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Experimental investigation on static and dynamic mechanical properties of steel fiber reinforced ultra-high-strength concretes

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HIGHLIGHTS

- A SFR-UHSC produced with common materials and standard curing methods was studied.
- Under static loadings, SFR-UHSC exhibits good ductility, toughness and plasticity.
- Under dynamic loadings, SFR-UHSC cracks along various paths without fragmentation.
- Mechanical properties of SFR-UHSC are improved by the addition of steel fibers.
- SFR-UHSC has a slightly lower strain rate effect than ordinary concrete.

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ABSTRACT

Nowadays, high-rise, long-span and complicated structures are springing up. Accordingly, there is an increasing need for concretes with high strength even ultra-high strength, low cost and low construction difficulties. In the present study, steel fiber reinforced ultra-high-strength concrete (SFR-UHSC) was designed and produced with common materials and standard curing methods. To obtain a good performance, a low water-to-binder ratio of 0.22, a superplasticizer and several readily available mineral admixtures were applied. Static mechanical and Split Hopkinson press bar tests were carried out to evaluate the mechanical performances of SFR-UHSC. It is found that under static loadings, SFR-UHSC exhibits good ductility, toughness and plasticity. In details, compared with cubic and prism compressive strengths as well as Young's modulus of SFR-UHSC, much more increases of splitting tensile and flexural strengths are obtained by the introduction of steel fibers. When the volume fraction of steel fiber increases, the ratio between prism and cubic compressive strengths decreases while the ratio of tensile strength to compressive strength increases. On the other hand, in the scenario of high strain rate, SFR-UHSC has a good energy absorption capacity and compressive toughness. When subjected to impact loadings, SFR-UHSC cracks along various paths without fragmentation. Moreover, dynamic compressive strength is increased by both increasing strain rate and steel fiber content while its strain rate effect is slightly lower than that of ordinary concrete.

1. Introduction

Ordinary concrete can no longer meet the need due to the complexity of structures themselves and service environment for high-rising buildings, bridges, offshore structures and hydraulic structures [1]. By employing a low water-to-binder ratio, fine and active admixtures (i.e., silica fume, fly ash and ground granulated blast furnace slag, etc.) as well as special curing technologies, high strength concrete (HSC) or ultra-high strength concrete (UHSC) has been achieved [2]. It is well-known, however, the ratio between tensile strength and compressive strength of plain HSC and UHSC is quite low for their brittle nature. To overcome these drawbacks, various treatments have been taken by researchers, such as addition of discontinuous fibers, use of continuous textile reinforcements and external strengthening with fiber-reinforced polymer (FRP) [2]. Among these, it has been widely accepted that introduction of fibers into concrete is an effective way to enhance concrete tensile strength, fracture toughness and dynamic mechanical properties as well as durability [3].

During the last few decades, steel fiber is one of the most widely used fibers to reinforce the properties of concrete for its easiness to be obtained and to be included in concrete matrix [4,5]. Through

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experimental means, the basic static mechanical properties of steel fiber reinforced high strength or ultra-high strength concretes (SFR-HSC and SFR-UHSC, respectively) were tested [6–10]. Considering the complicated stress state of concrete, Lu and Hsu [11] conducted a series of tests to evaluate the effect of steel fiber reinforcement on the behavior of HSC under triaxial compression. In light of that SFR-HSC and SFR-UHSC are most utilized in protective structures which may undertake dynamic loadings with high strain rate, the dynamic behaviors of SFR-HSC and SFR-UHSC were investigated. The effects of steel fiber shape, aspect ratio, distribution directions and hybrid steel fibers were often explored [6,9,12–19]. Based on the available experimental data, Xu and Shi [3] carried out an investigation on correlations among compressive strength, splitting tensile strength and flexural strength of steel fiber reinforced concrete (SFRC). What's more, some nonlinear numerical simulations have also been conducted on SFRC by modifying constitutive relationship of ordinary concrete [14] or employing direct tension force transfer model [20], multilevel computational model [21], computational fluid dynamics [22] and Delaunay triangulation to mesh the computation areas [23], etc. It can be viewed through the aforementioned studies that a relatively mature understanding of SFR-HSC and SFR-UHSC is forming currently. Nevertheless, a more comprehensive and thorough investigation is still in need to study both the static and dynamic mechanical properties of SFR-UHSC.

Herein this work, the SFR-UHSC including gravel aggregate was designed and produced with common materials and standard curing methods. To guarantee its performances, a low water-to-binder ratio of 0.22, a superplasticizer and several readily available mineral admixtures (i.e., silica fume, fly ash and ground granulated blast furnace slag) were employed. After a brief introduction of the whole experimental process, test results on the basic static mechanical properties (compressive, splitting tensile and flexural strengths as well as Young's modulus) of SFR-UHSC were reported and analyzed. Moreover, with SHPB experiments, the dynamic behavior of SFR-UHSC under high strain rate, namely, the failure patterns, stress-strain relationship, dynamic compressive strength, energy absorption capacity and compressive toughness were also described. The effects of steel fiber contents and strain rate on the mechanical performances of SFR-UHSC were discussed.

2. Experimental program

2.1. Materials and mixture proportion

Four batches of SFR-UHSC specimens with different steel fiber contents were prepared for the experiment. As tabulated in Table 1, the following materials were used in the fabrication of concrete specimens. The cement was early-strength-type Portland cement (P II 52.5R) with measured compressive strengths of 41.0 MPa (3 d) and 53.2 MPa (28 d) while flexural strengths of 6.23 MPa (3 d) and 7.63 MPa (28 d), respectively. The admixtures included silica fume (produced in Ningxia of China, SiO_2: 97%, specific area: 2×10^4 m^2/kg), fly ash (density: 2210 kg/m^3, specific area: 550 m^2/kg) and GGBS (ground granulated blast furnace slag, density: 2850 kg/m^3, specific area: 450 m^2/kg). The river sand with diameter less than 5 mm, fineness modulus of 2.3 and density of 2650 kg/m^3 was utilized as fine aggregate. A superplasticizer based on poly carboxylic acid was used in all the concrete mixtures to guarantee their slump without loss of strength. The solid content of poly carboxylic acid water reducing agent was 40%, and when the content of superplasticizer is 0.5%, water reduction rate reaches to 30%. The final water-to-binder ratio was 0.22.

It has been proved in Wu et al.'s [8] work that the incorporation of hook-end steel fiber can effectively increase the strength of concrete, especially the flexural strength. Thence, the hook-end steel fibers (shown in Fig. 1) were also selected to prepare the SFR-UHSC in the present work and four different volume fractions of steel fibers, i.e., 0, 1%, 2% and 3%, were employed. The detailed physical properties of the steel fibers were defined in Table 2.

As one of the main differences from others [6–10,14–17,19], mixtures of SFR-UHSC in the present work contains coarse aggregate and gravel with diameters of 5 mm–20 mm and density of 2740 kg/m^3 was adopted. The detailed mix proportion for SFR-UHSC with different steel fiber contents are listed in Table 1.

2.2. Mix procedure and specimen preparation

To make the steel fiber distribute uniformly, a mix procedure as shown in Fig. 2 was employed. After the mixing process, the mixture was casted into steel molds. According to "Standard test methods for fiber reinforced concrete" of China [24], four batches of mold sizes were used: 100 mm × 100 mm × 100 mm for tests of cubic compressive strength and splitting tensile strength; 100 mm × 100 mm × 300 mm for measurements of prism compressive strength and Young's modulus; 100 mm × 100 mm × 400 mm for evaluations of flexural strength and toughness; and 100 mm × 100 mm × 170 mm for the test of dynamic properties. In reality, the SHPB test was not directly carried out on the specimens of 100 mm × 100 mm × 170 mm while cylindrical samples (with diameter of 75 mm and height of 50 mm) taken from the cuboid specimens was employed.

Freshly cast specimens were kept in molds for 24 h, and then demolded and cured in laboratory with relative humidity of 95% for 28 days at room temperature instead of in hot water. The ordinary curing condition for SFR-UHSC is also a main contribution of the present work.

2.3. Test methods

According to Chinese Standard CECS 13: 2009 [24], an Instron 1343 servo pressure testing machine was adopted to test the static

Table 1
Composition of SFR-UHSC matrix by weight.

Materials	Mix proportions (kg/m^3)			
	$V_f = 0$	$V_f = 1\%$	$V_f = 2\%$	$V_f = 3\%$
Portland cement (P II 52.5R)	413	413	413	413
Silica fume	32.5	32.5	32.5	32.5
Fly ash	65	65	65	65
GGBS	130	130	130	130
Water	143	143	143	143
Superplasticizers	9.75	9.75	9.75	9.75
River sand	730	708	686	664
Gravel aggregate	1097	1041	985	929
Steel fiber	0	78	156	234