Construction and Building Materials 163 (2018) 826–839

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of steel fiber content and type on static mechanical properties of UHPCC

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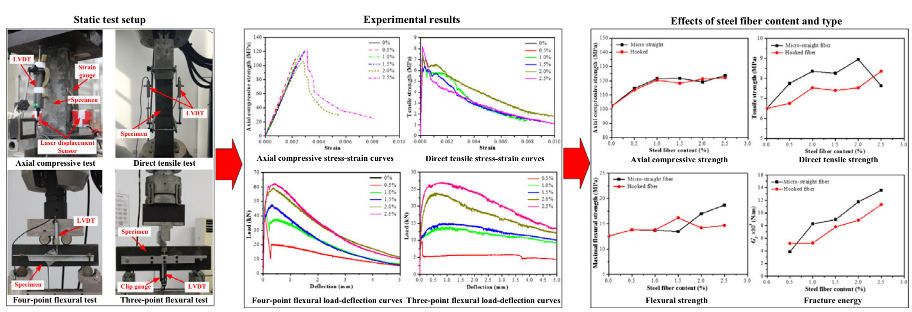
HIGHLIGHTS

- A series of cubic/axial compressive, direct tensile, four/three-point flexural tests on UHPCC are conducted.
- Six volume fractions (0–2.5%) and two types (micro-straight and hooked) of steel fibers are considered.
- Full compressive/tensile stress-strain curves and flexural load-deflection/CMOD curves are obtained.
- Effects of steel fiber content and type on the static properties of UHPCC are comprehensively discussed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form 1 December 2017
Accepted 27 December 2017

Keywords:
UHPCC
Steel fiber
Mechanical properties
Stress-strain curve
Flexural load-deflection curve

ABSTRACT

A series of cubic/axial compressive, direct tensile, four-point and three-point flexural tests on Ultra-high performance cementitious composites (UHPCC) specimens are conducted, in which six volume fractions (0–2.5%) and two types (micro-straight and hooked) of steel fibers are considered. The full compressive and tensile stress-strain curves, the flexural load-deflection/CMOD (crack mouth opening displacement) curves are obtained. It indicates that, (i) the steel fiber content and type have obvious strengthening effects on the cubic compressive strength; (ii) for the axial compressive strength, the steel fiber type has little influence and the enhancing effect of the steel fiber content becomes less obvious when the volume fraction exceeds 1.0%; adding steel fibers has little effect on the compressive elastic modulus and Poisson's ratio; (iii) for the direct tensile strength, the steel fiber content has remarkable effect; the present micro-straight steel fiber has relatively better effect than the hooked steel fiber under same mixing ratio; (iv) the steel fiber content and type almost have no effects on the first crack flexural strength and the corresponding deflection, but show considerable effects on the flexural strength, load carrying capacity, energy absorption capacity, fracture toughness and fracture energy.

1. Introduction

Ultra-high performance cementitious composites (UHPCC) is a relativity new type of cementitious materials which has very low water-to-binder (W/B) ratio, high amount of high-range water reducer (HRWR), fine aggregates and high-strength steel fibers [1]. With the prominent mechanical properties, i.e., the high compressive and tensile strengths, high ductility as well as the high fracture energy, UHPCC becomes the most prospective construction materials for both civil and military structures, such as fortification, nuclear waste storage containment, highway bridge,

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https://doi.org/10.1016/j.conbuildmat.2017.12.184
0950-0618/

high-rise building, etc. [2]. Investigations of the mechanical behaviors of UHPCC are important and essential to provide valuable information for the structural design and calibration/validation of the constitutive model. As a part of the Project "Investigations of static and dynamic mechanical properties as well as the constitutive model of UHPCC", in the present paper, the static mechanical properties of UHPCC are mainly concerned.

For the existing experimental studies on the influence of steel fiber content on the static behavior of UHPCC, Hassan et al. [3] developed the simplified test methods to measure the elastic modulus, stress-strain curves and post-cracking behaviors of ultra-high performance fiber reinforced concrete (UHPFRC) specimens in both compression and tension. It was concluded that, addition of steel fibers (0% and 2.0% by volume) significantly increased the tensile strength and ductility of UHPFRC, but had relatively small effect on the compressive strength and elastic modulus. Wille et al. [4] conducted a series of direct tensile tests (dog-bone specimen with the length of 147 mm) to study the effect of steel fiber content (1.5–3.0% by volume) on the tensile properties of UHPFRC. The results showed that the tensile strength and the corresponding strain as well as the energy absorption capacity had a strong dependency on the steel fiber content. Liu et al. [5] studied the effect of steel fiber content (0–2.5%) on the tensile properties of ultra-high performance concrete (UHPC) with coarse aggregates. It was concluded that, both the first crack tensile strength and the fiber-bridging stress increased with the fiber volumetric ratio rising. Abbas et al. [6] (1.0%, 3.0% and 6.0% by volume), Kazemi et al. [7] (0–5.0% by volume), Wu et al. [8] (0–3.0% by volume), Yoo et al. [9,10] (1.0–4.0% by volume) have studied the influence of steel fiber content on the compressive and flexural behaviors of UHPFRC, respectively. It indicated that, with the increase of steel fiber content, the compressive strength gradually increased, while the flexural strength, deflection and CMOD (crack mouth opening displacement) at peak load pseudo-linearly increased correspondingly, and the steel fiber content had no noticeable influence on the first crack flexural strength and the corresponding deflection/CMOD.

As for the existing works on the influence of steel fiber type on the static behavior of UHPCC, Wille et al. [4] also experimentally studied the effect of steel fiber type (smooth, hooked and twisted) on the tensile properties of UHPFRC, which showed that the tensile strength and the corresponding strain as well as the energy absorption capacity were less affected by the steel fiber type. Liu et al. [5] also studied the effect of steel fiber type (smooth, spiral and hooked micro-fibers as well as hooked macro-fiber) on the tensile properties of UHPC with coarse aggregates. The results showed that the micro-hooked steel fiber had the most significant effect on the first crack tensile strength and the fiber-bridging stress. Wu et al. [8] also investigated the effects of three typical steel fibers (straight, corrugated and hooked-end) on the compressive and flexural properties of UHPC. It was concluded that the steel fiber type had little influence on the first crack flexural strength and the corresponding deflection, and the UHPC with hooked-end steel fiber had the highest compressive and flexural strengths.

Generally, considering the time and economic cost, limited works were performed to systematically assess the effects of steel fiber content and type on the static strengths as well as the full stress-strain curves and flexural load-deflection/CMOD curves of UHPCC. In the present paper, a series of cubic/axial compressive, direct tensile, four-point and three-point flexural tests on UHPCC specimens are conducted, in which two typical steel fibers (micro-straight and hooked) with six volume fractions of 0–2.5% are considered. The systematical full compressive and tensile stress-strain curves as well as the flexural load-deflection and flexural load-CMOD curves are obtained. The effects of steel fiber content and type on the cubic and axial compressive strengths, compressive elastic modulus and Poisson's ratio, direct tensile strength, flexural strength, load carrying capacity, energy absorption capacity, fracture toughness and fracture energy are comprehensively discussed. The present work is fundamental and the derived conclusions could provide helpful references for the analysis and design of the UHPCC structures.

2. Test program

2.1. Raw materials and mixture proportions

UHPCC was prepared in the State Key Laboratory of High Performance Civil Engineering Materials, Jiangsu Research Institute of Building Science in China, and the mixture proportions are given in Table 1. Chinese standard Graded 52.5 P.II type Portland cement (20–30 μm in particle diameter) from Xiaoyetian corporation, silica fume (particle size of 0.10–0.26 μm, density of 2.1 g/cm^3, specific surface area of 20,500 m^2/kg) from Elkem company and ultra-fine mineral admixture (density of 2.45 g/cm^3, specific surface area of 8500 m^2/kg, 28 d activity index of 115%) from SBT®-HDC (V) are used as the cementitious materials. Table 2 lists the chemical composition of cement and silica fume. The water-to-cementitious materials (W/CM) ratio and HRWR-to- cementitious materials ratio are 0.16 and 0.024, respectively. Six volume fractions (0%, 0.5%, 1.0%, 1.5%, 2.0% and 2.5%) of two typical steel fibers, including micro-straight (diameter of 0.2 mm, length of 13 mm, tensile strength of 2800 MPa) and hooked (diameter of 0.5 mm, length of 25 mm, tensile strength of 1200 MPa) are incorporated, as shown in Fig. 1. The water-reducing ratio of the PCA®-I polycarboxylic type HRWR is no less than 35%, which is developed by Jiangsu SOBUTE new material Co., Ltd.

Compared with the traditional high performance concrete, the ground fine quartz sand (the size is less than 0.6 mm) is substituted by easily obtained natural river sand (maximal diameter of 2.5 mm). Also the partial silica fume is replaced by the ultra-fine mineral admixture which includes fly ash and ultra-fine slag (the specific proportions is undisclosed for commercial security). Since the production of cement and fine quartz sand consumes much more energy and resources, and the silica fume is more expensive than fly ash and ultra-fine slag for its limited production, the present UHPCC is relative low-costs and energy saving.

2.2. Specimen preparation and curing

For the preparation of the UHPCC, a forced single-axis mixer with a capacity of 60 L and a constant mixing speed (47 rpm) was used. To achieve good workability, particle distribution and packing density, mixing procedure for the present UHPCC was controlled rigorously. Firstly, since the small particles tended to agglomerate and it was easier to break these chunks when the particles were dry, the cementitious materials (cement, silica fume, ultra-fine mineral admixture) and sand were put together simultaneously and dry-mixed uniformly for 3 min. Secondly, the water pre-mixed with super-plasticizer was then added gradually and mixed for 3–5 min. Finally, steel fibers were dispersed carefully by hand into the mixture and mixed for another 3–5 min in order to guarantee the fibers well distributed throughout the matrix. The shear action of steel fibers helped to destroy any remaining agglomerates in the fresh mixture, thus improving the workability of the composites.

After the prepared matrix was poured into the moulds, the freshly cast specimens were covered with plastic sheets to prevent moisture losing and kept at room temperature for 24 h. Then, they were demounted and cured in a standard curing room with the temperature of 17.7–21.7 °C and relative humidity of 98.4% for another 28 days. After that, the specimens were taken out of the standard curing room and stored at room temperature until the