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Hybrid effects of steel fiber and microfiber on the tensile behavior of ultra-high performance concrete

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ABSTRACT

Ultra-high performance concrete (UHPC) has ultra-high material performance including high strength and high flowability. However, its tensile strain capacity is generally lower than that of high ductile cementitious composite. This study experimentally investigated the effect of hybrid combinations of straight 0.2 mm diameter steel fiber and various microfibers on the mechanical properties of UHPC. Four types of hybrid fiber reinforced UHPCs including steel, basalt fibers, polyvinyl-alcohol, and polyethylene fibers were designed and then compressive strength, density, and tensile behavior were investigated. Test results showed that combining a synthetic fiber with high strength, such as PE fiber, and steel fiber can improve the tensile behavior of UHPC and basalt fiber was effective for improving the tensile strength of UHPC.

1. Introduction

Recently, the repair and rehabilitation of aged and deteriorated structures have become an important issue in the fields of architecture and civil engineering. According to the 2009 Report Card for America's Infrastructure presented at the National Press Club, the overall grade for American infrastructures was a "D". In addition, the magnitude and number of natural and man-made hazards is growing. To address these issues, there is a need for technological advances that improve either the condition or performance of the members of existing structures [1]. Ultra-high performance concrete (UHPC) has been studied and developed to meet this technical demand [2–4]. According to a Federal Highway Administration Report [5], since the first UPHC bridge was constructed, more than 90 UHPC bridges have been constructed in America, Australia, Austria, Croatia, France, Germany, Italy, Japan, Republic of Korea, Malaysia, Netherlands, New Zealand, and Slovenia, and recommendations on UHPC construction have been published in France, Japan, Republic of Korea, etc.

The main reason why research on UHPC is being widely performed, and UHPC is being used around the world, is due to the superior properties of UHPC. According to Association Française de Génie Civil [6], UHPC tends to have compressive strength over 150 MPa, fiber reinforcement to ensure non-brittle behavior, and a high binder ratio with special aggregates. Furthermore, UHPC tends to have a very low water content and can achieve proper rheological properties through controlling the packing density of solid ingredients and the addition of superplasticizer. However, the tensile ductility of UHPC is much lower than that of high ductile cementitious composites such as high-performance fiber reinforced cementitious composites [7–11].

To maximize the improvements possible through fiber reinforcement, a previous study reported that including two or more types of fiber can make complementary and additive contributions to performance in a concrete mix [12]. A combination of macrofiber with the diameter over 0.5 mm and microfiber with the diameter less than 0.022 mm has been demonstrated to be effective to improve the tensile behavior of concrete. This is attributed that the two types of fiber influence crack growth at different stages of the failure process [13,14]. It was also reported that a hybrid steel macrofiber and microfiber reinforced concrete showed higher strength and toughness compared with single type macrofiber reinforced concrete. This is because the microfibers induced the delay of macrocracks formation, which governs the tensile strength [15].

Straight steel fiber of 0.2 mm in diameter is generally used for UHPC [16]. Therefore, the effect of adding microfiber to UHPC may be different than the effects reported in previous studies. There has also been a lack of research on the combination of steel

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fiber and microfibers in UHPC until now. This study experimentally investigated the effect of the hybrid combination of straight steel fiber of 0.2 mm diameter and microfiber on the mechanical properties of UHPC.

2. Materials and methods

2.1. Materials and mixture proportion

The mix proportion of the UHPC investigated in this study before adding fiber is listed in Table 1. It was designed to have a compressive strength of 150 MPa when it was cured in water at a temperature of 23 °C ± 3 °C for 28 days. The water to binder ratio was held constant at 0.2 and Type I Portland cement with the specific surface area of 3413 cm^2/g and zirconia silica fume with the specific surface area of 8 m^2/g were used as a binder. Zirconia silica fume was adopted to increase the strength of the UHPC by pozzolanic reaction and to fill the voids created by free water in the matrix, as well as to increase the packing density and improve flowability by introducing ball bearings between larger particles. The chemical composition of zirconia silica fume was measured using X-ray fluorescence (XRF) and is listed in Table 2. The chemical composition of zirconia silica fume is similar to that of silica fume. The specific surface of zirconia silica fume, however, is about half that of the silica fume used in cementitious mixtures [17]. A filler of pure silica composed of over 99% SiO_2, with an average diameter of 2.2 μm, was adopted for increasing flowability and strength. The size of the filler was between that of the cement and zirconia silica fume. Therefore, it can increase the packing density, which results in low plastic viscosity and yield stress [18]. In addition, it can also fill voids, which results in an increase in strength and durability. Fine aggregate (an average particle size of 500 μm or less) with a density of 2.62 g/cm^3 was used to maintain adequate stiffness and volume stability [19]. Large aggregates were excluded because those lead to higher matrix toughness, which induce less steady state cracking condition. An expansion admixture (EA) and shrinkage reducing admixture (SRA) were adopted to reduce autogenous shrinkage. Optimized amounts of superplasticizer (SP) was used to achieve high flowability, and antifoamer was included to minimize the amount of air bubbles.

Table 3 lists the contents of fibers used to investigate the effect of a hybrid combination of steel fiber and microfiber on the tensile behavior of UHPC. Total fiber volume was held constant at 1.5 vol.% in all four mixes. The S1.5 is a control mixture, in which two types of steel fibers with lengths of 19.5 mm and 16.5 mm were added into the UHPC mortar. S1.0-B0.5, S1.0-PVA0.5, and S1.0-PE0.5 are hybrid fiber UHPC reinforced by basalt fiber, polyvinyl-alcohol (PVA) fiber, and polyethylene (PE) fiber, respectively, at 33% replacement by volume. The properties of the fibers are listed in Table 4. All fibers had a round cross-section.

2.2. Mixing, casting, and curing of specimens

Each of the four compositions was mixed in a Hobart type mixer. Powder type ingredients, i.e. cement, zirconia silica fume, filler, fine aggregate, EA, and SRA, were added to the mixer and mixed at a mixing speed of 90 rpm (revolutions per minute) for 10 min. Water, SP, and antifoamer were added and the mixture was then mixed at the same mixer speed until that the powder mixture changed into liquid, approximately 3–5 min. After the mixture became flowable, the mixture was mixed at a mixing speed of 270 rpm for about 3 min. Once a consistent mixture was reached, the steel fiber and microfiber were sequentially added, taking care to ensure uniform fiber dispersion; the mixture was then mixed for about 5 min. Finally, the mixture was mixed at a mixing speed of 90 rpm for 1 min to eliminate bubbles. After mixing, each mixture was cast into molds (six specimens for the uniaxial tension test and six 50 mm cubes for the cube compression test). The molds were covered with plastic sheets to minimize the evaporation of water and cured in air at a temperature of 23 °C ± 3 °C for 2 days. The molds were then removed and the hardened specimens were cured in water until 28 days at a temperature of 23 °C ± 3 °C.

Table 2
Chemical composition of zirconia silica fume.

Material	Chemical composition (%)						
	SiO_2	ZrO_2	CaO	Al_2O_3	Fe_2O_3	MgO	etc.
Zirconia silica fume	96.00	3.0	0.38	0.25	0.12	0.1	0.15

Table 3
Fiber contents according to hybrid fiber system for UHPC.

	Fiber volume (%)				
	Steel 19.5	Steel 16.5	Basalt	PVA	PE
S1.5	1.0	0.5			
S1.0-B0.5	0.67	0.33	0.5		
S1.0-PVA0.5	0.67	0.33		0.5	
S1.0-PE0.5	0.67	0.33			0.5

Table 4
Properties of fibers.

Type of fiber	Diameter (μm)	Length (mm)	Tensile strength (MPa)	Density (g/cm^3)	Elastic modulus (GPa)
Steel	200	16.3, 19.5	2500	7.8	200
Basalt	12	12	2100	2.65	100
PVA	40	12	1100	1.3	41
PE	12	18	2700	0.97	88

2.3. Density test

The hardened densities of specimens, ρ, were calculated from Eq. (1) by measuring the weights of the specimens in air, W_A, and in water, W_W at 28 days in a saturated-surface-dry state.

$$\rho = \frac{W_A}{W_A - W_W} \times \rho_w \quad (1)$$

Here, ρ_w is the density of water (1 g/cm^3).

2.4. Mechanical tests

The compressive strength was measured on cube specimens measuring 50 mm × 50 mm × 50 mm according to ASTM

Table 1
Mix proportion of UHPC (weight ratio).

Compound	Binder		*w/b*	Filler	Fine aggregate	EA	SRA	SP	Antifoamer
	Cement	Zirconia silica fume							
Proportion	1	0.25	0.2	0.3	1.1	0.075	0.01	0.023–0.026	0.0007