Construction and Building Materials 150 (2017) 383–394

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Development of cost effective ultra-high-performance fiber-reinforced concrete using single and hybrid steel fibers

Doo-Yeol Yoo [a], Min Jae Kim [a], Sung-Wook Kim [b], Jung-Jun Park [b,*]

[a] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[b] Structural Engineering Research Institute, Korea Institute of Civil Engineering and Building Technology, 283 Daehwa-dong, Goyangdae-ro, Ilsanseo-gu, Goyang-si, Gyeonggi-do 10223, Republic of Korea

HIGHLIGHTS

- The use of S fibers is most efficient in improving flexural performance of UHPC at v_f of 2%.
- Hybrid H and S fibers are effective in improving flexural performance of UHPFRC with single H fibers.
- Hybrid T and S fibers are less efficient in terms of flexural performance than single T fibers.
- The optimum UHPFRC mixture is suggested in terms of flexural strength and cost effectiveness.

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 11 May 2017
Accepted 2 June 2017

Keywords:
Ultra-high-performance fiber-reinforced concrete
Flexural performance
Fiber hybridization
Steel fiber
Cost analysis

ABSTRACT

This study investigates the flexural behavior of ultra-high-performance fiber-reinforced concrete (UHPFRC) with single and hybrid steel fibers. To do this, three different types of steel fibers, i.e., hooked, twisted, and straight fibers, were considered, and a UHPFRC commercially available in North America was used as a comparison. To suggest a low-cost UHPFRC exhibiting the best flexural performance, test data and cost of fibers were analyzed based on a literature review. Test results indicate that straight steel fibers provide the best flexural performance, including strength, deflection capacity, energy absorption capacity, and cracking behavior, compared with hooked and twisted fibers, especially when many fibers (2% by volume) were incorporated. Hybrid reinforcement (hooked + straight fibers) efficiently improved the flexural performance of the UHPFRC with single hooked fibers, but the twisted + straight fibers were less effective than the UHPFRC with single twisted fibers. The optimum UHPFRCs contained 2 vol% single straight steel fibers (l_f/d_f of 19.5/0.2) or hybrid 0.5 vol% long (l_f/d_f of 30/0.3) and 1.5 vol% medium-length (l_f/d_f of 19.5/0.2) straight steel fibers; they showed better flexural strength and cost effectiveness than other types of UHPFRCs.

1. Introduction

In the mid-1990s, reactive powder concrete (RPC), which was the forerunner of various types of ultra-high-performance fiber-reinforced concrete (UHPFRC) currently available worldwide, was first developed by Richard and Cheyrezy [1]. To achieve high strength, they [1] designed the mixture proportions based on packing density theory, determining the optimum size of the granular materials, and performed heat curing at 90 °C and 400 °C with pressure. Furthermore, to obtain excellent post-cracking tensile performance, they incorporated micro-straight steel fibers with a length of 13 mm at volume fractions, v_f, of 1.5–3.0%. Since then, various types of UHPFRCs based on RPC have been proposed in many countries [2-5]. ACI Committee 239 [5] defines ultra-high-performance concrete (UHPC) as concrete with a minimum compressive strength of 150 MPa that meets specified durability, tensile ductility, and toughness requirements. Meeting those requirements needs a high volume of fibers in most cases.

To improve the post-cracking tensile or flexural properties of UHPFRC, hybrid reinforcing systems have been introduced by some researchers [6-12]. In particular, most researchers have blended macro- and micro-fibers for hybrid UHPFRC because the macro-fibers efficiently improve post-cracking ductility, and the micro-fibers efficiently increase the tensile strength [12]. Park et al. [12] and Kim et al. [6] evaluated the tensile and flexural performance of UHPFRC with hybrid macro- and micro-steel fibers. Both

* Corresponding author.
E-mail addresses: dyyoo@hanyang.ac.kr (D.-Y. Yoo), mandufa345@hanyang.ac.kr (M.J. Kim), swkim@kict.re.kr (S.-W. Kim), jjpark@kict.re.kr (J.-J. Park).

http://dx.doi.org/10.1016/j.conbuildmat.2017.06.018
0950-0618/

researchers [6,12] fixed the volume fraction of macro-fibers at 1%, whereas the volume fraction of the micro-straight fibers varied from 0% to 1.5%. The UHPFRC with hybrid 1 vol% macro-twisted (l_f/d_f of 30/0.3) and 1.5 vol% micro-straight (l_f/d_f of 13/0.2) fibers produced the best tensile performance, including strength, strain capacity, and cracking behavior. On the other hand, the UHPFRC with hybrid 1 vol% macro-hooked (l_f/d_f of 62/0.775) and 1.5 vol% micro-straight fibers exhibited the best flexural performance in terms of strength, deflection capacity, and energy absorption capacity. (Herein, l_f is the fiber length (mm), and d_f is the fiber diameter (mm).) In addition, increasing the volume of micro-fibers improved both the tensile and flexural performance. Kwon et al. [10] investigated the tensile performance of UHPFRC with hybrid micro-straight and macro-hooked steel fibers, fixing the volume fraction of the micro-fibers at 1% and varying the macro-fibers from 0.5% to 2%. The tensile strength increased with an increasing volume of macro-hooked fibers, but the highest strain capacity was obtained when 1 vol% micro- and 1.5 vol% macro-fibers were blended. Ye et al. [9] reported that UHPFRC with single, long ultra-fine straight fibers (l_f/d_f of 19/0.2) exhibited higher flexural strength than a hybrid UHPFRC with end-hook and flattened end fibers. Yoo et al. [8] also noted that, compared with UHPFRC with single long straight fibers (l_f/d_f of 30/0.3), UHPFRC that blended long fibers with short straight fibers (l_f/d_f of 13/0.2) showed deteriorated flexural performance. On the other hand, blending long fibers with medium-length straight fibers (l_f/d_f of 19.5/0.2) improved the flexural performance. However, negative synergy values were obtained in all hybrid specimens because the improvement in flexural performance was not directly proportional to the fiber volume content due to some detrimental effects obtained with increasing the amount of fibers. Based on the test results of Yu et al. [7], a hybrid UHPFRC with 1.5 vol% short (l_f/d_f of 13/0.2) and 0.5 vol% ultra-short (l_f/d_f of 6/0.16) straight fibers provided a higher flexural strength than a UHPFRC that included 2 vol% single short or ultra-short straight fibers.

Other studies have been performed to develop hybrid UHPFRC with excellent tensile or flexural performance. However, compared with the studies of single fiber-reinforced UHPC, research on hybrid UHPFRC remains very limited. Because some studies [6,10,12] that examined the effectiveness of hybrid reinforcements with both deformed and straight fibers did not use a constant volume of fiber, it is difficult to determine the optimum replacement ratio for macro- to micro-fibers at a given fiber volume fraction. Furthermore, although Kwon et al. [10] claimed that their new hybrid UHPFRC was developed at a reasonable cost, they did not include a cost analysis. To the best of the authors' knowledge, no published study on developing hybrid UHPFRC has yet included a cost analysis.

Accordingly, this study examines the flexural performance of UHPFRC with hybrid deformed (hooked and twisted) and straight steel fibers at the identical volume fraction of 2%. Replacement ratios of 0%, 0.5%, 1%, 1.5%, and 2% were considered for hybrid reinforcements (hooked + straight or twisted + straight fibers). To find a cost effective UHPFRC that exhibits excellent flexural performance, test data and cost analyses based on literature reviews were also performed.

2. Test program

2.1. Fabrication of UHPFRC

To fabricate UHPFRC, type 1 Portland cement and silica fume (SF) were used as cementitious materials. The specific surface area and density of the cement and SF were 3413 cm^2/g and 3.15 g/cm^3 and 200,000 cm^2/g and 2.10 g/cm^3, respectively, as summarized in Table 1. Silica sand and silica flour were adopted as the fine aggregate and filler, respectively, and their sizes, 0.2–0.3 mm and 10 μm in diameter, respectively, were determined based on the packing density theory and preliminary rheological and mechanical test results [13]. Ma et al. [14] and Orgass and Klug [15] reported that including coarse aggregate into UHPFRC has several advantages, such as low cost, less shrinkage, high fluidity, and less mixing time, without causing any noticeable reduction in compressive strength. However, including coarse aggregate did reduce flexural strength by reducing the bond strength of the fibers [16]. Because one of the most important advantages of UHPFRC over ordinary concrete or fiber-reinforced concrete (FRC) is its excellent tensile or flexural performance, coarse aggregate was excluded. The mixture used in this study is similar to UHPFRC mixture commercially available in North America [17]. To obtain very high strength, a low water-to-binder ratio of 0.2 was adopted along with a polycarboxylate superplasticizer (density of 1.01 g/cm^3 and dark brown color). Superplasticizer was added to obtain the proper fluidity without fiber segregation from the matrix, that is 240–250 mm according to ASTM C1437 [18]. The detailed mix proportions used in this study are summarized in Table 2, and the mixing sequence can be found in a previous study [19].

Table 1
Compositions and physical properties of cement and silica fume.

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	–
Specific surface area (cm^2/g)	3413	200,000
Density (g/cm^3)	3.15	2.10

* Type 1 Portland cement.

To compare the flexural behavior of UHPFRC according to the fiber type and hybridization, three different types of high-strength steel fibers were adopted: straight, hooked, and twisted. The detailed geometrical and physical properties of the fibers are given in Table 3. According to a previous study [19], UHPFRC containing medium-length straight steel fibers with an aspect ratio (l_f/d_f) of 97.5 exhibited better flexural performance than UHPFRC including straight fibers with aspect ratios of 65, 81.5, and 100. Therefore, the medium-length straight steel fiber, called "S", with an aspect ratio of 97.5 was used in this study. The straight and hooked steel fibers have a circular shape, whereas the twisted fiber has a triangular section and is twisted three times within the fiber length [20]. The fiber volume content was 2% by volume in all samples. Thus, to create a hybrid fiber reinforcement system, a portion of the hooked or twisted fibers was replaced with S fibers to maintain an overall volume fraction of 2%. To evaluate the flexural performance of the newly developed hybrid UHPFRCs, a commercially available UHPFRC [17] incorporating 2 vol% short straight (SS) steel fibers (l_f/d_f of 13/0.2), the *control specimen*, was also considered as a comparison. The designation systems used are summarized in Table 4. The letters S, H, and T denote the straight, hooked, and twisted steel fibers, respectively, and SS denotes the short straight fibers used in the control specimen. The subsequent numbers indicate the volume fraction of each fiber in percent. For example, H1.5-S0.5 indicates specimens with 1.5 vol% hooked fibers and 0.5 vol% straight fibers.

Because UHPFRC is a type of self-consolidating concrete, its fiber distribution characteristics, which significantly affect the flexural performance, are influenced by the casting process. Therefore, an identical casting method, placing the concrete at the one end of the mold and allowing it to flow, was used for all specimens.