MECHANICAL PROPERTIES OF HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITE WITH HIGH STEEL FIBER VOLUME FRACTION

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Abstract

Due to the recent rapid progress in the field of construction technology, structures have become larger and taller with dense population. Their functions have also become more diverse and complex, and the risk of unexpected loadings, such as explosions and fire, also increased. In the event of explosion incidents collisions or impacts to concrete structures, a restoration to the original condition is very difficult and the risk of upcoming damage such as progressive collapse is also high.

In conventional structures, the concept of protection from unexpected loads such as explosion and collision includes an increase of the thickness of concrete wall. However, the drawback of this concept is that the inherent function of the structure weakens as the structure thickness increases. To ensure an effective a resistance technology, a development of high performance fiber reinforced cementitious composites (HPFRCCs) is essential.

High volume fraction of fibers will effectively enhance the fracture resistance especially when exposed to high frequency loadings. This study investigated the mechanical properties of a slurry infiltrated fiber concrete (SIFCON), one of typical types of HPFRCC, with respect to the fiber volume fraction, 6.0 to 8.0 % by 0.5 % increment. The used fiber was 0.7 mm diameter and 60 mm long with a hooked-end. The measured compressive and flexural strengths were proportional to the fiber volume fractions but the strength increment efficiency was better when the fraction exceeded 7.0 %.

Keywords: HPFRCC, Fiber volume fraction, Flexural behaviour, Blast resistance

1. Introduction

Concrete is largely used as a material of structural components that support the compressive stress of a structure because of its brittle nature. Conventional concrete is generally a brittle material whose tensile strength and critical tensile strain are very low compared to the compressive strength. Studies have been performed actively worldwide on high performance fiber reinforced Cementitious Composites (HPFRCCs), which are

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reinforced with steel fibers, to search different methods to prevent their brittle fracture, improve their tensile behavior, and simultaneously advance their energy absorption capacity. In general, if steel fibers are mixed into concrete, the initial fracture can be delayed; therefore fiber reinforcement is expected to increase the tensile strength and improve the ductility of concrete by suppressing crack propagation.

Due to the recent rapid progress in the field of construction technology, structures have become larger and taller with dense population. Their functions have also become more diverse and complex, and the risk of unexpected loadings, such as explosions and fire, also increased. In the event of explosion incidents collisions or impacts to concrete structures, a restoration to the original condition is very difficult and the risk of upcoming damage such as progressive collapse is also high.

In conventional structures, the concept of protection from unexpected loads such as explosion and collision includes an increase of the thickness of concrete wall. However, the drawback of this concept is that the inherent function of the structure weakens as the structure thickness increases. To ensure an effective a resistance technology, a development of HPFRCC is essential.

High volume fraction of fibers will effectively enhance the fracture resistance especially when exposed to high frequency loadings. This study investigated the mechanical properties of a slurry infiltrated fiber concrete (SIFCON), one of typical types of HPFRCC, with respect to the fiber volume fraction, 6.0 to 8.0 % by 0.5 % increment. The used fiber was 0.7 mm diameter and 60 mm long, aspect ratio of 86, and tensile strength of 1,200 MPa with a hooked-end.

2. Materials and Experimental Details

2.1 Materials

2.1.1 Cement

A type of cement used in this study was Type I ordinary Portland cement from company S. in Korea. Physical properties and chemical compositions of the cement are shown in Tab. 1.

Tab.1: Material properties of used ordinary Portland cement

Physical properties							
Specific gravity	Fineness (cm^2/g)	Stability (%)	Setting time(min)		Compressive strength(MPa)		
			Initial	Final	3 days	7 days	28 days
3.15	3,400	0.1	230	410	23	31	40

Chemical compositions (%, mass)						
SiO_2 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Al_2O_3 (%)	Ig-loss (%)
21.95	2.81	60.12	3.32	2.11	6.59	2.58

2.1.2 Silica fume

Silica fume is typically used to increase strength and durability in the more densely packed microstructure of the cement matrix. In this study, 15% of the ordinary Portland cement, by weight, was replaced with the silica fume. Physical properties and chemical compositions of the silica fume are shown in Tab. 2.

Tab.2: Material properties of used silica fume

Physical properties				
Specific gravity		Fineness (cm^2/g)		
2.1		200,000		
Chemical compositions (%, mass)				
SiO_2 (%)	CaO (%)	MgO (%)	SO_3 (%)	Al_2O_3 (%)
96.00	0.38	0.10	-	0.25

2.1.3 Aggregate

This study used fine aggregates with a diameter of less than 0.5 mm manufactured from J-company in Korea, to improve the in-fill performance of the slurry and to reduce segregation of the material. Also, the ratio of the fine aggregates to the combined binder mixture was set to 1:0.5, and coarse aggregates were not used for infilling between steel fibers. The particle size distribution of the fine aggregate is shown in Fig. 1.

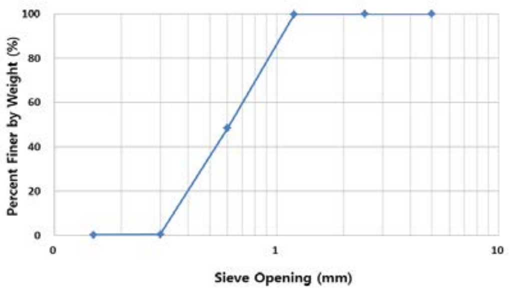


Fig. 1: Grading curve of fine aggregate

2.1.4 Polycarboxylate high range water reducer (HRWR)

To enhance the fluidity of the slurry and acquire the desired in-fill performance, a polycarbonate-based high performance water reducing agent was used. Table 3 shows the properties of the high performance water reducing agent.

Tab.3: Properties of Polycarboxylate high range water reducer (HRWR)

Principle component	Specific gravity	pH	Alkali content (%)	Chloride content (%)
Polycarboxylate	1.05 ± 0.05	5.0 ± 1.5	less then 0.01	less then 0.01

2.1.5 Steel fiber

The steel fiber used had a density of 7.8 g/cm^3, a length of 60 mm, a diameter of 0.7 mm, aspect ratio of 86, and tensile strength of 1,200 MPa with a hooked-end. This study investigated the mechanical properties of SIFCON, one of typical types of HPFRCCs, with respect to the steel fiber volume fraction, 6.0 to 8.0 % by 0.5 % increment. It was used to improve the fracture toughness under application of tensile and flexural stresses. The used steel fiber shape is shown in Fig. 2.

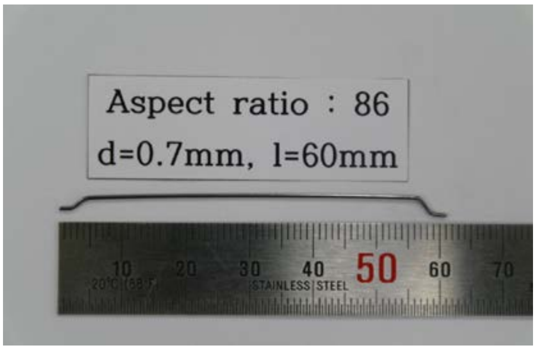


Fig. 2: Type of steel fiber (aspect ratio 86)

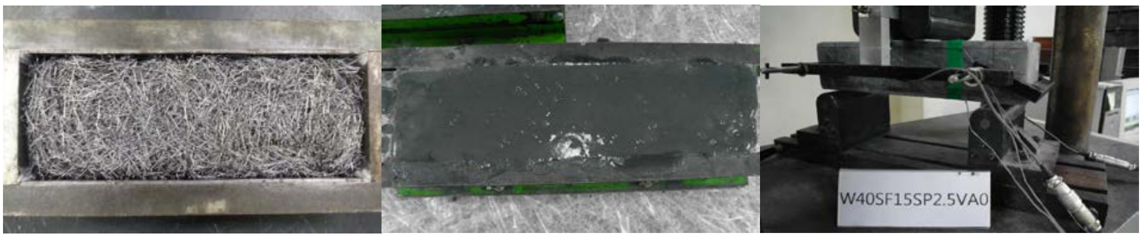
2.2 Mixing and specimen preparation

To obtain the optimum in-fill performance through a preliminary mix, the ratio of water to the combined binder mixture of the slurry was set to 0.4. This ratio was used for infilling the internal space of steel fibers that were placed there earlier, and the HRWR was set to 2.5 % of the weight of the combined binder mixture. The mixing proceeded after setting 0.5 as the amount of fine aggregates to the combined binder mixture and by replacing 15 % of the cement with silica fume. In addition, an up-down agitation mortar mixer was utilized so that the HRWR could fully execute its function. Tab. 4 shows the mixing proportions of the in-fill slurry used in this study.

Tab.4: Mixing proportions of slurry matrix

W/B ratio	0.4
HRWR	2.5 % (cement weight percent)
Fine aggregate content	1 : 0.5 (binder : fine aggregate)
Silica fume	15 % (cement weight percent)

The compressive strength of the slurry was measured to be almost 62 MPa. In addition, a total of five variables were considered with respect to the steel fiber volume fraction such as 8.0, 7.5, 7.0, 6.5 and 6.0 % by using the steel fibers for standard concrete with the aspect ratio of 86; three specimens were prepared for each variable. Fig. 3 shows the specimen fabrication procedure.



(a) Placing steel fiber (b) pouring slurry (c) four-points flexural test

Fig. 3: Specimen fabrication procedure and four-points flexural test

2.3 Test procedure

A flexural experiment based on the standard *ASTM C 1609 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)* was performed in this study by constructing a rectangular specimen with dimensions of 100×100×400 mm to evaluate the flexural performance of the in-fill slurry HPFRCC according to the steel fiber volume fraction. It was loaded at four-points by a 200-ton-class universal testing machine (UTM), as shown in Fig. 3 (c). A deflection displacement at the center of the specimen was also measured using a Japanese yoke with two linear variable differential transformers (LVDTs). The loaded power was applied by displacement control at a speed of 1 mm/min.

The flexural strength f was estimated using Eq. (1) of ASTM C 1609 to evaluate the flexural performance:

$$f = (PL)/(bd^2) \quad (1)$$

where P is the maximum load measured during the experiment, L is the span length (300 mm), b is the width (100 mm), and d is the height (100 mm) of the specimen. A flexural toughness that is proposed by ASTM C 1609 was calculated to evaluate the energy absorption capacity according to the steel fiber volume fraction.

Fig. 4: Set-up of the experiment on compressive strength

According to the ASTM C 1609 the flexural toughness is analyzed by the area under the load-deflection curve up to a net deflection of 1/150 of L .However, the definition according to ASTM C 1609 was not appropriate for this experimental set-up, hence the area under 1/150 of L was replaced by 20 mm. After the adjustment, the energy absorption capacity according to the steel fiber volume fraction was evaluated. In addition, the experiment for measuring the compressive strength was performed using a specimen with dimensions of 100×100×100 mm. Fig. 4 depicts the set-up of the experiment on compressive strength.

3. Test Result and Analysis

3.1 Flexural behavior

A comparison of the load-deflection curves of the specimens with different steel fiber volume fraction is shown in Fig. 5. The load of the in-fill slurry HPFRCC according to the steel fiber volume fraction tended to consistently increase until it reached the maximum load after initial fracture.

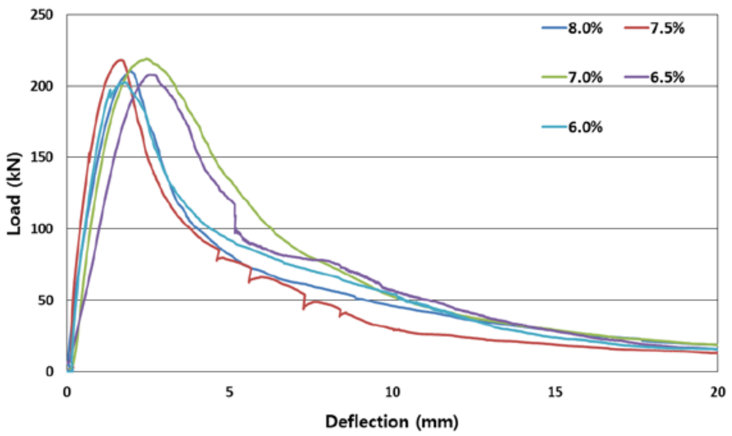


Fig. 5: Load-mid span deflection curve with respect to steel fiber volume fraction

The maximum load of all variables also occurred before or after a deflection of 3 mm regardless of the steel fiber volume fraction. This means that the mechanical properties of the cementitious composite improved to resist loads such as impact or collision by absorbing enough energy even after the initial fracture through the bridging effect as a result of the high steel fiber volume fraction. By increasing the bonding strength of the steel fibers owing to the high strength of the slurry matrix, rupture of the steel fibers in the fracture surface was also observed along with the withdrawal of the steel fibers. Figs. 6 to 10 show the load-deflection curves of specimens with different steel fiber volume fraction. Analysis of experimental result for the concrete specimen with a steel fiber volume fraction of 8.0 % showed that it had excellent flexural resistance at the maximum load of 212 kN (equivalent to a flexural strength of 63.6 MPa). Also, it showed that the residual strength remained after reaching the maximum strength. Based on this result, it was determined that collapse resulting from the brittle fracture of the concrete structures can be prevented by the additional residual strength in the case of extreme load from an unexpected impact or collision. Results of the experiment on flexural behavior as function of the steel fiber volume fraction showed the same level of maximum load regardless of the steel fiber volume fraction. It also showed that the specimen with the steel fiber volume

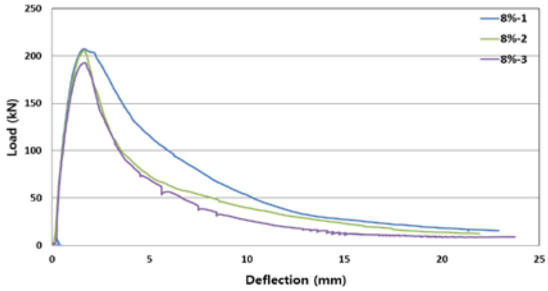


Fig. 6: Load-deflection curve with 8.0% steel fiber volume fraction

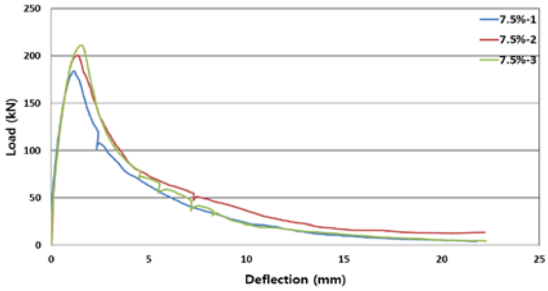


Fig. 7: Load-deflection curve with 7.5% steel fiber volume fraction

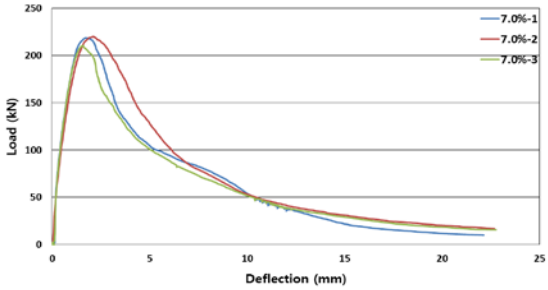


Fig. 8: Load-deflection curve with 7.0% steel fiber volume fraction

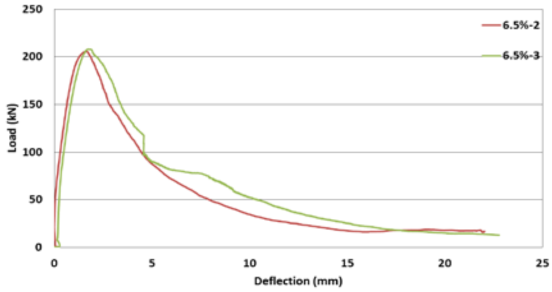


Fig. 9: Load-deflection curve with 6.5% steel fiber volume fraction

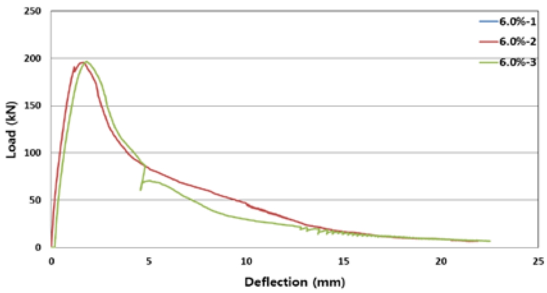


Fig. 10: Load-deflection curve with 6.5% steel fiber volume fraction

fraction of 7.0 % exhibited the best flexural resistance against the maximum load of 217 kN. The flexural strength showed negligible difference with changes in the steel fiber volume fraction as the flexural strength of HPFRCC with the high steel fiber volume fraction had an insignificant level of dependence on the density of internal steel fibers in the specimen. The residual strength remained unchanged after a certain level of deflection and was the highest in the specimens with the steel fiber volume fraction of 7.0 and 6.5 %. Fig. 11 shows a photo obtained at the end of the last experiment on the in-fill slurry HPFRCC specimens. Since sudden fracture had not occurred yet and the specimens showed a continuous load resistance, excellent fracture resistance capacity can be observed. In the flexural experiment on variables, the steel fiber volume fraction in general had a larger effect on the flexural toughness after fracture than the changes in the flexural strength. On the contrary, when steel fibers with a diameter of 0.7 mm and a length of 60 mm were used in the experiment, the analysis (Fig. 5) showed that the overall shapes of the load-deflection curves were similar to each other and the steel fiber volume fraction had almost no effect on both the flexural strength and the flexural toughness. Increases within an appropriate range of the steel fiber volume fraction were shown to have very small effect on the flexural behavior of HPFRCC. It was determined that cementitious composites with steel fibers showed homogeneous behavior because the strength of the slurry matrix was high. Therefore, it is necessary to analyze the effect of changes in diameter and length of the steel fibers on these characteristics of behavior.

Fig. 11: High ductile behaviour in flexural test

3.2 Flexural strength and flexural toughness

Fig. 12 compares the results of the experiment on the flexural strength of specimens with different steel fiber volume fraction. In the case of the specimen with 8.0 % steel fiber volume fraction, a maximum flexural strength of about 62 MPa was obtained, which is equivalent to approximately 75 % of the compressive strength, indicating that the specimen had excellent resistance to flexure, unlike concrete with general fiber reinforcement.

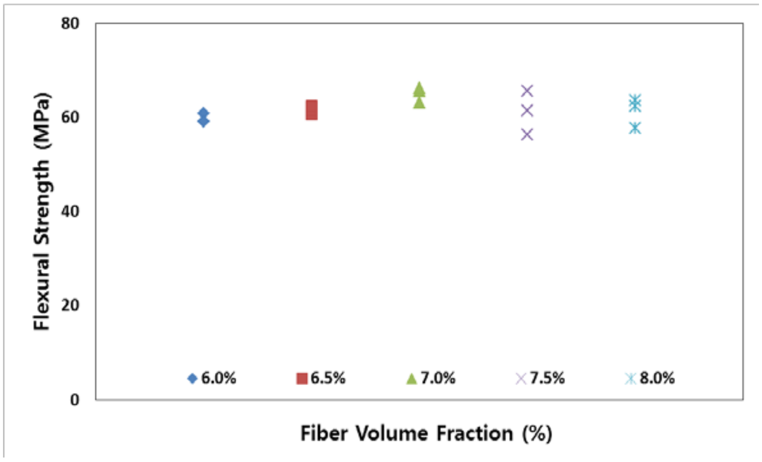


Fig. 12: Test results of flexural strength according to the steel fiber volume fraction

The specimens with 7.5, 7.0, 6.5, and 6.0% steel fiber volume fraction showed flexural strength of about 61, 65, 62, and 60 MPa,respectively, i.e., the flexural strength was above 60 MPa for all specimens. The difference among these values of flexural strength according to the steel fiber volume fraction is small enough to be ignored. Table 5 shows the estimation results of flexural strength and flexural toughness in detail according to each variable of the steel fiber volume fraction.

Tab.5: Flexural strength and flexural toughness obtained from flexural test

Variables (V_f, %)	Flexural strength (MPa)	Flexural toughness (N·m)	Average of Flexural strength (MPa)	Average of Flexural toughness (N·m)
8.0	62.3 63.6 57.8	1459.6 1204.7 952.5	61.2	1205.6
7.5	56.3 61.5 65.6	645.6 1161.7 1115.3	61.1	1074.2
7.0	65.7 66.2 63.1	1427.4 1581.4 1395.1	65.0	1468.0
6.5	60.6 61.6 62.4	1300.5 1214.5 1381.3	61.5	1298.8
6.0	60.8 59.1	1311.5 1053.0	60.0	1182.3

In this study, it was intended to analyse the characteristic of flexural toughness in accordance with ASTM C 1609. Because the measured deflection level far exceeded the flexural toughness, which is defined in ASTM C 1609 as the area under the load-deflection curve up to a deflection of 1/150 of span length L. The flexural toughness as a function of the steel fiber volume fraction was relative compared to the area under the curve up to a deflection of 20 mm (vs. L /15). Fig. 13 shows the flexural toughness according to the steel fiber volume fraction. Based on a comparison of flexural toughness up to a deflection of 20 mm, the energy absorption capacity of about 1,074 N·m was the lowest for the specimen with 7.5 % steel fiber volume fraction, whereas it was 1,468 N·m for the specimen with 7.0 % steel fiber volume fraction, about 1.4 times the fracture energy of the specimen with 7.5 % steel fiber volume fraction. It was determined from these results that just like the flexural strength; the difference in flexural toughness according to the steel fiber volume fraction was also negligible. Based on the result of the analysis of flexural strength and flexural toughness, the behavior characteristics obtained through our experimental research were, in general, slightly different from the general tendency for the steel fiber volume fraction to significantly affect the initial fracture or fracture toughness after the maximum load. It was analyzed that the behavioral characteristic considerably effect not only the increase in fracture toughness according to the steel fiber volume fraction but also the flexural strength through the combined behavior of the slurry matrix strength and high steel fiber volume fraction of the HPFRCC that was considered in this study. Therefore, we concluded that it was favorable to maintain the steel fiber volume fraction above a certain level to increase the flexural strength and flexural toughness to increase the required resistance against impact or collision load, while satisfying the performance at the same time. However, the findings are limited to steel fibers with a diameter of 0.7 mm and length of 60 mm, and additional studies are required if steel fibers with other sizes and aspect ratios are used.

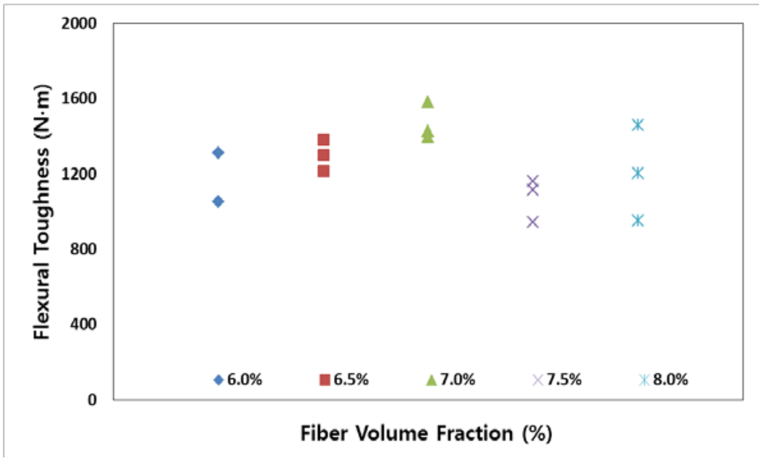


Fig. 13: Test results of flexural toughness according to the steel fiber volume fraction

3.3 Compressive strength

In this review of the reported effects of fibers on the compressive behavior of general fiber reinforced mortar or concrete, it came across one study stating that they had no effect on the compressive strength. On the whole, however, most reports showed that fibers had some effect on the increase in compressive strength of the reinforced mortar or concrete.

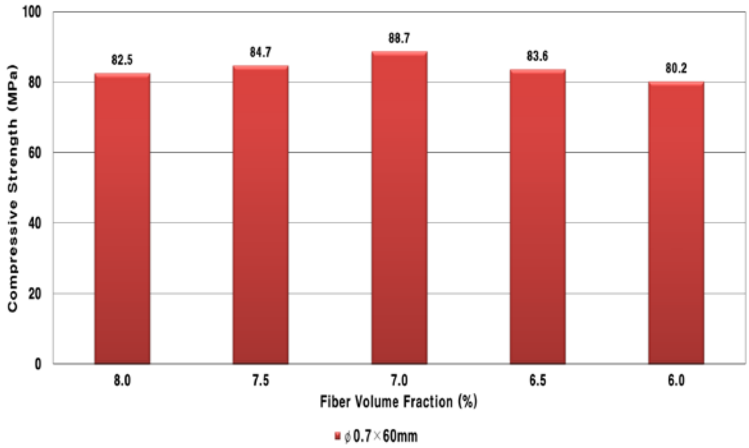


Fig. 14: Test results of compressive strength according to the steel fiber volume fraction

Fig. 14 shows a comparison of the compressive strength of HPFRCCs with different steel fiber volume fraction. The compressive strength of about 89 MPa was the highest for the specimen with 7.0 % steel fiber volume fraction, while the compressive strength of about 80 MPa was the lowest for the specimen with 6.0 % steel fiber volume fraction. The compressive strength was enhanced by about 30 to 40% depending on the steel fiber volume fraction, considering that the compressive strength of the slurry matrix alone was 62 MPa. The compressive strength was enhanced because the steel fibers effectively absorbed the energy that was released at compressive failure owing to the bridging effect of the steel fibers by fiber reinforcement. In addition, the increase in compressive strength with fiber reinforcement is expected to be closely related to the slurry matrix strength, geometric characteristics, etc., and an additional study on the compressive behavior will be necessary.

4. Conclusions

This study analyzed the mechanical characteristic of in-fill slurry HPFRCC with changes in the fiber content to improve the resistance of a concrete structure against unexpected loads such as impact or collision. The steel fiber used in this study had a diameter of 0.7 mm and a length of 60 mm.

1. The load of in-fill slurry HPFRCCs was continuously increased with the steel fiber volume fraction owing to the high steel fiber volume fraction after initial fracture, and sufficient residual strength was obtained from the maximum strength. The sufficient residual strength had a positive effect on the brittle fracture of the structure when an unexpected load such as impact or collision was applied.
2. The maximum flexural strength was about 61 MPa, which is a very high value for the specimen with the steel fiber volume fraction of 8.0 %. The highest flexural strength of 65 MPa was shown by the specimen with the steel fiber volume fraction of 7.0 %. The difference in flexural strength according to the steel fiber volume fraction was small.
3. The flexural toughness also had values similar to the flexural strength. Like the flexural strength, the best energy absorption capacity was exhibited by the specimen with the steel fiber volume fraction of 7.0 %.
4. Upon flexural failure, the steel fibers withdrew and ruptured on the fracture surface. This shows that the bonding between the fibers used and the slurry matrix was sufficiently high.
5. The load–deflection curves of specimens with different steel fiber volume fraction were similar, and the steel fiber volume fraction had almost no influence on the flexural strength and flexural toughness. The increase in the steel fiber volume fraction within the range of appropriate levels had less influence on the flexural behavior. In addition, it was determined that the steel fibers and slurry matrix showed homogeneous behavior in the HPFRCCs because of the excellent strength of the slurry matrix.
6. In order to increase the required resistance against impact or collision loads, while satisfying the performance requirements at the same time, it was favorable to maintain the steel fiber volume fraction above a certain level to increase the flexural strength and flexural toughness.
7. The results of this study are limited to steel fibers with a diameter of 0.7 mm and length of 60 mm. Additional studies are required if steel fibers with other sizes and aspect ratios are used.
8. The highest compressive strength of about 89 MPa was shown by the specimen with 7.0 % steel fiber volume fraction, while the lowest compressive strength of about 80 MPa was shown by the specimen with 6.0 % steel fiber volume fraction. The compressive strength was enhanced by about 30 to 40 % according to the steel

fiber volume fraction, considering that the compressive strength of the slurry matrix alone was 62 MPa.

9. The compressive strength was enhanced because the steel fibers effectively absorbed the energy that was released in the compressive failure caused by the bridging effect of the steel fibers. The compressive strength is expected to be closely related to the slurry matrix strength, geometric characteristic, etc. Therefore, an additional study on compressive behavior is necessary.

Acknowledgements

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