Journal of Ceramic Processing Research. Vol. 16, Special. 1, pp. s56~s62 (2015)

J O U R N A L O F
Ceramic
Processing Research

Influence of steel fiber content and aspect ratio on the strength of high strength concrete

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The aim of this research is evaluating the strength properties of high strength fiber-reinforced concrete depending on replacement ratio and aspect ratio. As a part of producing SUPER concrete which has high ductility with fiber-reinforcement, both high mechanical properties and improved ductility should be achieved. Hence, mainly mechanical properties of the concrete with fiber was studied and from the results of the experiment, it was not shown the significant influence on compressive strength with fiber replacement ratio and aspect ratio, while as the fiber replacement ratio and aspect ratio were increased, the tensile and flexural strengths were improved. Especially, for fiber aspect ratio of 100, when the fiber replacement ratio was 2%, the most desired ductility was obtained.

Key words: Fiber-reinforced concrete, Replacement ratio, Aspect ratio, SUPER concrete.

Introduction

The high strength concrete of 100 MPa grade compressive strength has been developed and applied to high rising, enlargement, and elongation of structures with the rapid development of concrete technology [1]. High strength concrete has the advantage of expanding the usable space of the building with its high strength and thus reduced cross-section of the columns and members in response to load as highly strengthened [2]. Despite of this mechanical advantages of high strength concrete, the high strength concrete has the drawbacks of less ductility and low tensile and flexural strength compared to its compressive strength [3, 4]. Especially, because of the brittleness and weak capacity of energy absorption, the structure can experience the sudden destruction under the dynamic load is more prominent.

As a solution of these disadvantages of high strength concrete, there are many research and new materials with high toughness cement composite materials such as ECC (Engineered Cementitious Composite) [5], RPC (Reactive Powder Concrete) [6], SIFCON (Slurry Infiltrated Fiber Concrete) [7], SIMCON (Slurry infiltrated Mat Concrete) [8], etc. are developed. In Korea, studies on fiber reinforced concrete with high toughness by adding plenty of fiber have been introduced and among them, many studies on steel fiber reinforced concrete mixing discontinuous and short steel fiber have been conducted. According to the former research conducted, steel fiber-reinforced concrete has been reported as an excellent material with high tensile and flexural strength by bridging action of fiber distributed in concrete matrix, inhibiting the generation and growth of cracks and increasing the safety performance of concrete under the dynamic load and shock, and explosion. Regarding the protective function of the fiber-reinforced concrete, Kim *et al*. [9] reviewed the mechanical properties of hybrid fiber-reinforced concrete mixing steel fiber and (polyester) fiber at the same time and as a result, it was found that significant improvement of flexural and tensile strengths compared to the concrete without the fibers. Compared to the concrete with solely steel fiber, however, the increase rate of flexural strength and tensile strength was reported to be less. Also, Ku *et al*. [10] reviewed the flexural behavior of amorphous steel fiber-reinforced concrete and showed that flexural strength and flexural toughness index increased more than existing steel fiber-reinforced concrete while the flexural strength difference depending on amorphous fiber types is insignificant. In the case of worldwide research, Yazici *et al*. [11] reviewed mechanical properties of the fiber-reinforced concrete depending on the replacement ratio and aspect ratio of steel fiber in 60 MPa grade of compressive strength concrete and reported that flexural strength and tensile strength increase as the replacement ratio and aspect ratio of

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steel fiber increase. In this research, the highest performance was achieved at 1.5% of replacement ratio.

As stated above, adding steel fiber is the most well known method of producing high-performance concrete and there are many studies on characteristic behaviors such as compression, flexural and tensile strength depending on adding steel fiber and reinforced materials have been carried out in order to change the characteristic of brittle fracture of a cementitious materials to ductility fracture. Based on these improvement of concrete properties with fiber reinforcement, in South Korea, the research about producing the concrete with high toughness and the performance of high protection and anti-explosion, so called SUPER concrete, has been performed in order to complement the disadvantages of high strength concrete and improve its performance in recent years. Therefore, in this research, as a part of SUPER concrete development project with high toughness and 120 MPa grade of high strength, the influence of the replacement ratio and aspect ratio of straight steel fiber on mechanical properties of fiber-reinforced concrete.

Experiment

Experimental design

The experimental plan of this study is shown in Table 1 and the mix proportions are shown in Table 2. The Plain mortar was designed to satisfy the target compressive strength of 120 MPa (water-to-binder ratio (w/b) of 0.23), slump flow of 650 ± 150 mm and air content of 4.5 ± 1.5%. Regarding the binder, cement, zirconium powder, blast furnace slag, filler, expanding additive, and shrinkage reducing admixture were mixed before mixing with water. The mix proportion of the pre-mixed binder was same for all mixtures as shown in Table 3. For steel fiber, 0.2 mm in diameter, and 20 mm of length (aspect ratio: 100) was added with 0, 1, 1.3, 1.5, and 2% of entire mortar volume. The fiber with 0.2 mm of diameter, and 16 mm of length (aspect ratio: 80) was added 1, and 1.5% of entire mortar volume, so total five different mortars were prepared. As the tests conducted, slump flow, and air content were measured for fresh state mortar and compressive, flexural, and tensile strength at prefixed ages were measured for hardened mortar state.

Materials

In this study, all tests were conducted in mortar phase. The powders consisting binder were ordinary Portland cement (OPC), zirconium powder (Zr), blast furnace slag (BS), filler, expanding additive, and shrinkage reducing admixture were used and these

Table 1. Experimental plan.

Mixture	Target compressive strength (MPa)		120
	Target slump flow (mm)		650 ± 50
	Target air content (%)		4.5 ± 1.5
	Steel fiber (aspect ratio 100)	Diameter (mm)	0.2
		Length (mm)	20
		Replacement ratio (%)	0 (Plain), 1, 1.3, 1.5, 2
	Steel fiber (aspect ratio 80)	Diameter (mm)	0.2
		Length (mm)	16
		Replacement ratio (%)	1, 1.5
Experiment	Fresh state properties		• Slump flow • Air content
	Hardened state properties		Compressive behaviors (strength and deformation capacity) • Flexural behaviors (strength and deformation capacity) • Tensile behaviors (strength and elongation capacity)

Table 2. Mix proportions.

Phase	w/b	Unit mass (kg/m^3)						
		Water	Pre-mixing binder*	Sand	Steel fiber**		SP***	AA***
					Fiber length 20	Fiber length 16		
Mortar	0.23	221.3	1258.7	846.8	V_f = 0, 1, 1.3, 1.5, 2	V_f = 1, 1.5	17.7	0.7

*Pre-mixing binder contains cement, zirconium, blast furnace slag, filler, expanding additive, shrinkage reducing admixture.
**V_f means added ratio to the entire volume of mortar mixture. Depending on the fiber length and fiber content, the mixtures were coded to fiber length-fiber content (i.e., 20-1% means the mixture including the fiber of 20 in length for 1 %.
***SP: superplasticizer, AA: antifoaming agent.

Table 3. Mix proportion of pre-mixed binder (for 1 m^3 mortar mixture).

Component	Cement (kg/m^3)	Zr (kg/m^3)	BS (kg/m^3)	Filler (kg/m^3)	EA (kg/m^3)	SRA (kg/m^3)
Portion (weight)	769.9	57.7	134.7	231.0	57.7	7.7

Table 4. Physical and chemical properties of cementitious powders.

Type*	Specific surface area (cm^2/g)	Density (g/cm^3)	Ig. Loss (%)	Chemical composition (%)					
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
OPC	3,413	3.15	1.40	21.01	6.40	3.12	61.33	3.02	2.32
BS	3,850	2.13	3.82	34.2	14.1	0.72	64.9	6.25	1.84

*OPC: ordinary Portland cement, BS: blast furnace slag.

Table 5. Physical and chemical properties of zirconium powder.

Specific surface area (m^2/g)	Moisture absorption (cm^3/g)	Moisture desorption (cm^3/g)	Ig. Loss (%)	Chemical composition (%)		
				SiO2	ZrO2	MgO
8.76	10.8	2.0	1.01	95.6	3.9	0.02

Table 6. Physical properties of steel fibers.

Type	Diameter (mm)	Length (mm)	Aspect ratio	Tensile strength (MPa)
SF 1	0.2	20	100	2,000
SF 2	0.2	16	80	2,000

components were pre-mixed before the fiber addition. The physical and chemical properties of OPC and BS are shown in Table 4, and the physical and chemical properties of zirconium powder is shown in Table 5. The filler, and expanding additive used were quartz particles, and calcium sulfa aluminate (CSA) type materials, respectively, and these materials were commercially available in South Korean market. The shrinkage reducing admixture was liquid phase and commercial product in South Korea. Since filler, expanding additive, and shrinkage reducing admixture were general products, the properties of these materials are not shown in this paper. The fine aggregate used was the natural river sand with less than 0.5 mm of particle size. As the chemical admixtures, polycarboxylate-based superplasticizer and anti-foaming admixture were used. Both chemical admixtures were general products available from South Korean market. oThe straight steel fibers used were both short steel fibers of 20, and 16 mm of length and 0.2 mm of diameter. The physical properties of fibers are shown in Table 6.

(a) slump flow (b) air content (volumetric method)

Fig. 1. Tests methods for the fresh state mortar.

(a) compressive behaviors (b) flexural behaviors (c) direct tensile behaviors

Fig. 2. Tests methods for the hardened mortar.

Tests methods

For fresh state properties, slump flow and air content were measured. Each test method was shown in Figure 1, and the tests procedures were followed ASTM C1437 [12], and ASTM C231 [13] standards, respectively. For hardened mortar properties, the tests methods are shown in Figure 2. The compressive strength and elastic modulus were measured with following ASTM C39 [14], and ASTM C469, respectively. For flexural strength measurement, ASTM C78 [15] standard was used, while the tensile strength was measured with the specimen casted as shown in Figure 2(c), and direct tensile force application method. The direct applied tensile strength test method was suggested by Korean institute of construction technology for SUPER concrete. All mechanical properties were measured at 28 days after the mixing.

Results and Discussions

Fresh state properties

Slump flow and air content

As a fresh state mortar properties, the influence of steel fiber replacement ratio and aspect ratio on the slump flow and air content were evaluated and those performances were tested. The results of slump flow and air content of the mortars are shown in Figures 3, and 4, respectively. Based on the target slump flow value of 650 ± 50 mm, and air content of 4.5 ± 1.5%, the fluidity of Plain mortar mixture showed very high fluidity of 740 mm slump flow value, and 4% of air content. For slump flow test results, in spite of the high fluidity of the Plain mixture, as the mixture contained steel fibers, the slump flow of the mixtures were decreased, and the slump flow value was decreased as the fiber replacement ratio was increased. In this result, the fluidity of the mortar mixtures are considered that it is decreased by the surface area of fiber contact with cement matrix increasing due to the number of steel fiber increasing per unit volume as the replacement ratio of steel fiber increases and this is determined to be similar to the results of former study [16]. Also, according to the fluidity result depending on the aspect ratio of steel fiber, fluidity was found to increase slightly more in the mortar mixtures with the steel fiber 16 mm in length than the mortar mixtures with steel fiber 20 mm in length. As the replacement ratio and aspect ratio of steel fiber increase, air content was generally increased. It can be stated that bonding interface between cement matrix and steel fiber is increased, and thus air content increases by the pores of the bonding interface at this time. On the other hand, despite the increase in air content by steel fiber, target air content was satisfied in all mixtures because air content of steel fiber is considered to have been controlled by the antifoaming agent used in the formulation of this study.

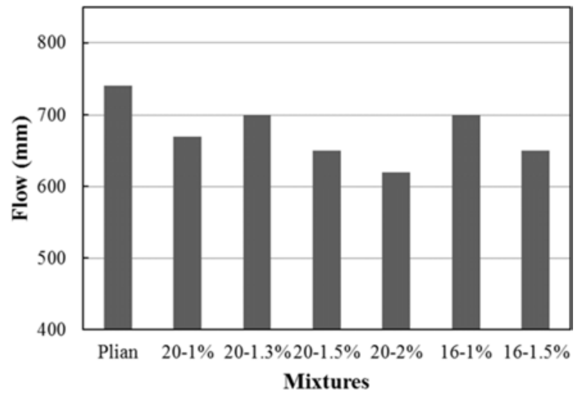

Fig. 3. Influence of fiber content and aspect ratio on slump flow of fresh mortar.

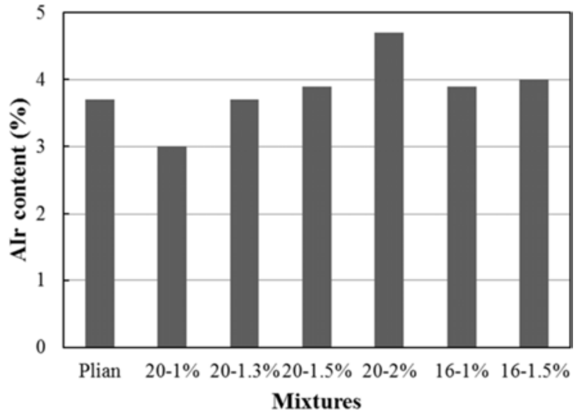

Fig. 4. Influence of fiber content and aspect ratio on air content of fresh mortar.

Hardened state properties

Compressive behaviors

To evaluate the basic hardened mortar properties, compressive strength was measured. During application of compressive force, the elastic modulus of the hardened mortar under the compressive conditions was tested. The influences of replacement ratio and aspect ratio of the steel fiber on the compressive strength and elastic modulus were shown in Figures 5 and 6, respectively. According to the former literature, the effect of compressive strength of concrete due to steel fiber reinforcement is insignificant so changes in the compressive strength is not significant [17]. According to the experimental results of this study, when comparing Plain mortar mixture without any fiber and mortar mixtures with various replacement ratio and aspect ratios of steel fiber, the compressive strength improvement was not shown and a little difference was found. For all mortar mixtures, the compressive strength values were satisfied the range of 120 MPa, the target strength. Elastic modulus also showed a similar tendency to compressive strength, indicating that there is no significant difference, most in the range of 36 ~ 39 GPa.

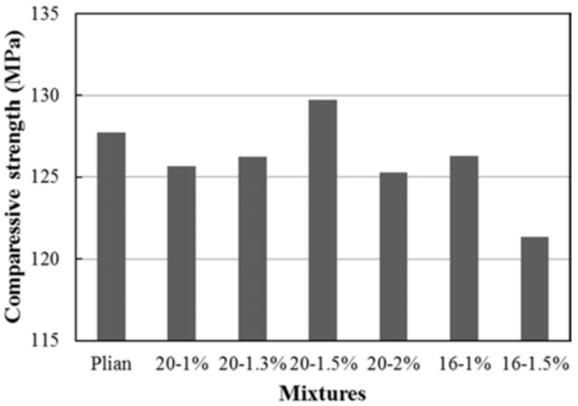

Fig. 5. Influence of fiber content and aspect ratio on compressive strength of mortar.

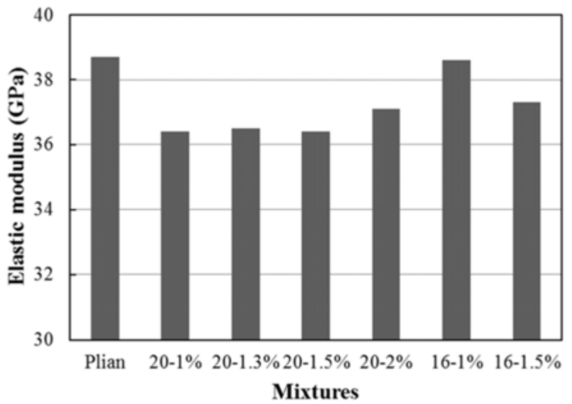

Fig. 6. Influence of fiber content and aspect ratio on elastic modulus of mortar.

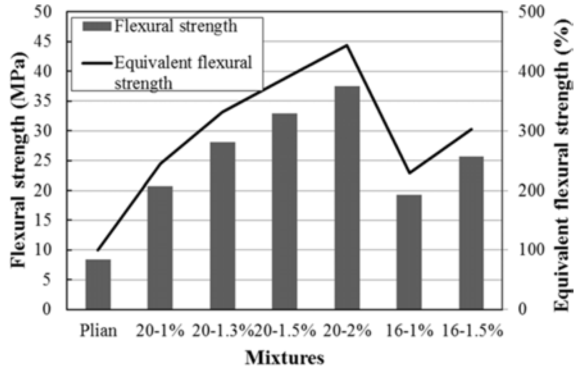

Fig. 7. Influence of fiber content and aspect ratio on flexural strength and equivalent flexural strength (flexural strength of Plain mixture is zero).

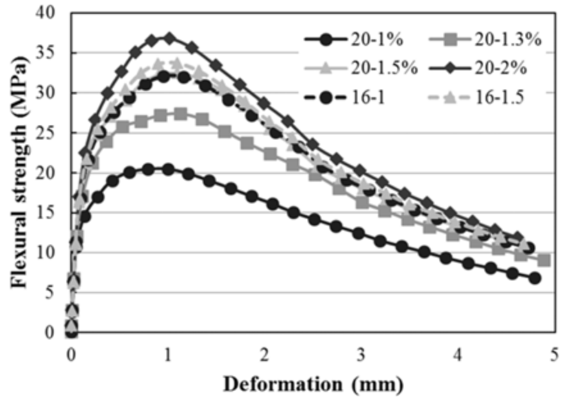

Fig. 8. Flexural strength - strain curves depending on fiber content and aspect ratio.

Flexural behaviors

Figures 7-10 show the result of the flexural behavior characteristics depending on steel fiber replacement ratio and aspect ratio. For a flexural strength and equivalent flexural tensile strength, as shown in Figure 7, the 20 - 2% mortar mixture showed high flexural strength of 37.5 MPa that was 4.2 times higher compared to Plain mixture without fibers. Not only for this increased flexural strength as the fiber replacement ratio was increased, the equivalent flexural strength was increased in proportion to flexural strength and showed high strength of 9.48 MPa. As shown above, as the replacement ratio of steel fiber increases, the flexural performance of concrete is improved by pull-out of steel fiber increasing per unit area and flexural performance is considered to have been improved because steel fiber played a role of bridging action suppressing the cracking starts and controlling the spread of cracks.

On the other hand, when the replacement ratio of steel fiber is same but the aspect ratio is different, flexural strength and equivalent flexural strength were increased as the aspect ratio increased. Accordingly, comparing to the 16 - 1.5% mortar mixture of aspect ratio 80, 20 - 1.5% mixture with aspect ratio 100 showed 32.87 MPa of flexural strength which was 7.24 MPa increased. Hence, from this result, it is considered that the resistance to flexural force of concrete can be improved as the aspect ratio of steel fiber is increased because bridging action can be continued longer time and control the development of the cracking for longer time with higher aspect ratio of the fiber than the fiber of lower aspect ratio.

Figure 8 shows the flexural strength-deformation relationship. Similar to the result of Figure 5, as the replacement ratio and aspect ratio of steel fiber increase, the flexural strength of the mortar was increased. Additionally, after the initial crack occurred, the strain-hardening of recovering the strength during increasing deflection was shown in the range of 0.5 - 1 mm. It indicates that the maximum strength is greater than initial cracking strength. After initial cracking, equivalent flexural strength holding the cracking plane due to the steel fiber reinforcement effect, thus ductile behavior was shown instead of rapid brittle behavior.

Figures 9 and 10 are the results of analyzing flexural behaviors based on the flexural strength and stain curves in Figure 8. First, the flexural strengths at several points were expressed (Figure 9). In this analysis, the flexural strengths at initial cracking point,

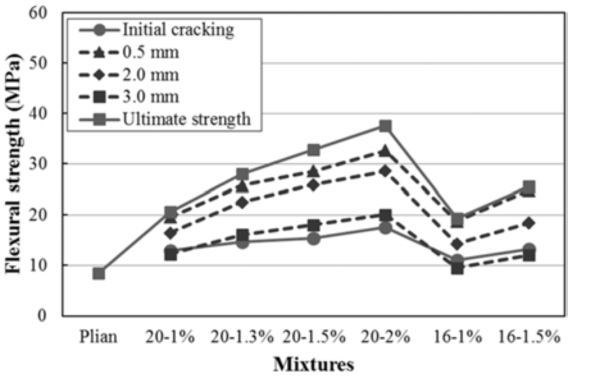

Fig. 9. Flexural strengths at some points depending on fiber content and aspect ratio.

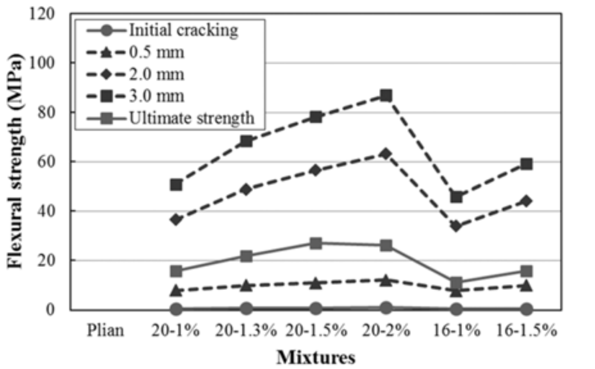

Fig. 10. Toughness at some points depending on fiber content and aspect ratio.

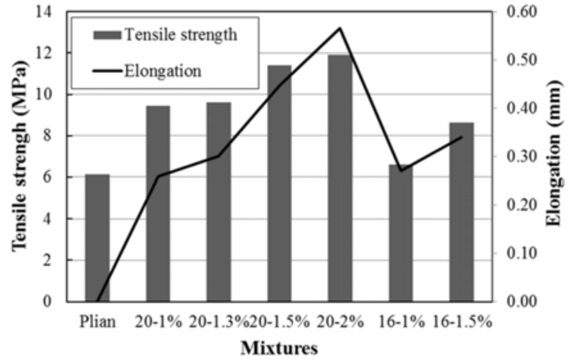

Fig. 11. Influence of fiber content and aspect ratio on direct tensile strength and elongation.

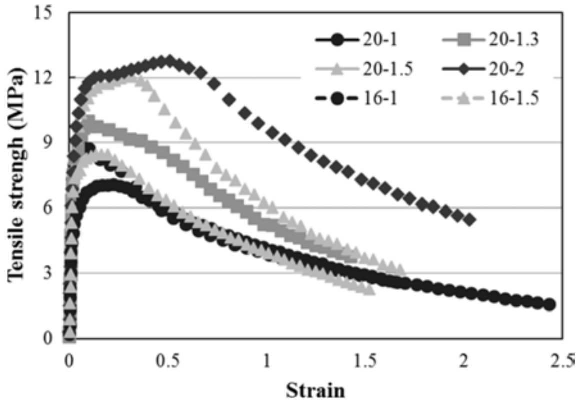

Fig. 12. Direct tensile strength-strain curves depending on fiber content and aspect ratio.

deformation of 0.5, 2.0, and 3.0 mm points, and the ultimate stress points were obtained. Additionally, the toughness at same points were calculated based on the each space under the curve at each point. From the results, as the replacement ratio of steel fiber increases, energy absorption capacity was improved, especially 20-2% mixture showed outstanding energy absorbing capacity compared to other mixtures. However, when the mixture contained the steel fibers of 16 mm in length and the aspect ratio of 80, at the same replacement ratio, flexural behavior showed poor performance compared to the mortar mixtures including the steel fiber of 100 aspect ratio.

Tensile behaviors

Figures 11 - 13 are the results of the direct tensile behavior depending on the aspect ratios and replacement ratios of the steel fiber. Figure 11 shows direct tensile strength and elongation and Figure 12 shows the direct tensile strength-strain curve. Generally, as the replacement ratio of steel fiber increases, both direct tensile strength and deformation capacity tend to increase and thus, compared to Plain mixture without fiber, the mixture 20 - 2% showed high direct tensile strength of 11.93 MPa that was 2 times higher than the Plain mixture and the elongation showed 0.565 mm of high deformation capacity. Additionally, in the case of the same replacement ratio but different aspect ratios, direct tensile strength and deformation capacity were improved as the aspect ratio is increased. Thus, 20 - 1.5% mixture showed approximately 30% higher direct tensile strength and elongation than 16-1.5% mixture. This result can be analyzed to be a similar tendency to the flexural behavior result and the strain hardening behavior after initial cracking in all mixtures and ductile fracture after the maximum strength point were shown.

The direct tensile strength and elongation at initial cracking point and ultimate strength point depending on the fiber replacement ratio and aspect ratio shows in Figures 13 and 14. In the case of initial cracking, the initial crack strength was high as the replacement ratio and aspect ratio were high, while the difference of deformation capacity was not significant depending on the replacement ratios and aspect ratios of the steel fiber.

On the other hand, in the case of the ultimate direct tensile strength, as the replacement ratio and aspect ratio was increased, the ultimate direct tensile strength and deformation capacity were increased. It was as similar to the case of the flexural strength results, when the longer fiber was used, the attached space between steel fiber and cement matrix was increased due to the increased specific space of the fibers, and hence the

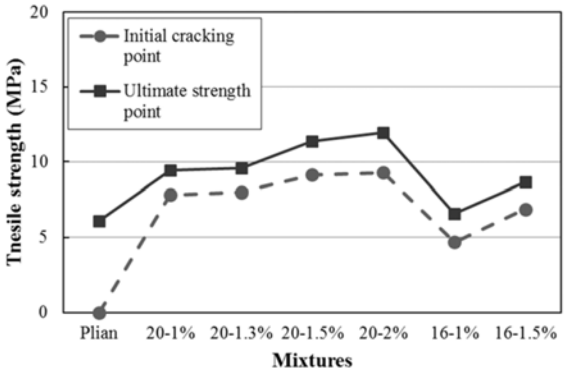

Fig. 13. Direct tensile strength at initial cracking point and ultimate strength point depending on fiber content and aspect ratio.

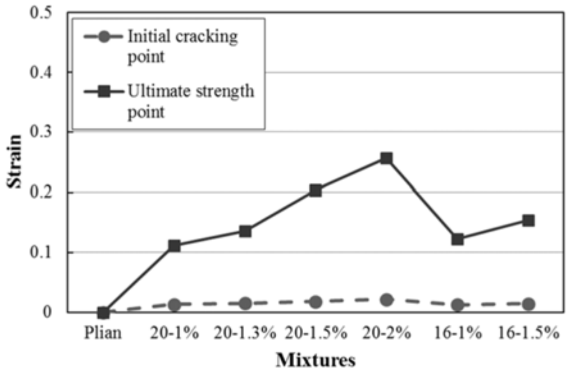

Fig. 14. Strain at initial cracking point and ultimate strength point depending on fiber content and aspect ratio.

Macro crack is suppressed. Furthermore, after the cracking, it is considered that because of the bridging effect of the fibers, the micro-cracking is evenly redistributed under the tensile stress, and thus the direct tensile strength and deformation capacity are improved.

Conclusions

This study reviewed strength properties of the fiber-reinforced high strength cement mortar depending on the replacement ratio and aspect ratio of steel fiber and the following conclusions could be obtained:

(1) The fresh state properties of the fiber-reinforced high strength cement mortar were tested and as the replacement ratio of steel fiber increased, fluidity decreased and air content increased. On the other hand, fluidity was slightly reduced as the aspect ratio of steel fiber is higher.

(2) Comparing to Plain mixture, there was no significant influence on compressive strength and elastic modulus under the compressive behavior depending on the replacement ratio and aspect ratio of steel fiber.

(3) The fiber-reinforced high strength cement mortar showed outstanding flexural strength as the replacement ratio and aspect ratio of steel fiber were higher. Especially, when the mixture contained 2% of the steel fiber with 100 aspect ratio, the flexural strength was improved by approximately more than 4 times, and deformation capacity and energy absorption capacity compared to Plain mixture without fiber reinforcement.

(4) From the direct tensile strength tests, generally, similar trend to the flexural strength test was shown: the cement mortar with 2% of 100 aspect ratio steel fiber showd the most improved tensile strength and elongation capacity.

Acknowledgements

This research was supported by a grant (13SCIPA02) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement (KAIA).

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