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Enhancing the flexural performance of ultra-high-performance concrete using long steel fibers

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

[a] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea
[b] Department of Civil Engineering, Daegu University, 201, Daegudae-ro, Jillyang, Gyeong-san, Gyeong-buk 712-714, Republic of Korea
[c] School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 136-713, Republic of Korea

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ABSTRACT

In this study, the flexural performance and fiber distribution characteristics of ultra-high-performance concrete (UHPC) were investigated according to the fiber length. To do this, three different fiber lengths having an identical diameter were used. Enhancements in flexural strength and energy absorption capacity were observed when longer fibers (or higher aspect ratios of fiber) were used, whereas insignificant effect of fiber length on the first cracking properties (i.e., first cracking strength and corresponding deflection) was obtained. Fiber length had a little influence on the degree of fiber dispersion, but a significant influence on the fiber orientation. A higher fiber orientation coefficient along the flow distance was obtained when shorter fibers were used. A finite element analysis incorporating previously suggested material models was performed and verified by comparing the analytical results with the present experimental data.

1. Introduction

Ultra-high-performance concrete (UHPC) is characterized by a unique deflection–hardening (sometimes, strain–hardening) behavior with multiple micro-cracks [1]. Due to its unique and superior tensile and flexural performance along with an extremely high compressive strength (>150 MPa), the use of UHPC in architectural and civil structures, where bending prevail, guarantees the enhancement in the load carrying capacity, energy absorption capacity, and durability. However, despite these advantages, the use of UHPC in real structures has been limited by several reasons such as the high cost, large variation of tensile performance, and lack of the design and analysis techniques which should incorporate a sophisticated tension–softening curve (TSC).

The high cost of UHPC commercially available in Korea is mostly caused by the high prices of steel fiber and superplasticizer, as summarized in Table 1, and the additional cost for heat curing. In particular, the use of lower amount of steel fibers can be one of the most promising methods reducing its cost, because the price of high strength steel fibers is considerably expensive compared to other drying components making the UHPC matrix. (2% by volume of smooth steel fibers occupies approximately 33% of total cost of UHPC.) Therefore, some of researchers [2–7] have tried to reduce the required amounts by using different types of steel fibers. The best-known methods for improving the tensile and flexural performances of UHPC without increasing the total volume contents of fibers can be divided into two categories: (1) using hooked or twisted steel fibers [2,4,7] and (2) increasing the fiber length (or aspect ratio) of steel fibers [3,5–7]. Even though the use of hooked or twisted steel fibers increases both tensile and flexural strengths and energy absorption capacity, the information is still lacking on the design and analysis technique and fiber distribution characteristics due to the complexity of the fiber geometry. In contrast, a great deal of useful information regarding the design technique and fiber distribution characteristics due to its simple geometry exists on the smooth steel fibers [1,5,8–11]. In addition, an increase in the length of smooth steel fiber improves flexural performance including post-cracking strength and fracture energy by increasing the peak pullout load and corresponding slip between the matrix and the fiber, owing to the increase in effective bonding area of fibers at crack surfaces [1,5]. For this reason, an increase in the length of smooth steel fibers can be a simpler way to improve tensile and flexural performances, and the information related to the design of UHPC structures can relatively easily be provided.

As reported by numerous studies [1,3–6,9,11–13], the tensile and flexural performances of UHPC are influenced by many factors,

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* Corresponding author.
E-mail address: ysyoon@korea.ac.kr (Y.-S. Yoon).

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Table 1
Cost portion of UHPC with 2% of steel fibers.

Cement	Silica fume	Silica flour	Silica sand	Superplasticizer	Steel fibers (V_f = 2%)
3.7%	7.4%	11.1%	12.7%	30.9%	32.8%

including not only the fiber properties (e.g., geometry, shape, and volume content), but also the matrix strength, interfacial properties between the fiber and matrix, and fiber orientation and dispersion. Above all, in accordance with the test results obtained by Ferrara et al. [13], the tensile performance is significantly influenced by the fiber orientation. Thus, to rationally analyze the tensile performance of UHPC, the fiber distribution characteristics such as fiber orientation, fiber dispersion, and number of fiber in unit area should be investigated. Therefore, Lee et al. [14] developed a digital image analysis technique for quantitatively evaluating the fiber orientation and dispersion in engineered cementitious composites. Furthermore, in recent years, some of researchers [1,6,15] extended their algorithm for UHPC, and thus, more rational analysis of the effect of fiber distribution characteristics on the tensile and flexural performances became possible.

This research investigated the flexure performance of UHPC beams according to the fiber length with the consideration of fiber distribution characteristics. The specific objectives were to evaluate the implication of fiber length on: (1) the load carrying capacity and energy absorption capacity, which is analyzed by using toughness value, at various deflection points under flexure and (2) the fiber orientation, dispersion, and number of fibers along the flow distance. In addition, a numerical analysis was performed to predict the flexural behavior of UHPC beams by incorporating the previously suggested linear compressive model and tri-linear TSC.

2. Experiments

2.1. Materials, specimen preparation, and determination of first cracking point

For cementitious materials, type 1 Portland cement with a specific surface of 3,413 cm^2/g and a density of 3.15 g/cm^3 and silica fume with a specific surface of 200,000 cm^2/g and a density of 2.10 g/cm^3 were used. The detailed chemical compositions of used cement and silica fume can be found elsewhere [1]. Sand with a grain size less than 0.5 mm was used as fine aggregate, and silica flour with 98% SiO_2 and a diameter of 2 μm was added to the mixture. In order to evaluate the implication of steel fiber length on the flexural performance and fiber distribution characteristics, smooth steel fibers with an identical diameter of 0.2 mm and three different lengths of 13, 16.3, and 19.5 mm were incorporated at a 2% volume fraction within a UHPC matrix. The geometrical and physical properties of used steel fibers are summarized in Table 2. To provide suitable workability and viscosity for all mixtures, a high performance water-reducing agent, polycarboxylate superplasticizer (density of 1.01 g/cm^3 and dark brown color), was added by 1.6%. The mix proportions used in this study are given in Table 3, and the detailed mixing sequence for UHPC can be found in a previous paper [7].

Due to the self-consolidating properties of UHPC, the structural elements are generally produced by placing UHPC at a certain point and allowing it to flow [10,16]. Therefore, the beam specimens with a cross-sectional dimension of 100 mm × 100 mm and a length of 400 mm were also fabricated by placing UHPC at the end of the specimen and allowing it to flow, as shown in Fig. 1.

Immediately after casting UHPC, the beams were covered with plastic sheets and cured at room temperature for 48 h. After then, the beams were demolded and steam cured at a high temperature of 90 ± 2 °C for 3 days. Then, the beams were removed from the heat-curing room and stored at room temperature until testing day. All specimens were tested in a dry condition at the age of 28 days.

Since UHPC exhibits deflection–hardening behavior, it is important to separately determine the first cracking and post-cracking peak points. In order to define the first cracking point, Yoo et al. [5,11] performed three-point flexural tests of notched UHPC beams and reported that the first cracking point of UHPC beams with smooth steel fibers can be defined as the point where nonlinearity in the load–deflection (or load-CMOD) curve becomes evident, regardless of fiber length and content. Similarly, in this study, a sudden increase in deflection with a slight decrease in load was obtained just after the limit of proportionality (LOP) in the load–deflection curve due to the initiation of matrix cracking, as shown in Fig. 2, and thus, the LOP in the load–deflection curve was also defined as the first cracking point for UHPC beams under four-point flexure.

2.2. Test setup and procedure

Since the fiber distribution characteristics are strongly influenced by the fluidity of UHPC, a flow table test was performed as per ASTM C 1437 [17]. Fresh UHPC was filled in a cone-shaped steel mold, and then, the mold was lifted off very carefully for allowing the fresh UHPC to flow. After then, the flow table was dropped 25 times within a period of 15 s, and the average value of the maximum flow diameter and the perpendicular diameter

Table 2
Properties of steel fibers.

	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		16.3	81.5			
L_f = 19.5 mm		19.5	97.5			

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

Table 3
Mix proportion.

Relative weight ratios to cement						Steel fiber (V_f,%)	Flow (mm)
Cement	Water	Silica fume	Sand	Silica flour	Superplasticizer		
1.00	0.25	0.25	1.10	0.30	0.016	2%	230–240

Where, V_f = volume fraction of fiber.