with SF with a relatively higher flexural strength than the concrete mixture with PF at both 7-day and 28-day ages. Despite this difference in the performance of the mixtures with different fibers, the concrete mixture with hybrid fibers showed improved flexural strength values at both 7-day and 28-day ages. Also, similar to the compressive strength result, the improvement of flexural strength at 28-day age showed a higher than the improvement at 7 days of age with approximately 29% and 19%, respectively.

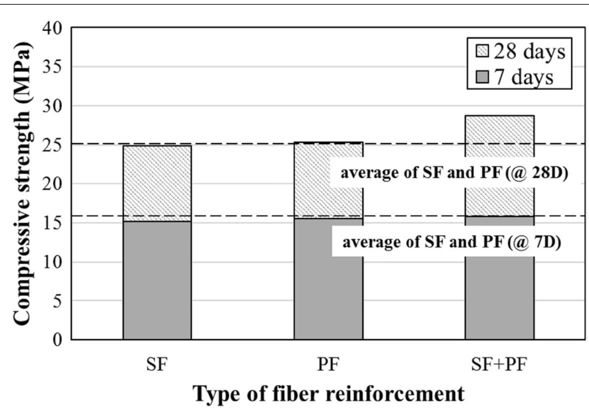

Fig. 6 Influence of fiber combination on compressive strength of concrete mixtures (dot line expresses average value of SF and PF).

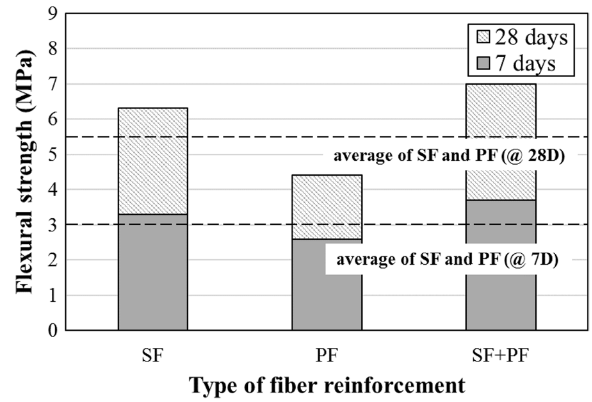

Fig. 7 Influence of fiber combination on flexural strength of concrete mixtures (dot line expresses average value of SF and PF).

As shown in Fig. 8, unlike the compressive and flexural strength results, at 7-days of age, the concrete mixture with PF showed a slightly higher tensile strength than the concrete mixture with SF. Generally, the steel fiber is difficult to break by tensile forces but can be pulled out, while polymeric fiber is easily broken by tensile forces. Therefore, at 7-day age, the concrete with SF experienced pulling out rather than breaking due to a weaker concrete mix that was unable to hold the fibers. The tensile strength improvement of the mixture with SF between the 7th day and the 28th day was higher than the mixture with PF. Since the main factor of resistance against tensile forces was pulling rather than fiber breakage for the concrete mixture with PF, there was less improvement between the 7th and 28th day. Despite this different trend of the concrete mixtures with a single fiber, the concrete mixture with hybrid fibers showed trend similar to the compressive and flexural strength trend showing improvement in performance. At 7-day age, the tensile strength of the concrete mixture with hybrid fibers was 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 shown in Figs. 9 and 10 for 7-day and 28-day ages, respectively. From the results, the concrete mixture with SF generally dropped tensile strength at a very early stage, but after that, strain-hardening behavior was shown and continuously absorbed energy. On the other hand, in the case of the concrete mixture with PF, initially a relatively higher strength was shown than the mixture with SF, but after the yield point, a steep decrease of strength was observed. Hence, based on these results, it can be stated that some SF could be pulled out at initial tensile

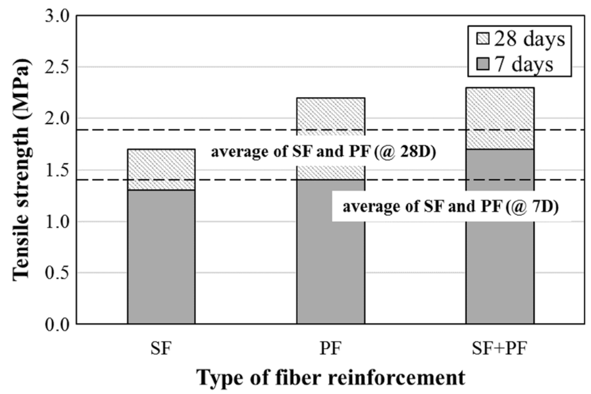

Fig. 8 Influence of fiber combination on tensile strength of concrete mixtures (dot line expresses average value of SF and PF).

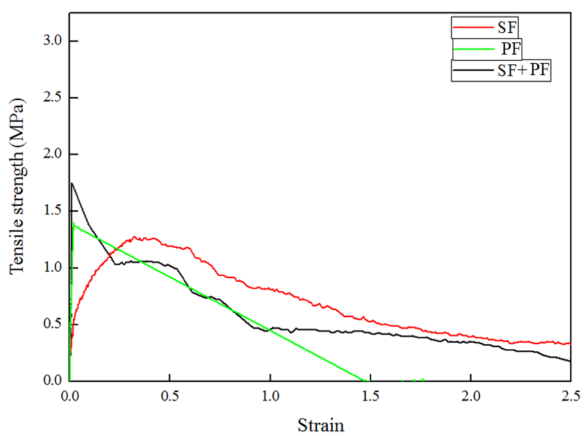

Fig. 9 Influence of fiber combination on toughness of concrete mixture at 7-day age.

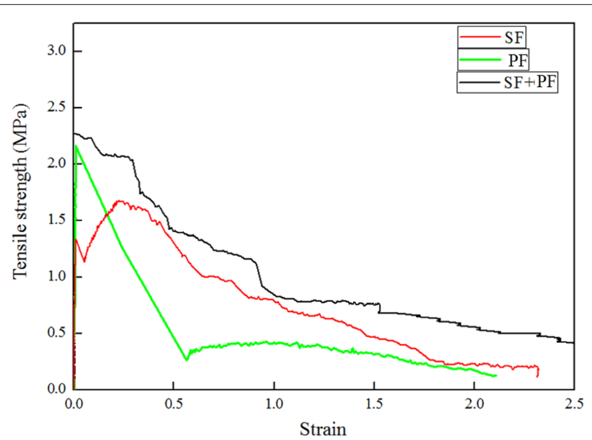

Fig. 10 Influence of fiber combination on toughness of concrete mixture at 28-day age.

forces, while the remaining fibers could resist and absorb energy while PF was difficult to pull out by tensile forces, although it could be broken when the tensile forces were applied. Furthermore, at 28-days, the cementitious matrix became hardened and it firmly secured the fibers to prevent pull out (as shown by a comparison of all tensile strengths in Figs. 9 and 10). The hybrid fibers mixture showed a strong synergetic effect 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 FRC mixtures, it is clear that the reinforcement with hybrid fibers had a better performance than the reinforcements with a single fiber. Furthermore, considering the fresh state test results, it can be suggested that using hybrid fibers of different types can achieve improved mechanical properties with favorable workability of the concrete rather than using a single fiber.

3.3 Protecting Performance

Using a high velocity projectile, the different fiber combination effect on the protection performance of concrete was evaluated. Since there was no standardized measurement method on protection performance against high velocity projectiles, the concrete panels after the impact test were observed on the impacted side and back side. As shown in Fig. 11, the concrete panels including a single fiber type showed penetrated damage. Namely, both concrete panels with single type fiber suffered spalling out of concrete on the back side with a resultant hole on the impacted surface the size of projectile. However, in the case of the concrete panel with hybrid fibers, a clearly improved protection performance prevailed over the results of the two concrete panels representing single fiber reinforcement. In the case of the concrete panel with hybrid fibers reinforcement, on the impacted side, relatively wide damage was shown instead of penetration. Since the penetration of the projectile was prevented, cracking from the center of the panel occurred without concrete loss. Hence, it is determined that because of the high pulling resistance and toughness by PF and SF, respectively, in the concrete panel with the hybrid PF/SF, the impact resistance improved and efficiently absorbed the impact energy. Summarizing the mechanical properties and protecting performance of the concrete samples with various fiber conditions, the hybrid fibers of SF and PF showed relatively improved mechanical properties and protection performance with the synergetic effect of hybrid fibers.

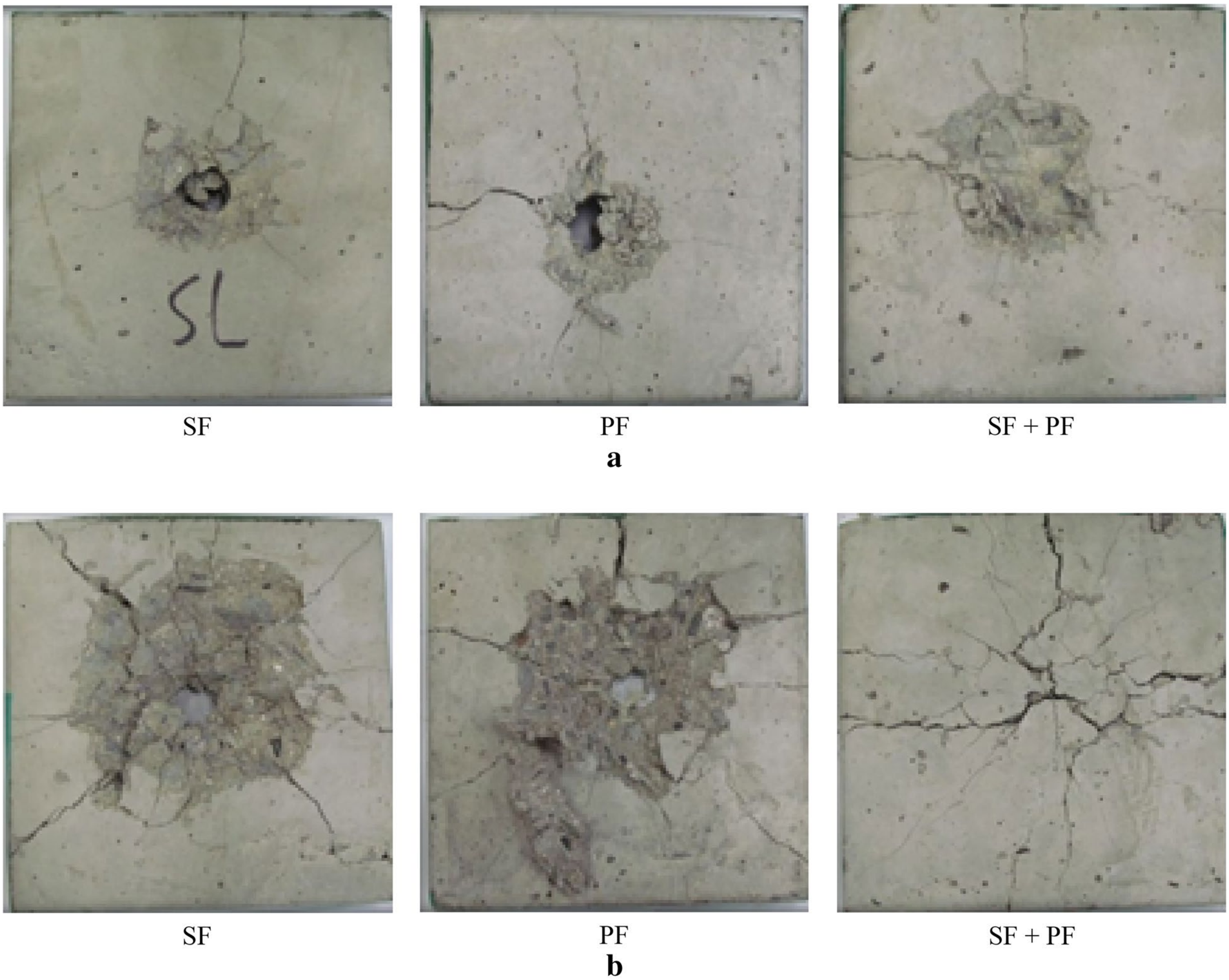

Fig. 11 Influence of fiber combination on protecting performance of concrete panel against the impact; **a** is the impacted side (front) and **b** is the back side.

4 Field Applications

4.1 Field Conditions for Site and Mixtures

Based on the lab-based experiment, the FRC with hybrid fibers was applied in an actual building construction project via the general ready mix concrete system. The target building was a chemical plant for manufacturing cosmetics. During the manufacturing process of the cosmetics, high pressured gas had to be injected, and the special area for this process had to be protected against unexpected explosion or flying debris caused by the explosion. The main structure type was the reinforced concrete (RC) structure. In this research, the suggested hybrid fibers reinforced concrete was applied on the outer wall of the protected area. The applied amount of FRC was approximately 50 m^3 for a 3 m depth of the protecting wall. The concrete mixture was placed using the normal ready-mix 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 lab-based test, the field applied concrete mixture contained the maximum size 25 mm coarse aggregate. For improving fiber, the hybrid fibers of SF to PF at a 1:1 ratio replaced 1% of the entire volume of the mixture.

The concrete mixture was mixed in the ready-mix concrete plant with the central mix method. However, the designated ready mix concrete plant was a general plant for normal ready mixed concrete; it did not have the setting for fiber introduction, and thus the fiber was introduced manually through the material feeding entrance for pre-measured amounts. The mixing time for FRC was increased by 1 to 2 min instead of 30 to 40 s of normal concrete mixing to provide sufficient workability and dispersion of fibers. Other process of delivering and the placing process of concrete was the same as the general process with the agitator trucks and truck pump following the South Korean ready-mixed concrete standard of KS F 4009 (Korea Standards Association 2011).

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 mechanical properties were measured. The testing samples were obtained from the first and third agitator trucks to arrive at the construction site, and tested samples were obtained before and after the pumping. Each test was conducted following ASTM C143, C1611 (2010), C231 (2010), and C39 methods for slump, slump flow, air content, and compressive strength, respectively. The compressive strength was tested at 7 and 28-day ages.

4.3 Results of Field Applications

First, the fresh properties of field-applied FRC were compared between the beginning and the end of pumping, as shown in Table 5, which reveals that the fluidity of the concrete mixture increased after the pumping. Generally, workability of concrete is decreased in slump or flow after the pumping. However, unlike former studies, in this research with FRC, 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. Despite the improved fluidity of the mixture, the air content decreased. However, in general, the properties of fresh state fiber-reinforced concrete mixture are acceptable to apply to field construction and there was no problem on placing the process of the wall.

The field processed FRC mechanical properties were evaluated with compressive strength. As summarized in Table 6, all concrete samples showed over 30 MPa, which was higher than the target compressive strength of 25 MPa. After pumping the concrete mixture, a slightly increased compressive strength was observed. The decreased air content and well oriented fiber contributed to the improved compressive strength. However, to obtain more detail, it is necessary to study the relation between pumping and the performance of FRC. In this research, the goal of the experiment was evaluating field applicability of FRC; thus the relationship between pumping and performance is not discussed in this paper.

5 Conclusions

In this research with the goal of applying FRC in field conditions, the workability, mechanical properties, and protection performance of hybrid fibers reinforced concrete mixtures were evaluated, and a field application was conducted with the assistance of a professional ready-mix concrete company. According to a series of experiment, the following conclusions can be obtained:

1. By using the hybrid fibers of SF and PF, FRC could have a high workability. This was not the case when using the single fiber, which showed better performances than the average value of each single-type fiber-reinforced mixture.
2. For mechanical properties of compressive, flexural, and tensile strengths, the mixture with the hybrid fibers showed improved values, more so than any single type-fiber reinforced mixture.
3. Regarding the protection performance against flying debris, the FRC panel reinforced by hybrid fibers showed the most desirable performance of protecting the high velocity projectile.

Table 5 Influence of pumping on fresh properties of the field applied FRC.

Experimental conditions[a]	Slump (mm)	Slump flow (mm)	Air content (%)
The first test			
Before pumping	130	225/220	4.0
After pumping	170	240/300	3.6
The second test			
Before pumping	135	230/240	3.8
After pumping	160	310/280	3.5

[a] The fresh state concrete tests were conducted with the concrete mixture obtained from the randomly chosen agitator trucks: the first and fifth trucks arrived in the field were chosen.

Table 6 Influence of pumping on compressive strength of the field applied FRC.

Experimental conditions[a]	Compressive strength (MPa)	
	7-day age	28-day age
The first test		
Before pumping	20.9	30.9
After pumping	23.8	32.7
The second test		
Before pumping	21.8	31.0
After pumping	24.2	33.1

[a] The fresh state concrete tests were conducted with the concrete mixture obtained from the randomly chosen agitator trucks: the first and fifth trucks arrived in the field were chosen.

4. The hybrid fibers reinforcing FRC showed improved mechanical and protection performances with favorable workability. Based on these improved features of the hybrid fibers reinforcement, field application of hybrid fibers reinforced FRC was successful under the normal ready-mixed concrete system.

Authors' contributions
DH: manuscript writing and test execution supervision. YJP: test execution and data analysis. MCH: Supervisor of experiment and research. STY: Corresponding author and adviser on data analysis. All authors read and approved the final manuscript.

Author details
[1] Department of Architectural Engineering, Engineering Research Institute, Gyeongsang National University, Jinju, South Korea. [2] R & D Department, Okdang Industry, Seoul, South Korea. [3] Department of Architectural Engineering, Cheongju University, Cheongju, South Korea. [4] Department of Civil and Environmental Engineering, Inha Technical College, Incheon, South Korea.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
All measured data was obtained by lab and field tests. Only lab test results are provided in Excel format.

Consent for publication
Not applicable.

Ethics approval and consent to participate
Not applicable.

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References
ASTM C138. (2013). *Standard test method for density (unit weight), yield, and air content (gravimetric) of concrete*. West Conshohocken: ASTM International.
ASTM C143. (2012). *Standard test method for slump of hydraulic-cement concrete*. West Conshohocken: ASTM International.
ASTM C150. (2012). *Standard specification for Portland cement*. West Conshohocken: ASTM International.
ASTM C1611. (2010). *Standard test method for slump flow of self-consolidating concrete*. West Conshohocken: ASTM International.
ASTM C231. (2010). *Standard test method for air content of freshly mixed concrete by the pressure method*. West Conshohocken: ASTM International.
ASTM C39. (2012). *Standard test method for compressive strength of cylindrical concrete specimens*. West Conshohocken: ASTM International.
ASTM C618. (2013). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. West Conshohocken: ASTM International.
ASTM C78. (2010). *Standard test method for flexural strength of concrete (using simple beam with third-point loading)*. West Conshohocken: ASTM International.
Balaguru, P., & Shah, S. (1992). *Fiber-reinforced cement composites*. New York: McGraw-Hill.
Banthia, N., & Gupta, R. (2004). Hybrid fiber reinforced concrete (HyFRC): Fiber synergy in high strength matrices. *Materials and Structures, 37*(10), 707–716.
Bentur, A., & Mindess, S. (2006). *Fibre reinforced cementitious composites*. London: Taylor & Francis.
Ferrara, L., Park, Y. D., & Shah, S. P. (2007). A method for mix-design of fiber-reinforced self-compacting concrete. *Cement and Concrete Research, 37*(6), 957–971. https://doi.org/10.1016/j.cemconres.2007.03.014.
Hsie, M., Tu, C., & Song, P. S. (2008). Mechanical properties of polypropylene hybrid fiber-reinforced concrete. *Materials Science and Engineering: A, 494*(102), 153–157.
Japan Society of Civil Engineers. (2010). *JSCE E 531, Test method for tensile properties of continuous fiber reinforcing materials (suggestion)*. Tokyo: Japan Society of Civil Engineers.
KS F 4009. (2011). Ready-mixed concrete. Seoul: Korea Standard Association.
Lee, G., Han, D., Han, M. C., & Son, H. J. (2012). Combining polypropylene and nylon fibers to optimize fiber addition for spalling protection of high-strength concrete. *Construction and Building Materials, 34,* 313–320.
Li, V. L., & Leung, C. K. Y. (1992). Steady-state and multiple cracking of short random fiber composites. *Journal of Engineering Mechanics, 118*(11), 2246–2264.
Markovic, I., Walraven, J. C., & Van, M. J. (2003). Self compacting hybrid fiber concrete-mix design, workability and mechanical properties. In *Proceedings of the International RILEM Symposium on Self-Compacting Concrete* (pp. 763–775), Reykjavik, Iceland.
Park, S. H., Kim, D. J., Ryu, G. S., & Koh, K. T. (2012). Tensile behavior of ultra high performance hybrid fiber reinforced concrete. *Cemeny and Concrete Composites, 34*(2), 172–184.
Roussel, N. (2006). Correlation between yield stress and slump: Comparison between numerical simulations and concrete rheometers results. *Materials and Structures, 39*(4), 501–509. https://doi.org/10.1617/s11527-005-9035-2.
Saak, A. W., Jennings, H. M., & Shah, S. P. (2004). A generalized approach for the determination of yield stress by slump and slump flow. *Cememt and Concrete Research, 34*(3), 363–371.
Schowalter, W. R., & Christensen, G. (1998). Toward a rationalization of the slump test for fresh concrete: Comparisons of calculations and experiments. *Journal of Rheology, 42,* 865. https://doi.org/10.1122/1.550905.
Tattersall, G., & Banfill, P. (1983). *The rheology of fresh concrete*. London: PITMAN BOOKS LIMITED.
Yao, W., Li, J., & Wu, K. (2003). Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction. *Cememt and Concrete Research, 33*(1), 27–30.
Yazıcı, Ş., İnan, G., & Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. *Construction and Building Materials, 21*(6), 1250–1253.