Composites Part B 103 (2016) 74–83

Contents lists available at ScienceDirect

Composites Part B

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

Strain hardening ultra-high performance fiber reinforced cementitious composites: Effect of fiber type and concentration

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A R T I C L E I N F O

Article history:
Received 25 April 2016
Received in revised form
22 June 2016
Accepted 4 August 2016
Available online 5 August 2016

Keywords:
Fracture
Glass fiber
Mechanical properties
Steel fiber
Strain hardening
Ultra high performance

A B S T R A C T

An experimental work was carried out to investigate the effects of micro-steel, hooked-steel, and micro-glass fibers on the mechanical properties and ductility of Ultra-high Performance Cementitious Composites (UHPC). The aspect ratios of the of micro-steel, hooked-steel, and micro-glass fibers were 7.17, 55 and 722, respectively. At a water-binder ratio of 0.195, three groups of UHPCs containing 0.25, 0.5, 0.75, 1, 1.5, and 2% fiber volume fractions were produced and tested for compressive strength, splitting tensile strength, modulus of elasticity, flexural strength, load-displacement behavior, fracture energy, and characteristic length. Test results revealed that the mixes with 2% of micro steel fiber exhibited the best compressive strength of 180 MPa as well as the highest splitting tensile strength and modulus of elasticity. However, the mixes with 2% of hooked steel fiber displayed a strain hardening load-displacement behavior with a substantially enhanced ductility. The results also showed that the beneficial influence of using micro glass fiber began to decrease after 1.5% of the fiber volume.

1. Introduction

Investigations over the past years have yielded an innovative classification of highly resilient concrete called Reactive Powder Concretes (RPC), nowadays it is labeled and classified as Ultra-high performance Cementitious Composites or concrete (UHPC). UHPC is one of the newest developments in concrete technology, and remedies the lack of many concretes [1]. It has been applied to many huge strategic projects such as coupling beams in high-rise buildings, precast members, infrastructure rehabilitations, blast resistant structures, and special facilities like nuclear waste storage containers [2]. Producing UHPC necessitates a large cement content of 900–1200 kg/m^3, silica fume (SF) of 10–30% by weight of the cement, very fine quartz sand (0.15–0.40 mm) instead of using coarse aggregates, a water-binder ratio (w/b) less than 0.2, and an effective superplasticizer (SP) for the workability [3–7]. The mechanical properties that can be achieved include the compressive strength of greater than 150 MPa, flexural strength of 30–60 MPa, splitting tensile strength higher than 7 MPa as well as Young's modulus up to 60 GPa [8–11].

Comparing to its high compressive strength, plain UHPC had low tensile strength resulting in the main obstacles for its practical application [12]. Many properties such as; ductility, strain hardening behavior, fracture toughness, impact resistance and energy absorption capacity can be greatly improved via reinforcing UHPCs by fibers of different kinds [13–18]. Mechanically, UHPC reinforced by fibers is named as Ultra High Performance Fiber Reinforced Concrete (UHPFRC) that is able to resist the tensile stress through composite action between the cementitious matrix and embedded fibers. When crack occurs, micro fibers can bridge the potential cracks that triggered to provide resistance to crack propagation, whereas relatively longer fibers provide resistance to crack opening, thus enhancing the structural behavior and durability [19]. Commercially short fibers are available from different materials including steel, glass, carbon, and organic polymers [20]. The performances of UHPFRC are significantly affected by the fiber characteristics such as strength, stiffness, shape, aspect ratio, fiber volume fraction, Poisson's ratio, as well as orientation and distribution of the fibers [21–26].

There are many attempts to increase the performance of UHPCs using fibers of different features. Lee and Chisholm [27] studied the effect of straight steel fibers with the aspect ratio of 65 on the mechanical properties of RPC. Addition of 2% steel fibers led to primarily improved tensile strength of the composite apart from a marked increase in the compressive strength. Wille et al. [25] carried out an experimental study on the tensile behavior of different

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http://dx.doi.org/10.1016/j.compositesb.2016.08.004
1359-8368/

Table 1
Properties of Portland cement and silica fume.

Constituent (%)	Cement	Silica fume
CaO	57.87	0.45
SiO_2	17.99	90.36
Al_2O_3	3.88	0.71
Fe_2O_3	3.36	1.31
MgO	1.49	–
SO_3	2.47	0.41
K_2O	–	1.52
Na_2O	–	0.45
Cl	0.005	–
Loss of ignition	3.37	3.11
Insoluble residue	0.34	–
Free CaO	2.18	–
Specific surface (m^2/kg)	394[a]	21,080[b]
Specific gravity	3.15	2.2

[a] Blaine specific surface area.
[b] BET specific surface area.

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) mixes using four types of high strength steel fibers. It was observed that both the tensile strength and the maximum post-cracking strains were significantly improved by using deformed steel fiber instead of smooth one. Moreover, Hoagn et al. [28] studied the effects of short and long steel fibers (the aspect ratios of 85 and 70, respectively) on the properties of UHPCs. Test results indicated that a reasonable combination of two steel fibers guaranteed the high flowability as well as the flexural strength over 20 MPa, and the compressive strength exceeding 150 MPa. In spite of many investigating on the use of steel fibers in UHPCs, there are few studies on the UHPCs reinforced with micro glass fibers and/or with hooked steel fibers. Ghorpade [29] utilized to reinforce the high performance concrete (HPC) by incorporating 12 mm long glass fibers at of 0.5, 1.0, and 1.5% volume concentrations. The maximum compressive, splitting tensile, and flexural strengths were achieved at 1% fiber content.

In the study presented herein, an experimental program was conducted on the comparison of fibers to be able to achieve UHPC having the best mechanical properties associated with the satisfactory ductility. Three groups of UHPCs were designed in which micro steel, hooked steel, and micro glass fibers were utilized equally at a volume of 0, 0.25, 0.5, 0.75, 1, 1.5, and 2% to produce UHPFRCs. The investigational parameters were compressive strength, splitting tensile strength, modulus of elasticity, flexural strength, load displacement behavior, fracture energy, and characteristic length.

2. Experiments

2.1. Raw material

The cementitious materials used in the concrete production were ordinary Portland cement type I 52.5 R conforming to the TS EN 197 and commercial silica fume (SF). Chemical composition, physical and mechanical properties are given in Table 1. Quartz aggregate with a specific gravity 2.65 was utilized in three fractions, namely 0–0.4, 0.6–1.2, and 1.2–2.5 mm. A polycarboxilate type superplasticizer (SP) was used to fulfill the workability specifications in ASTM C 494 [30]. To provide fiber reinforcement, micro steel (MSF), hooked steel (HSF), and micro glass (MGF) fibers were used at different volume fractions of 0, 0.25, 0.5, 0.75, 1, 1.5, and 2%. The physical and mechanical properties of the fibers are presented in Table 2.

The mixture proportioning consisted of three groups of concretes each of which containing six mixes accounting for 0.25, 0.5, 0.75, 1, 1.5 and 2% of microsteel fiber, hooked steel fiber, and micro glass fiber, respectively. The control plain concrete was also produced with a w/b ratio of 0.195 and 1200 kg/m^3 of total binder. A grey type silica fume was used at 20% of the cement by weight in all

Table 2
Physical and mechanical properties, and aspect ratios of the fibers.

Name of fiber	Length (L) (mm)	Diameter (d) (mm)	Aspect ratio (L/d)	Density (g/cm^3)	Tensile strength (N/mm^2)
Micro steel brass coated	6	0.16	37.5	7.17	2250
Hooked end steel	30	0.55	55	7.85	1345
Micro glass	13	0.018	722	2.6	2000

Table 3
Mixture proportioning of UHPCs.

Group	Mix designation	Cement (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fiber (kg/m^3)	Quartz aggregate (kg/m^3)
Control		960.0	240.0	234.0	45.0	0.0	793.7
1	MSF0.25	960.0	240.0	234.0	45.0	17.9	787.1
	MSF 0.5	960.0	240.0	234.0	45.0	35.9	780.5
	MSF 0.75	960.0	240.0	234.0	45.0	53.8	773.8
	MSF 1	960.0	240.0	234.0	45.0	71.7	767.2
	MSF 1.5	960.0	240.0	234.0	45.0	107.6	754.0
	MSF 2	960.0	240.0	234.0	45.0	143.4	740.7
2	HSF0.25	960.0	240.0	234.0	45.0	19.6	786.4
	HSF 0.5	960.0	240.0	234.0	45.0	39.3	779.2
	HSF 0.75	960.0	240.0	234.0	45.0	58.9	771.9
	HSF 1	960.0	240.0	234.0	45.0	78.5	764.7
	HSF 1.5	960.0	240.0	234.0	57.0	117.8	720.7
	HSF 2	960.0	240.0	234.0	57.0	157.0	706.2
3	GF0.25	960.0	240.0	234.0	45.0	6.5	791.3
	GF 0.5	960.0	240.0	234.0	45.0	13.0	788.9
	GF 0.75	960.0	240.0	234.0	42.0	19.5	793.9
	GF 1	960.0	240.0	234.0	39.0	26.0	798.8
	GF 1.5	960.0	240.0	234.0	78.0	39.0	698.3
	GF 2	960.0	240.0	234.0	96.0	52.0	649.3