Experimental Study on Dynamic and Static Mechanical Properties of Steel Fiber Reinforced Concrete

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***Abstract*—The steel fiber reinforced concrete(SFRC) shows better performance under blast and impact loading than conventional concrete in virtue of its better ductility. The mixture proportions of SFRC were designed with the content of steel fibers varied from 0 to 1.5%. The compressive and tensile strength were investigated using Φ50×100mm and Φ70×30mm specimens respectively, and SHPB tests were performed using Φ70×36cm. The results of experiments show that the compressive strength and the splitting strength gradually increased with the increase of steel fibre content, and the tensile property significantly increases more enhanced than the former; SFRC is a material with obvious strain-rate effect，and the shape of the dynamic stress-strain curve is basically the same; The formulae of SFRC's DIF are obtained by fitting the test results would provide a good reference for actual engineering calculation, which may benefits to the science and engineering design.**

***Index Terms*—SFRC; SHPB; mechanical properties; effect of strain rate; dynamic increase factor**

I. Introduction

Concrete is one of the engineering materials widely used in civil engineering, but it has the shortcomings of brittle failure because of its low tensile strength and low elongation rate. Due to the loading, the phenomenon of the damaged and spallation of concrete always is easy to take place [1]. Thus, it is necessary to reinforce concrete by interfusing kinds of fibers with greater tensile strength and higher extension rate to significantly improve the mechanical properties, the tensile strength, flexural strength and anti-blast performance of concrete [2]. The improvement of its performance has been verified by incorporating the steel fiber, basalt fiber, polypropylene fiber into the concrete [3], [4]. In particular, the steel fibers are currently used in civil applications to increase the anti-blast capacity of structures or to extend the structural integrity of deteriorated structures. As the SFRC is a composite material, the effective contents of steel fiber is one of the main factors affecting the mechanical properties of SFRC [5].

At present, there is a solid foundation for the experimental research with the rapid development in SFRC technology. Mohammadi and Bischoff et al. [6], [7] respectively using a drop-hammer machine and SHPB studied the impact resistance and dynamic mechanical properties of SFRC by experimental test. It had been observed that the concrete containing fibres at 2.0% volume fraction gave the best performance under impact loading, and that mechanical properties could be significantly improved with the increase in fiber volume fraction. Adel Ka ̌kea et al. [8] prepared six groups SFRC of different forms with different content. The results showed that the compressive strength and peak flexural strength of the upshot concrete were strongly improved by the presence of 2% volume fraction of fibers. Zhang et al. [9], [10] launched the research of the cracking rate of SFRC under different loading rate influence, especially at low and high loading rates. The crack velocity in SFRC kept almost constant, not like that in plain concrete, the crack proceeded with increasing speed and the main crack propagated in an almost constant way. The work presented by Almusallam et al. showed that hybrid-fibers could improve the impact resistance of RC slabs/plates and the generalized equations were developed to predict the penetration depth and the ballistic limit [11], [12]. On the basis of these, it is very important to carry out the dynamic and static mechanical tests of the SFRC with higher strain rate.

In this paper, the SFRC specimens incorporated with different steel fibers volume fraction are investigated, and the mechanical properties of SFRC are studied and analyzed through the experiments. Based on empiric formula in actual application, the relation of DIF versus strain rate was presented combined with the basic mechanical parameters of the SFRC. The research benefits to the science and engineering design.

II. Materials and Specimens of SFRC

A. Mixture Proportion Design

The main components of SFRC are ordinary portland cement, flyash, river sand, crushed stone, steel fiber, water and additive. Their apparent shape is shown in Fig. 1. The materials employed are summarized in Table I .In order to improve the coefficient of cement paste coated

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steel fiber, the water/cement ratio was 0.35, and the additive was 8.10 kg/m^3. The specimens of SFRC were made by secondary synthesis with fiber fraction varied from 0 to 6 %. The SFRC was composed of two groups ---- steel fiber cement slurry and benchmark plain concrete, and the mixture proportions of them were designed respectively. The mixture proportion will be eventual synthesis by adding of components of each usage material. The advantage of this method is that the steel fibers were fully wrapped by cement slurry, not agglomerated, so the fiber fraction can be high to 6%. Mixture proportions for all are shown in Table II.

Figure 1. apparent shape of (a) river sand, (b) crushed stone, (c) steel fiber.

TABLE I. MATERIAL PROPERTIES OF SFRC

Cement	P• I 42.5 Portland cement
Fine aggregate	River sand Apparent density (dry) = 2580 kg/m3 Maximum size = 5 mm
Coarse aggregate	Crushed stone loose density(dry) = 1480 kg/m3 Maximum size = 10 mm
Admixture	Flyash Density = 2360 kg/m3
Fiber	Steel fiber Density = 7750 kg/m3, Diameter = 0.20 mm Length = 30.0~38.0 mm
Additive	Polycarboxylate Superplasticizer

TABLE II. MIXTURE PROPORTIONS

Vf(%)	W/B(%)	Cement (kg/m^3)	Flyash (kg/m^3)	River sand (kg/m^3)	Crushed stone (kg/m^3)
0	0.35	391.00	59.00	698	1090
0.75	0.35	450.45	67.97	676.19	1055.95
1.50	0.35	504.87	76.18	645.39	1007.84

Notations:V_f=Steel fibre volume Fraction; W/B=Water/(cement+flyash)

B. *Test Specimens*

First, the dry mix were stirred evenly composed of cement, flyash, stone, sand and steel fibers. Second, the mixed solution was added in the dry mix. Then the mixture was poured into square molds which would suffer from vibrating and smoothing. The blocks should be demolded in the next day, and put into the standard nursing room. After 28d, they were took out from the nursing room to air-dry. The procedure of evolution is shown in Fig. 2. The test specimens were made finally through coring, cutting and polishing. They were divided into three groups according to the steel fiber content with 0,0.75%, and 1.5%. In order to obtain the mechanical properties of the SFRC, the uniaxial compression tests and brazilian disc splitting tests were launched, as the specimens shown in Fig. 3. The size of uniaxial compression test specimens is Φ50×100mm; The specimens of Φ70×30mm were adopted in brazilian disc splitting tests.

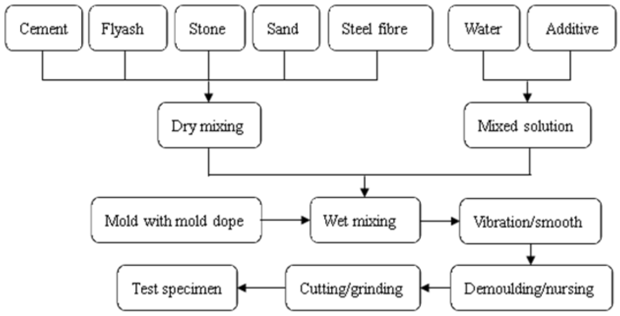

Figure. 2. The flow chart of execution processing on making specimen.

a b

Figure 3. Typical test specimen: (a) Uniaxial compression test, (b) Brazilian disc splitting and SHPB test.

In order to investigate the the dynamic compressive mechanical behavior of SFRC, the circular target samples were made for the contact explosion experiment. The manufacturing procedure of test program is introduced as shown in Fig. 2.SFRC specimens were divided into three kinds of steel fiber content which were were 0, 0.75%, and 1.5%. The size of SHPB test specimens is Φ70×36mm.The specimen is shown in Fig. 3.

III. EXPERIMENTAL PROGRAM

Uniaxial compression test and brazilian disc splitting test were lanched in computer controlled electro-hydraulic servo test machine (shown in the Fig. 4). The Load was exerted by the displacement control method. The loading rate of uniaxial compression test is 0.01mm/s, and the loading rate of brazilian disc test is 0.7 mm/s.

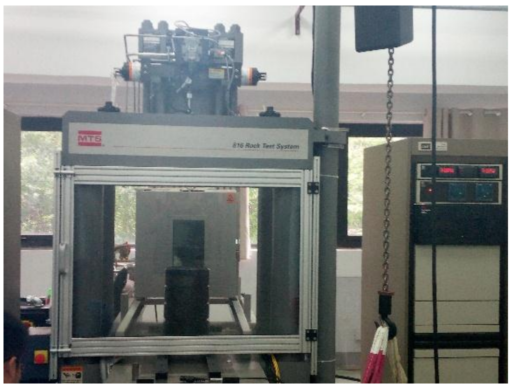

Figure 4. Computer controlled electro-hydraulic servo test machine

The high strain rate tests were conducted using a split Hopkinson pressure bar (SHPB) apparatus with the bar diameter of 74mm and the striker length of 800mm, as shown in Fig. 5. The specimen with different amount of steel fiber concrete was tested, which was simply supported by free boundary.

Figure 5. The device of large diameter split Hopkinson pressure bar

IV. Experimental Results

A. *Compression and Brazilian Disc Splitting Tensile Tests Results*

The failure forms of uniaxial compression test and brazilian disc splitting test are shown in the Fig. 6. The compressive strength of SFRC was obtained by the uniaxial compression test. The splitting tensile strength f_t was measured by Brazilian disc splitting test ,given by the following formula Eq. (1) [13].

$$f_t = \frac{2F}{\pi Dh} \tag{1}$$

where F represents the axial force, D represents the diameter of the test piece, and H represents the thickness of the specimen.

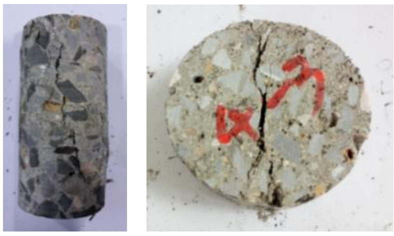

Figure 6. The failure of SFRC specimens: (a) Uniaxial compression test, (b) Brazilian disc splitting test.

According to the results of uniaxial compression test and brazilian disc splitting test, and the basic mechanical parameters of SFRC were obtained, as shown in Table III.

TABLE III. The Basic Mechanical Parameters of SFRC

V_f(%)	f_c(MPa)	f_t(MPa)	E(GPa)
0	45.14	4.79	29.35
0.75	55.76	5.39	30.28
1.5	63.57	6.08	31.96

It is convenient to nondimensionalize these parameters with the plain concrete basis(V_f =0%). Fig. 7 shows the histogram of these non-dimensional parameters.

As can be seen from the histogram in the diagram, the compressive strength and the splitting strength gradually increased with the increase of steel fibre content. The elastic modulus of SFRC remains substantially unchanged in virtue of the relative values. It is summarized that the tensile property significantly increases more enhanced than the compressive property with the increase of content of steel fiber. This is consistent with the above research and the current research [5]-[14].

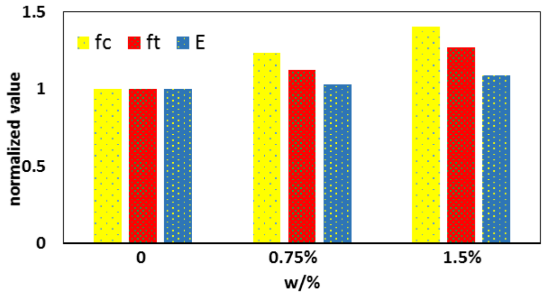

Figure 7. The normalized value of SFRC properties

B. *SHPB Tests Results*

In SHPB tests the corresponding stress-strain curves at different strain rates were obtained under high strain rates based on the original waveforms. The stress versus strain curves of plain concrete measured are shown in Fig. 8. The stress versus strain curves of 0.75% SFRC measured are shown in Fig. 9. The stress versus strain curves of 1.5% SFRC measured are shown in Fig. 10.

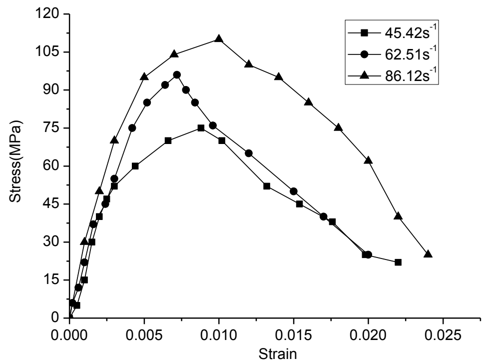

Figure 8. The stress-strain curve of of plain concrete

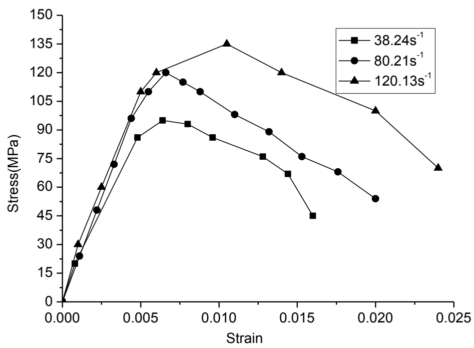

Figure 9. The stress versus strain curves of 0.75% SFRC

According to the characteristics of the curves in the graph, the strength increases with strain rate, and the shape of the dynamic stress-strain curve is basically the same. the experimental results showed that SFRC is a material with obvious obvious strain-rate effect.

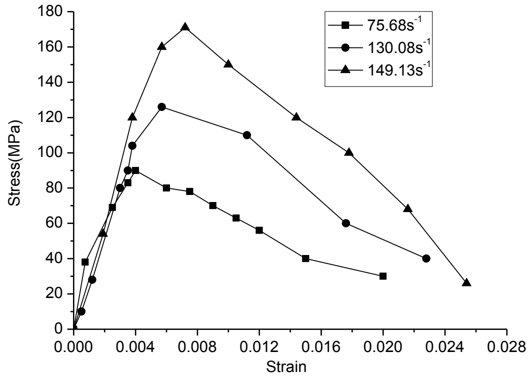

Figure 10. The stress versus strain curves of 1.5% SFRC

V. Discussion on the Results of SFRC

The ratio of abilities determined at a high strain rate caused by dynamic loading to those under static loading is known as the dynamic increase factor (DIF), commonly used to quantitatively describe the effect of strain rate on material properties. The DIF of concrete is dependent on concrete strength and strain rate of loading. There were many existing researches on DIF, and a series of spalling thickness formulas are put forward [15], [16]. The most comprehensive used equation for the DIF of compressive strength is given by Logarithmic or exponential function. The compressive strength σ_0 and its corresponding strain rate $\dot{\varepsilon}_0$ under uniaxial compressive are normalized factors, and the stress and strain rates are normalized to obtain the logarithmic curve of DIF, as shown in Fig. 11. The formulae obtained by fitting the test results are as follows：

Plain concrete: $$\mathrm{DIF}_p = 1.21\ln(\dot{\varepsilon}/\dot{\varepsilon}_0) - 2.94 \quad (2)$$

0.75% SFRC: $$\mathrm{DIF}_{0.75} = 0.62\ln(\dot{\varepsilon}/\dot{\varepsilon}_0) - 0.57 \quad (3)$$

1.5% SFRC: $$\mathrm{DIF}_{1.5} = 1.64\ln(\dot{\varepsilon}/\dot{\varepsilon}_0) - 5.74 \quad (4)$$

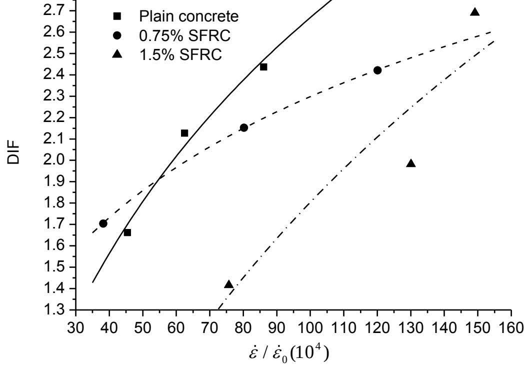

Figure 11. The relationship curvers of DIF versus strain rate

The curves show that the DIF of plain concrete grows faster with the increase of strain rate, and the higher the content of steel fiber, the less the strain rate effect. According to the experiment study [17], [18], it is not only the strain rate but also the content of steel fiber that influence the compressive strength of SFRC. So, the influence of them should both been considered at the same time in engineering design. As a result, the formula (2), (3) and (4) of the experimental results would be beneficial to the engineering design, which may provide a good reference for actual engineering calculation.

VI. Conclusions

The mixture proportions of SFRC were designed with the content of steel fibers. The compressive strength and the splitting tensile strength changed along with the various volumetric content of the steel fibers. The main results by analyzing the performance of SFRC with combinations of these factors are summarized as follows:

- The compressive strength and the splitting strength gradually increased with the increase of steel fibre content, and the tensile property significantly increases more enhanced than the former. The elastic modulus of SFRC remains substantially unchanged in virtue of the relative values.
- SFRC is a material with obvious strain-rate effect, and the higher the content of steel fiber, the less the strain rate effect. The shape of the dynamic stress-strain curve is basically the same.
- The DIF of plain concrete grows faster with the increase of strain rate, and the formulae of SFRC's DIF are obtained by fitting the test results.

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