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Effect of fiber length and placement method on flexural behavior, tension-softening curve, and fiber distribution characteristics of UHPFRC

Doo-Yeol Yoo [a], Su-Tea Kang [b], Young-Soo Yoon [a,*]

[a] School of Civil, Environmental and Architectural Engineering, Korea University, 1, 5-ga, Anam-dong, Seongbuk-gu, Seoul 136-713, Republic of Korea
[b] Department of Civil Engineering, Daegu University, 201, Daegudae-ro, Jillyang, Gyeong-san, Gyeong-buk 712-714, Republic of Korea

HIGHLIGHTS

- Enhancement of flexural performance was achieved through increase of fiber length.
- Shorter fiber length exhibited better fiber orientation and dispersion and higher number of fibers in unit area.
- Improved flexural strength and fiber dispersion were obtained for the specimen with concrete placed at maximum moment region.
- Generalized tension-softening model of UHPFRC was suggested considering fiber length and placement method.

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ABSTRACT

This study investigates the effect of fiber length and placement method on the flexural behavior, tension-softening curve, and fiber distribution characteristics of ultra-high-performance fiber-reinforced concrete (UHPFRC). Four different fiber lengths (L_f = 13, 16.3, 19.5, and 30 mm) were considered for two different placement methods. The ultimate flexural strength increased with increasing fiber length up to 19.5 mm, despite no noticeable difference in the first crack strength. Conversely, fiber length of 30 mm showed deterioration of flexural performance due to the decrease of fiber number existed across the crack surface. Both of first crack and ultimate flexural strengths were affected by the placement method; the specimen with concrete placed in the center (at maximum moment region) exhibited higher strength than that with concrete placed in the corner. The reasons were confirmed by image analysis that poorer fiber dispersion and fewer fibers across the crack surface were obtained for the specimen with concrete placed in the center than its counterpart. Finally, a tri-linear softening curve for UHPFRC was suggested based on inverse analysis and verified through comparison between the finite element analyses and the test data.

1. Introduction

Recently, there have been extensive efforts to improve the strength of concrete. However, increased strengths have invariably been accompanied by brittle failure, which limited the application of high strength concrete in many structures. On the other hand, recently developed ultra-high-performance fiber-reinforced concrete (UHPFRC) has both high strength and ductility through the incorporation of a large amount of steel fibers [1]. In particular, owing to its superb post-cracking ductility under tension and flexure, UHPFRC has been attractive for use in civil infrastructure, where bending prevails. However, its unique tensile behavior is affected by many factors such as fiber properties (e.g., strength, stiffness, Poisson's ratio, geometry, shape, and volume fraction), matrix properties (e.g., strength, stiffness, Poisson's ratio), interface properties, and fiber distribution characteristics [2,3]. Thus, to use UHPFRC in civil infrastructure, the tensile behavior must be carefully investigated.

To date, numerous studies have evaluated the effect of fiber and matrix properties on the tensile and flexural behaviors of UHPFRC [3,4–10]. Among others, an increase in fiber aspect ratio (or fiber length) has been one of the most convincing methods to improve the flexural performance including strength and fracture energy capacity by increasing the effective bonding area between the fiber and the matrix at crack surfaces [10]. However, poor fiber dispersion and fiber balling occurred when fiber aspect ratio and length increased [11,12], which may cause deterioration in flexural performance. For this reason, the flexural performance of UHPFRC should be investigated according to the fiber length.

* Corresponding author. Tel.: +82 2 3290 3320; fax: +82 2 928 7656.
E-mail address: ysyoon@korea.ac.kr (Y.-S. Yoon).

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Table 1
Mix proportion.

Relative weight ratios to cement						Steel fiber (V_f, %)
Cement	Water	Silica fume	Sand	Silica flour	Superplasticizer	
1.00	0.25	0.25	1.10	0.30	0.016	2%

Where, V_f = volume fraction of fiber.

Table 2
Chemical compositions of cementitious materials.

Composition % (mass)	Cement	Silica fume
CaO	61.33	0.38
Al_2O_3	6.40	0.25
SiO_2	21.01	96.00
Fe_2O_3	3.12	0.12
MgO	3.02	0.10
SO_3	2.30	–
K_2O	–	–
F-CaO	–	–
Specific surface (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.10

Where, cement = type 1 Portland cement.

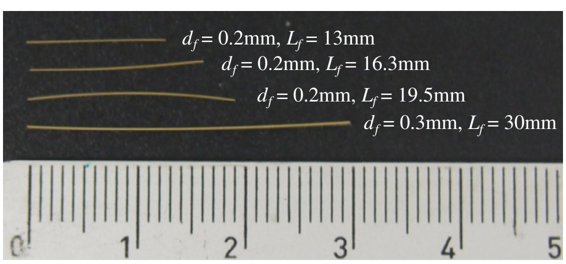

Fig. 1. Pictures of fibers.

Although many researchers have investigated the tensile and flexural behaviors of UHPFRC, most have not considered the fiber distribution characteristics. However, Ferrara [13] recently reported that the tensile performance is strongly affected by the fiber orientation and dispersion, and thus, the casting process should be reasonably designed to exhibit proper fiber enhancement. Kang and Kim [6] also experimentally verified the effect of fiber orientation on flexural behavior. In their study, to confirm the fiber orientation effect, the fiber arrangement was intentionally controlled by placing concrete parallel and transverse to the tensile distance, without considering the variation of fiber orientation and dispersion along the flow direction. However, UHPFRC elements are generally fabricated by placing concrete at a target position and leading it to flow. This is because UHPFRC shows high fluidity and self-consolidating properties, and this placement method can provide fiber alignment in the tensile direction [13,14]. Thus, the flexural performance of UHPFRC made using this placement method needs to be explored by considering the fiber orientation and dispersion at the crack surface and along the flow distance.

In order to practically use UHPFRC in real structures, design and analysis techniques that consider a tension-softening model should be developed. However, not only is the research into developing tension-softening model for UHPFRC still very limited [4,5,7,15,16], but also these suggested softening models are only valid for UHPFRC with micro-fibers (mostly fiber length of 12 mm or 13 mm). Up to data, to the best of the authors' knowledge, no published study exists that is related to a suggestion of generalized tension-softening model, which is valid for the UHPFRC mixes with various fiber lengths and placement methods. Thus, a rational and generalized tension-softening model for UHPFRC is required to be developed in addition to the investigation of tensile and fracture properties.

Accordingly, in this study, the effect of fiber length and placement method on flexural properties and fiber distribution characteristics of UHPFRC was investigated. The detailed objectives were to investigate the effect of fiber length and placement method on: (1) strengths and deflection capacities at first crack and peak load under flexure and (2) degree of fiber dispersion, number of fibers, and fiber orientation distribution using image processing technique. Furthermore, a tri-linear tension-softening curve, which is applicable for UHPFRC including diverse fiber lengths and placement methods, was suggested by inverse analysis, and it was verified using finite element analysis through comparison with the present test data.

2. Experimental program

2.1. Materials and specimen preparation

The mix proportion used in this study is given by the weight ratio in Table 1. The chemical compositions and physical properties of cementitious materials used are also summarized in Table 2. Silica flour including 98% SiO_2 with diameter of 2 μm and sand with grain size smaller than 0.5 mm were used, whereas coarse aggregate was excluded in the mixture. To investigate the effects of fiber length on the compressive and flexural behaviors, four different fiber lengths (L_f = 13, 16.3, 19.5, and 30 mm) were incorporated by 2 vol.%, which led to four series of test specimens. The photos and properties of steel fibers used are presented in Fig. 1 and Table 3, respectively. To prevent fiber breakage before pullout, the fiber with a length of 30 mm was designed with a diameter of 0.3 mm by assuming that the bond strength of fiber is rarely affected by the fiber diameter [17].

The mixing sequence of UHPFRC was as follows. Cement, silica fume, silica flour, and sand were first premixed for approximately 10 min. Water premixed with superplasticizer was added in the dry state and mixed for another 10 min thereafter. When the mixture became flowable, steel fibers were dispersed and then mixed for an additional 5 min.

Since UHPFRC has flowable and self-consolidating characteristics, the structures or specimens made of UHPFRC are fabricated by placing concrete at a certain point and allowing it to flow [14,18]. Thus, in this study, to investigate the effect of placement method on the flexural behavior, fracture properties, and fiber distribution characteristics, two different placement methods were adopted, as shown in Fig. 2; (1) placing concrete at the center of the specimen and (2) placing concrete at the corner of the specimen.

Table 3
Properties of steel fibers.

Type of fiber (mm)	Diameter (mm)	Length (mm)	Aspect ratio (L_f/d_f)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
L_f = 13 mm	0.2	13.0	65.0	7.8	2500	200
L_f = 16.3 mm	0.2	16.3	81.5			
L_f = 19.5 mm	0.2	19.5	97.5			
L_f = 30 mm	0.3	30.0	100.0			

Where, L_f = length of fiber, d_f = diameter of fiber.