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Behavior of steel fiber-reinforced cementitious composites under direct tension and flexure

*Seongwoo Gwon[1], Seungpil Kim[2], Eunjong Ahn[3], and Myoungsu Shin[4]

[1], [2], [3], [4] School of Urban and Environmental Engineering, UNIST, Ulsan 689-798, Korea
[1] ksw4430@unist.ac.kr

ABSTRACT

The purpose of present study is to investigate effects of the properties and volume fraction of steel fibers on the mechanical behaviors of cementitious composites, subjected to compression, direct tension, and flexure. Hooked and straight steel fibers were blended with different volume ratios. Various mix designs were prepared and tested in two steps. In the 1st step, three mix designs with two types of steel fibers were prepared with two different fiber volume fractions of 1.0% and 1.5%, respectively. Mechanical tests were conducted to evaluate the modulus of elasticity, compressive stress-strain, direct tensile stress-strain, and flexural tensile stress-deflection responses.

1. INTRODUCTION AND BACKGROUND

High performance fiber-reinforced cementitious composites (HPFRCC), studied and defined by Naaman (2006), consist of fine aggregates, super plasticizer, polymeric, cement, water, and fibers such as synthetic, steel or natural organic. HPFRCC is called 'Cementitious Composites' due to its exclusion of coarse aggregates, while fiber reinforced concrete (FRC) includes the coarse aggregates. HPFRCC is developed to mitigate the quasi-brittle failure manner under severe loading and its long term integrity (Kim 2009, Li 2003). In general, it exhibits large strain capacity after first cracking, while FRC just shows strain softening behavior. The major feature of fiber reinforced cementitious composites (FRCC) is the strain softening right after first cracking, causing multiple micro cracks in tension.

Because tensile stresses are transferred between cracks via consecutive fiber bridging and pullouts, HPFRCC can sustain high tensile ductility. HPFRCC provides not only a proper level of ductility but also higher energy dissipation (Li 2003). Through the fiber pullout occurred leading to gradual many micro cracks across a matrix, tensile forces are transferred between the cracks. The fibers provide better energy dissipation and stiffness retention without brittle failure manner. Moreover, in a structural system, HPFRCC is effective in enhancing shear strength, displacement capacity, and damage tolerance.

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1), 2), 3) Graduate student
4) Professor

Despite the aforementioned characteristics of HPFRCC studied by previous literatures, further investigations are required on high strength; the high strength concrete generally results in catastrophic brittle failure (Gettu 1990). Therefore, an achievement of tensile behaviors under excessive loading is essential for its applications to structural systems. Compressive and tensile strengths are the major indices of mechanical properties of concrete. Usually, the tensile strength can be obtained using direct tensile test, splitting tensile test or flexural test. However, among the methods, direct tensile test is not preferred due to its difficult operation.

Given the background mentioned so far, the purpose of this study is to investigate mechanical behaviors, especially tensile behaviors of cementitious composites reinforced by the steel fibers with different aspects and volume fractions. The experiments in two steps were conducted under different mix conditions. Main test variables are existence of coarse aggregates, water-to-binder ratio, types of micro fillers, aspects and volume fractions of steel fiber. Thus, the authors conducted two kinds of tensile tests among the three of them. Each of them is the direct tensile and third-point bending test, respectively. Compressive and elastic modulus tests were also performed.

2. EXPERIMENTAL SETUP

In this section, the experimental setup used to investigate the effect of aspects and volume fractions of steel fibers is described. All mix cases in two steps, including total five specimens, were performed by varying the proportions of ingredients and volume fractions of steel fibers. Several types of mechanical tests were conducted: the compressive strength, modulus of elasticity, direct tensile strength, and flexural strength tests. The compressive tests comply with ASTM standard (ASTM C39 2010) for the compressive strength of cylindrical concrete specimens. The hydraulic universal testing machine with 150 kN capacity was used to carry out the displacement controlled direct tensile tests with a rate of 0.5 mm/min based on the JSCE recommendation (JSCE 2007). And the flexural tests followed the standard test method for flexural performance of fiber-reinforced concrete per the ASTM standard (ASTM C1609 2012). For all experimental cases, two types of steel fibers were used: one hooked fibers and the other straight fiber. The detailed information and configuration of hooked steel fibers is summarized in Table 1. All specimens were cured in a controlled curing machine with a curing humidity of 60% and a curing temperature of 40 ℃ during 7 days. Three specimens were designed in 1st mix design, whose detailed composition of each type is presented in Table 2. In 2nd mix design, two specimens with only hooked steel fibers were manufactured: 2HF10Y and 2HF15N; see Table 2.

Table 1 Physical properties of hooked steel fibers

Length (mm)	Diameter (mm)	Aspect ratio (L/D)	Tensile strength (MPa)	
30	0.38	80	2,300	

Table 2 Mix proportions of 1st and 2nd mix design

Mixture code		1HF10Y	1SF15Y	1HF15N	2HF10Y	2HF15N
Maximum size of coarse aggregate (mm)		10	10	-	10	-
Slump (mm)		-	80 ~ 90	-	-	-
Air content (%)		4	4	4	4	4
Water/binder ratio (wt. %)		28.8	28.8	24.6	24.0	24.6
Sand/aggregate ratio (vol. %)		60	60	100	60	100
Fiber fraction (vol. %)		1.0	1.5	1.5	1.0	1.5
Ingredient contents (kg/m^3)	Water	223	222	239	238	241
	Cement	543	540	817	795	784
	Fly ash (GGBFS)	194	193	117	139 (GGBFS)	137 (GGBFS)
	Silica fume	39	39	39	60	59
	Sand	699	695	972	596	981
	Gravel	466	463	-	397	-
	Super plasticizer	2.7	2.7	3.9	3.38	4.34
	HPMC[1]	0.4	0.4	0.2	0.2	0.2
[1] HPMC is Hypromellose used as a viscosity modifying agent.						

3. RESULTS AND DISCUSSION

In this section, the results of mechanical tests are presented and discussed. Discussed are the compressive strength, modulus of elasticity, direct tensile strength, and flexural tests. The test results include both 1st and 2nd mix design specimens.

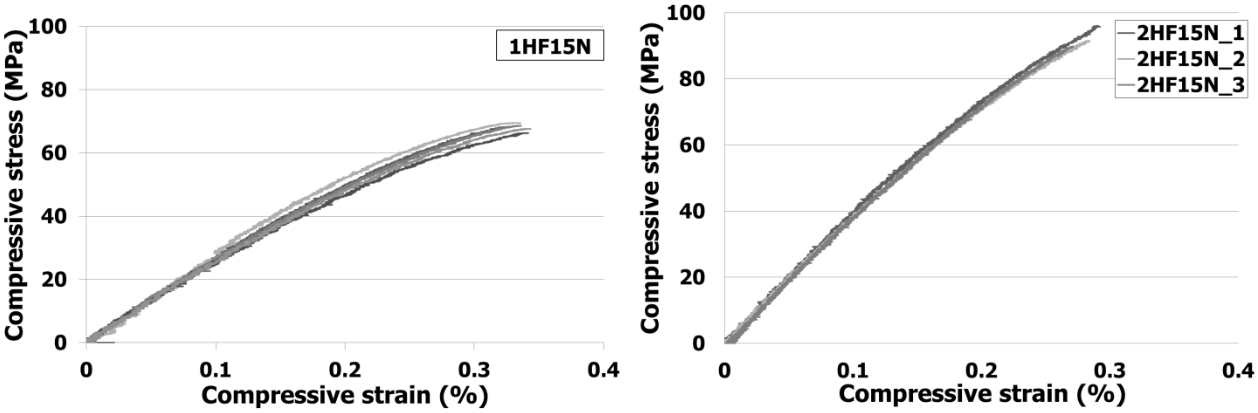
3.1 Compressive strength and Elastic Modulus

For 1st mix design, one representative compressive stress-strain response among three specimen cases is constructed (Fig. 1) and summary for the compressive strengths and elastic modulus (E_{fc}) is made in Table 3. Overall compressive stress-strain responses of all specimens had no softening curves after reaching maximum strengths, resulting from the high compressive strengths, which means brittle failure mechanism. Elastic modulus is generally proportional to the compressive strength. To compare the measured elastic modulus in a relation to the ordinary Portland cement concrete, one equation for the elastic modulus (E_{cc}) is used per Neville (1997):

$$\mathrm{E}_{cc} = 4730\sqrt{f_{c,max}} \tag{1}$$

Here, $\mathrm{f}_{c,max}$ is the measured compressive strength of concrete. In general, the E_{fc}-to-E_{cc} ratios suggest that the elastic moduli of 1st mix design specimens are generally average 27 % lower than that of Portland cement concrete. And the strain at

$f_{c,max}$ ranges from 0.0025 to 0.0034, which is slightly higher than that of Portland cement concrete.



(a) 1HF15N (b) 2HF15N

Fig. 1 Compressive stress-strain responses

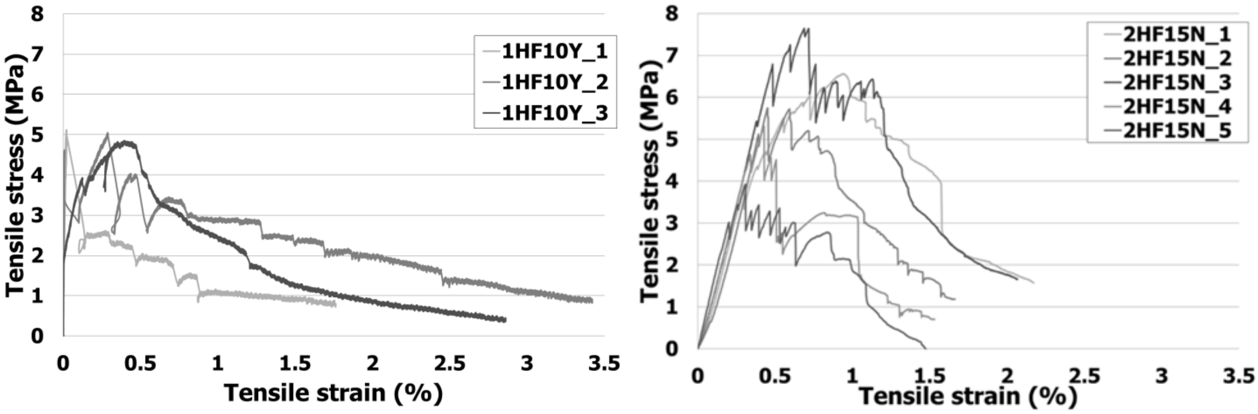
For 2nd mix design, one representative compressive stress-strain response among two cases is constructed (Fig. 1) and summary for the compressive strengths and elastic modulus is also given in Table 3. All tested specimens of 2nd mix design also showed no softening curves after reaching maximum strengths, which means the brittle failure. In general, the compressive strengths of 2nd mix design achieved higher strength than 1st mix design. In 2nd mix design, it was found that reduced water-to-binder ratios and the use of GGBFS instead of fly ash affected higher strength development.

Table 3 Compressive strengths and elastic modulus

Mixture name	Compressive strength (MPa)		Strain at maximum compressive stress		Elastic modulus, E_{fc} (GPa)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1HF10Y	49.6	1.6	0.0025	0.0003	25.2	3.5
1SF15Y	54.9	2.0	0.0027	0.0001	26.6	2.0
1HF15N	68.1	1.2	0.0034	0.0001	26.2	0.4
2HF10Y	93.3	1.8	0.0025	0.0004	50.3	13.1
2HF15N	92.5	3.2	0.0028	0.0001	38.3	0.4

3.2 Direct Tensile Strength

For 1st mix design, one representative direct tensile stress-strain response among three specimens is constructed (Fig. 2) and summarized in Table 4. The average of the two LVDTs' readings was used to estimate tensile strain during the whole tests. In general, the response of the normal concrete is brittle under tension; almost linear elastic responses appear up to the onset of the first crack, followed by a sudden drop in tensile stress. In contrast, the fiber-reinforced cementitious composites (FRCCs) show better ductility than the normal concrete. The existence of steel fibers can change the response after the first cracking; beyond maximum stress, the tensile stress drops step by step due to the gradual bridging effect developed along the length of specimens.



(a) 1HF10Y (b) 2HF15N

Fig. 2 Direct tensile stress-strain responses

For the 2nd mix design, one representative direct tensile stress-strain response among two specimens is constructed (Fig. 2) and summarized in Table 4. For each case, five specimens were tested. Overall tensile strengths of 2nd mix design specimens were increased; 13.3 MPa for 2HF10Y, and 18.3 MPa for 2HF15N.

Table 4 Direct tensile strengths

Mixture code	Direct tensile strength (MPa)		Strain at maximum stress (%)	
1HF10Y	4.89	0.16	0.24	0.19
1SF15Y	3.96	0.64	0.03	0.03
1HF15N	4.43	1.18	0.11	-
2HF10Y	3.9	1.1	-	-
2HF15N	5.8	1.4	-	-

3.3 Flexural Strength

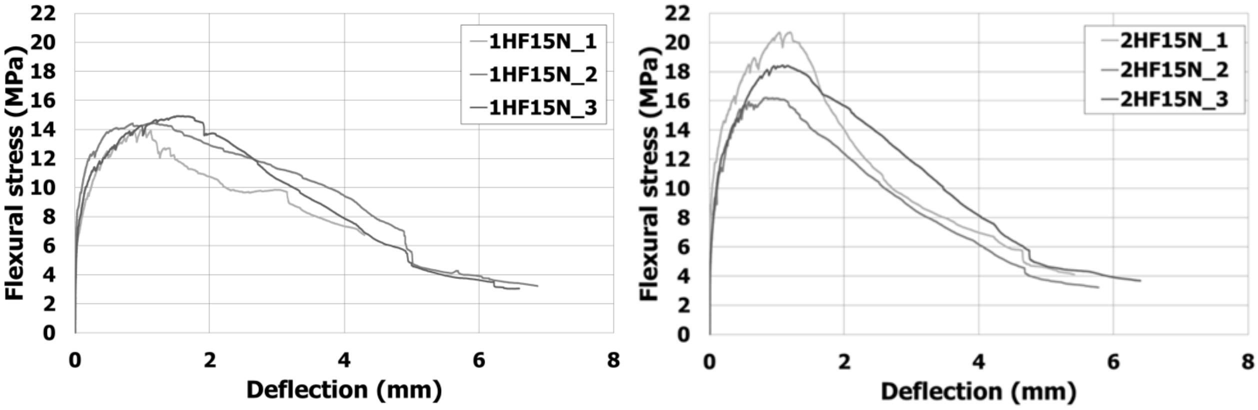
For flexural tensile strength tests, third-point bending tests were conducted following the standard regulation ASTM standard (ASTM C1609 2012). Each load-deflection curve presents the applied load versus the average deflection read by two LVDTs at the mid-span.

For the 1st mix design cases, one representative load-deflection response among three test cases is shown in Fig. 3. Each of them consists of at least three specimens. And the summary for the test results is given in Table 5. In a load-deflection response, the flexural stresses were obtained by following:

$$\sigma_f = \frac{Pl}{bh^2} \tag{2}$$

Where P is applied load and l is span length; 300 mm in this study. And b and h are the width and depth of the prismatic beam specimens, respectively.

Up to the end of all tests, micro cracks sensible by naked eyes were developed in the region especially between the two bottom supports. After then, the cracks at the mid span were widened and caused the failures. All inflection points where the linear elastic line starts to change to nonlinear line happened when flexural stress reached to 6 MPa, at which the micro cracks started to develop (Fig. 3).



(a) 1HF15N (b) 2HF15N

Fig. 3 Flexural stress-strain responses

Table 5 Flexural strengths

Mixture code	Maximum flexural stress (MPa)	
	Average	Standard deviation
1HF10Y	10.3	1.9
1SF15Y	7.7	0.9
1HF15N	14.5	0.5
2HF10Y	13.3	1.4
2HF15N	18.4	2.3

For the 2nd mix design, both 2HF10Y and 2HF15N achieved higher flexural strengths than those of 1st mix design cases (Table 5). The inflection points where the linear lines started to change to the nonlinear lines happened at approximately 7 MPa flexural stresses for all specimens. This value is bigger than that of 1st mix design cases and it is analyzed that the increased strengths of materials made the inflection values higher.

4. CONCLUSIONS

In this study, five specimen cases of steel fiber-reinforced cementitous composities were fabricated and tested with different aspects (hooked and straight) and volume fractions (1.0 % and 1.5 %) of steel fibers, varying the proportions of constituent binding materials, existence of coarse aggregate or not, water-to-binder ratios, and the types of micro fillers (fly ash and GGBFS). Several mechanical tests were performed especially focusing on improvement of tensile behaviors: direct tensile and flexural tests. Important findings and conclusions are summarized in the following.

- The hooked steel fibers were effective in bridging cracks in the composites. They induced better direct tensile and flexural behaviors than those via straight fibers.
- Lower water-to-binder ratios and replacement of fly ash by GGBFS improved both compressive and tensile strengths.
- In general, mix design cases in the 2nd step were more effective in the tensile behaviors. The 2nd mix design cases achieved higher compressive and tensile strengths, and they also sustained larger tensile strains, which would improve ductility.

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