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Effect of fiber content on mechanical and fracture properties of ultra high performance fiber reinforced cementitious composites

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ABSTRACT

This study investigated the mechanical properties of ultra high performance fiber reinforced cementitious composites (UHPFRCC) with four different fiber volume fractions (V_f = 1%, 2%, 3%, and 4%) within an identical mortar matrix. The higher amount of fiber resulted in an improvement of load carrying capacity and elastic modulus in compression up to 3 vol.% of fibers. A higher pullout strength was obtained from the inclusion of fibers in the matrix, and 2 vol.% of fibers provided the best performance in all aspects of fiber pullout behavior including average and equivalent bond strengths and pullout energy. The flexural strength was pseudo-linearly increased with increase in fiber volume fraction, despite an insignificant difference in the first cracking load. Furthermore, a bi-linear softening curve for UHPFRCC was suggested based on the result of inverse analysis, and it was verified through comparison with the experimental data.

1. Introduction

In recent years, extensive efforts have been made to improve the strength of concrete. However, the increase of strength has been accompanied by an inevitable brittle failure, thus creating many problems in its application to civil infrastructures. The incorporation of fibers in the concrete can nullify this brittle failure behavior by improving ductility, fracture toughness, and energy absorption capacity [1–3]. In particular, the recently developed ultra high performance fiber reinforced cementitious composites (UHPFRCC) exhibits both superior strength and ductility, and is also characterized by strain-hardening in tension with multiple micro cracks [4]. These outstanding properties are obtained by optimization of the granular mixture along with a low water-to-binder ratio (W/B) of 0.2, which results in homogenization of the microstructure, and by incorporation of high volume of steel fibers [5].

The tensile performance of UHPFRCC is considerably affected by the fiber characteristics such as fiber content, shape, aspect ratio, orientation, and distribution [6–11]. Above all, increasing amount of fiber is the most convincing method to improve the tensile performance including tensile strength and fracture energy capacity. This means that the demanded tensile strength can be achieved by using adequate amount of fiber. Therefore, the influence of volume contents of micro fiber (mostly employed as fiber reinforcement in UHPFRCC) on the tensile performance should be further investigated to provide more fundamental knowledge.

Meanwhile, to implement UHPFRCC in real structural members, it is necessary to develop a design and analysis technique with consideration of tensile fracture model. However, even though considerable efforts have been made to investigate the tensile properties of UHPFRCC and to improve the performance [8–12], a lack of research has been carried out that assesses the load carrying capacity of fibers along with an appropriate tension–softening curve for UHPFRCC with respect to fiber content [6]. The suggestion of the simplified softening curve is very useful in numerical analysis and structural design by considering a fiber bridging mechanism. For this reason, an adequate softening curve and fracture properties of UHPFRCC considering fiber content should be developed together with the investigation of tensile performance.

In most of previous studies [13–15], the fiber pullout test has been performed using a plain matrix, even though the bond strength is influenced by the fiber content in the matrix. According to few researches [16,17], the increase of fiber contents in the matrix causes an increase in pullout load and energy due to the fiber interlock. However, these researches were carried out using a relatively large amount of fibers ranging from 3% to 6% by volume, and information of the pullout behavior of micro steel fiber embedded in the UHPFRCC matrix with a small volume content of fiber is still insufficient.

Accordingly, this research aims to investigate the effect of fiber contents on the mechanical properties of UHPFRCC. The specific objectives are the estimation of fiber content effect on: (1) the load

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Table 1
Mix proportions (ratio in weight).

	W/B	Cement	SF	Filler	Sand	SP	Steel fiber	Flow (mm)
UH-V_1	0.2	1	0.25	0.30	1.10	0.012	V_f = 1%	235
UH-V_2						0.012	V_f = 2%	230
UH-V_3						0.014	V_f = 3%	225
UH-V_4						0.016	V_f = 4%	210

Where UH = ultra high performance fiber reinforced cementitious composites, W/B = water-to-binder ratio, SF = silica fume, SP = superplasticizer, V_f = volume fraction of fiber, V_n = n vol.% of fiber.

Table 2
Chemical composition of cementitious materials.

Composition % (mass)	Cement	Silica fume (SF)
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.

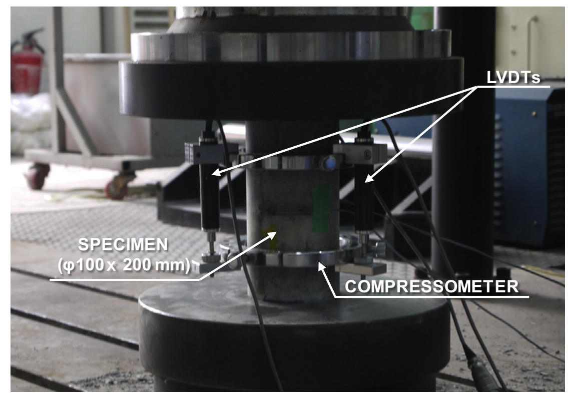

Fig. 1. Uniaxial compression test.

Table 3
Properties of steel fiber.

Type of fiber	Diameter (mm)	Length (mm)	Aspect ratio (l_f/d_f)	Density (g/cm^3)	Tensile strength (MPa)	Elastic modulus (GPa)
Smooth micro fiber	0.2	13	65	7.8	2500	200

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

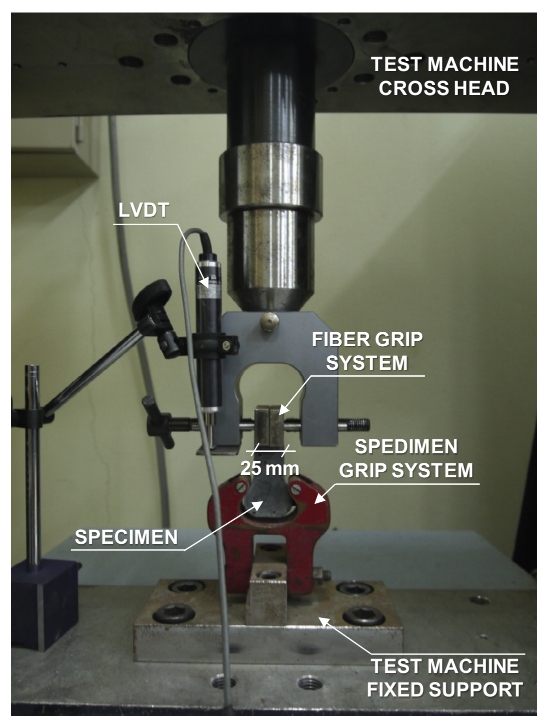

Fig. 2. Single fiber pullout specimen and test setup.

carrying capacity and elastic modulus in compression; (2) the bond strength and pullout energy of the fiber embedded in the composites (matrix and fibers); and (3) the flexural strength and deflection capacity. Furthermore, an optimized softening curve for the UHPFRCC incorporating various fiber contents was found using inverse analysis, and a simple bi-linear softening curve was also suggested.

2. Experimental program

2.1. Materials and mix proportions

The details of mix proportions used in this research are given in Table 1. Type 1 Portland cement and silica fume (SF) were used as cementitious materials. The chemical compositions and physical properties of the cementitious materials used are listed in Table 2. For all test specimens, a W/B of 0.2 was applied. Sand with grain size smaller than 0.5 mm and 2 μm diameter filler including 98% SiO_2 were used without coarse aggregate. To improve fluidity, a high performance water-reducing agent, polycarboxylate superplasticizer (SP) was added [18]. For the investigation of the effect of fiber content on the mechanical properties, micro steel fibers with a length of 13 mm and a diameter of 0.2 mm were considered in four different volume ratios (1%, 2%, 3%, and 4%), leading to four series of test specimens. The properties of smooth micro fiber are presented in Table 3. The test specimens were cured at room temperature for the first 48 h prior to demolding. After demolding, heat curing (90 ± 2 °C) was performed for 3 days.

2.2. Test setup and procedure

2.2.1. Flow and compression tests

In order to investigate the workability, a flow table test was carried out according to ASTM C 1437 [19]. A total of twelve cylindrical specimens with dimensions of ∅ 100 × 200 mm were used