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Experimental study on dynamic mechanical properties and constitutive model of basalt fiber reinforced concrete

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HIGHLIGHTS

- The dynamic mechanical properties of BFRC at different strain rates and fiber contents are investigated.
- The effects of strength grade, fiber contents and strain rates on the of BFRC are studied.
- The internal structure of concrete and the distribution of fiber are studied.
- A dynamic constitutive damage law is established under impact loading.

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ABSTRACT

Basalt fiber reinforced concrete, a new high performance cement-based composite material, is a focus of attention and has developed rapidly in recent years. In this paper, the impact behavior of BFRC with six kinds of volume content (0%, 0.05%, 0.1%, 0.15%, 0.2%, 0.25%) subjected to various high strain rates was investigated using a 74 mm-diameter split Hopkinson pressure bar (SHPB) apparatus. And the effects of volume fractions and strain rate on dynamic compressive strength and toughness were studied according to the stress-strain curves obtained by the experiment. From the microscopic point of view, by analyzing the scanning electron microscope (SEM) photographs, this paper made a research on the micro-properties and pore structure of BFRC. The fiber distribution situation and the interface between fibers and cement were observed. By studying the micro-properties and pore structure of BFRC, the interface properties and the strengthening mechanism of BFRC were analyzed. In the end, the dynamic constitutive law of BFRC was derived based on an improved Zhu-Wang-Tang (ZWT) dynamic constitutive model which took into account the material damage. The new equation was used to fit the experimental stress-strain curves.

1. Introduction

Basalt fiber reinforced concrete (BFRC) is a new type of fiber reinforced concrete, which is made of high performance basalt fiber and concrete [1]. It belongs to the category of multiphase heterogeneous composite materials. BFRC can not only keep the advantage of high compressive strength, but also greatly improve the tensile cracking and impact mechanics properties. Basalt fiber as a material to improve the properties of concrete has got more and more attention, and its field of engineering application is becoming more extensive.

In real-life applications, many concrete structures are designed to withstand normal design loads as well as uncertain dynamic loads such as impact, explosion, earthquake, etc. Therefore, the study on the dynamic properties of BFRC under high strain rate impact has practically significant in dynamic analyses of concrete structures. At present, the application of basalt fiber in concrete to improve its properties has become a hot area, but the research on dynamic mechanical properties under the impact load is still insufficient. The dynamic characteristics of concrete under high strain rates are different from that in the case of static loads. The physical properties and static responses of BFRC have been well studied in practical structural design, but studies on the dynamic properties of BFRC, especially under high strain rate loading conditions, are limited.

The split Hopkinson pressure bar (SHPB) equipment is often used to study the mechanical properties of materials under high strain rate loading [2,3]. Large diameter bars, with diameters such as Ø51 mm, Ø76 mm, Ø100 mm, are usually used to study dynamic properties of concrete [4–7]. The SHPB device can conveniently record the dynamic curves of the stress-strain, stress-time and

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strain rate-time. The dynamic curves can reflect the loading process of concrete. For instance, Ross and Tedesco [8] studied the dynamic properties of concrete by means of an Ø51 mm SHPB device and concluded that the strength of concrete increased linearly as the strain rate increased. With SHPB equipment, Lok et al. [9] tested the dynamic mechanical properties of the steel fiber reinforced concrete, and analyzed the mechanism of the steel fiber to improve the impact compressive strength and energy-absorption capacity of the concrete. A Ø74 mm SHPB with variable cross-section was developed for studying the dynamic properties of the concrete by Hu et al. [10]. The results showed that concrete materials were not only sensitive to the strain rate effect, but also had very obvious damage softening effect.

Jone Sung Sim et al. [11] indicated that after the concrete was mixed with basalt fiber, the tensile strength of concrete increased by 0.5–1 times, the elongation increased by 3–5 times and toughness also improved. Dias et al. [12] investigated the basalt fiber reinforced geopolymer concrete. Compared with ordinary portland cement concrete, it was found that basalt fiber could better enhance the fracture toughness of the geopolymer concrete, and the optimum fiber content was about 1%. The physical and mechanical properties, flexural strength and compressive strength of 28 d basalt fiber reinforced mortar were tested by Zielinski et al. [13] and the optimum volume fraction of fiber was given. The dynamic properties and dynamic constitutive relationship of BFRC under high strain rates have not been sufficiently studied.

In this paper, we used the improved SHPB device to study the dynamic mechanical properties of BFRC at different strain rates and fiber content. In order to explore the fiber enhancement mechanism of concrete, from the micro perspective of photos collected by scanning electron microscopy (SEM), we observed the microscopic appearance and studied the internal structure of concrete and the distribution of fiber in the concrete. Finally, a dynamic constitutive damage law was established for BFRC materials under impact loading.

2. Experiment framework

2.1. Description of specimens

Since the dynamic mechanical properties of BFRC are highly related to the material parameters and the test device, we carried out a parametric study considering these several influence factors such as the water-cement ratios, fiber contents and impact strain rates. Three different strength grades were considered, namely, C25, C35 and C45. The mixtures of cement, water and sand are given in Table 1. The basalt fibers added in the mortar mixtures are shown in Fig. 1 and their property parameters are presented in Table 2. Six sets of basalt fiber contents were used, which are 0 (plain concrete), 1.325 kg/m^3, 2.65 kg/m^3, 3.975 kg/m^3, 5.3 kg/m^3, 6.625 kg/m^3, respectively. Ordinary Portland cement with the strength grade of 42.5 was used. The river sand, after sieving control of the particle size (e.g., smaller than 3 mm), was employed as the fine aggregates. The detritus, after sieving control of the particle size (5–10mm), was employed as the coarse aggregates.

Specimen size is an important factor affecting the dynamic mechanical properties of concrete. The optimal ratio of specimen height to diameter is changed with the experiment process. Wang et al. [14] pointed out that the optimum length diameter ratio of pressure specimens is 0.4–0.5 in the SHPB test. To reduce the dispersion effect of strain signals and to obtain more accurate experimental results, we selected the length diameter ratio of 0.4–0.5. The cement mortar tubes were cut into Ø74 mm (diameter) × 32 mm (height) cylindrical specimens, and the length diameter ratio is 0.43. A typical specimen is illustrated in Fig. 2. A process of coring, slicing and polishing was carried out to ensure the fiber uniformity and the flatness of the specimen surface (e.g., surface roughness ≤ 0.2 mm [15]), so as to make the contact between the specimens and the impact bars as perfect as possible. The test conditions of BFRC specimens are given in Table 3.

Table 1
Mix composition of control concrete mixes (kg/m^3).

Strength grade	Cement	Water	Sand	Detritus
C25	345	230	730	1095
C35	438	230	610	1133
C45	523	230	534	1134

Fig. 1. 12 mm chopped basalt fiber.

2.2. Quasi-static test

Before carrying out the dynamic test, we study the quasi-static characteristics of the BFRC materials so as to obtain some reference of their dynamic properties. The specimens have a strength grade of C45 and six amounts of fiber contents. The size of the specimens for the static test is 150 mm × 150 mm × 150 mm. Three specimens were prepared and tested for each case and the averages of the experimental results were recorded. The static compressive test was conducted using the static structure testing machine at Hohai University Structural Engineering Laboratory.

2.3. Dynamic test: SHPB setup

The SHPB equipment mainly consists of three parts: pressure bar system, testing and data acquisition system and data processing system, as shown in Fig. 3. The test specimen is placed between the incident bar and the transmission bar, as illustrated in Fig. 3. The nitrogen pressure chamber system can accelerate the striker bar. And then the striker bar hit the incident bar. Thus the impact loading is generated and spreads into the specimen. The loading strain rate can be controlled through changing the nitrogen pressure in the chamber. The compressive impact tests on the BFRC specimens were carried out using the SHPB equipment, at Hohai University (Nanjing, China). This device is able to measure the material stress-strain relationship of the specimen under impact loading. The length of incident bar and transmission bar are 3200 mm, 1600 mm, and the diameter is Ø74 mm.

The SHPB equipment is a widely used system in material property testing and characterization under high strain rates. The experimental principle is based on the two basic hypotheses: (1) one-dimensional plane-section assumption, (2) stress uniformity assumption [16]. Noteworthy, two additional components in the classic SHPB system to improve the equipment test performance were employed, namely, brass shapers and universal confinement