Dynamic Mechanical Properties of Basalt Fibre Reinforced Foam Concrete at High Strain Rates

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Abstract. Dynamic compressive properties of basalt fibre reinforced foam concrete (BFFC) under different strain rates (from 0 to 2000 /s) were investigated. Series of experiments were conducted on BFFC (900, 1100 and 1300 kg/m³) with 0.2% volume fraction fibre content respectively. Split Hopkinson pressure bar (SHPB) system was utilized to measure the dynamic response of BFFC. Mechanical properties including stress strain characteristics, strain rate sensitivity and peak strength of BFFC were discussed. The results show that BFFC reveal strain-hardening phenomenon and strain rate sensitivity under high strain rates, the peak compressive strength was significantly improved with the increase of density.

Keywords: Foam concrete, basalt fibre, dynamic mechanical properties, SHPB, strain rate.

1. Introduction
Foam concrete is a type of lightweight concrete with density normally from 600-1900 kg/m³. The special pore structure of foam concrete give itself advantages of lightweight, thermal insulation and energy dissipation, but caused the defects such as low strength, brittleness and air shrinkage at the same time [1]. Fibre reinforcement is an effective way to improve the mechanical performance while maintaining good characteristics of foam concrete. Basalt fibre is a new type of inorganic environment-friendly and high-performance fibre with great development potential, which possesses superiorities of low cost, low pollution, high strength, corrosion resistance, high temperature resistance and biodegradation resistance [2].

As a kind of silicate fibre, basalt fibre shows better ability of three-dimensional uniform dispersion in cement base material compared with other fibre, and thus can obviously enhance the cement-based material [3]. As a result, basalt fibre reinforced foam concrete (BFFC), which is made by using basalt fibre as a reinforcement material in foam concrete, have great potential in not only inheriting the advantages of foam concrete like lightweight, heat preservation, heat insulation, shock absorption, etc., but also enhancing the strength and toughness of traditional foam concrete. Many scholars have carried out researches on the performance of basalt fibre reinforced concrete, but there are still few about BFFC [4]. In order to investigate the mechanical especially the dynamic mechanical properties of BFFC, 0.2% (volume fraction) fibre content of BFFC for 3 density group (900, 1100, 1300 kg/m³) are placed under different strain rate (0, 1000, 2000 /s) in this paper.
2. Experimental method

2.1. Specimen preparation

It is pre-foam method that is used to produce foam concrete.

2.1.1. Raw materials. The main raw materials of BFFC include cementitious materials, admixtures, foams, admixtures and basalt fibre. It is worth noting that because aggregate is easy to precipitate in wet foam mixture and increase foam loss, only a small amount of fine aggregate is needed when target density is beyond 1000 kg/m³. P-Itype Portland cement is selected as cementitious material to reduce the mixed material effect. Fly ash is added to partially replace cement to reduce shrinkage, improve workability and save cost. Silica powder and super plasticizer, which is beneficial to the uniform dispersion and stability of foam in slurry, are utilized to improve the workability of foamed concrete slurry and enhance the strength of BFFC. Fine sand with particle size not exceeds 0.46mm is selected as aggregate to properly improve the strength and reduce the shrinkage. The average length of basalt fibre is 10 mm and the monofilament diameter is 12.2 μm. The chemical composition of basalt fibre is summarised in Table 1. Protein based foaming agent is utilized, with foamability listed in Table 2.

Table 1. Chemical composition of basalt fiber (by mass fraction)

| SiO₂ | Al₂O₃ | CaO | MgO | Na₂O+K₂O | TiO₂ | Fe₂O₃+FeO |
|------|-------|-----|-----|-----------|------|-----------|
| 52-58| 14-19 | 5-9 | 3-6 | 3-6       | 0.5-2.5| 9-14      |

Table 2. Foamability of protein based foaming agent

| Foam expansion | Settlement (1h)/mm | Bleeding rate |
|----------------|--------------------|--------------|
| 25             | 50                 | 50%          |

2.1.2. Mix design. The mix design of BFFC refers to the conventional foamed concrete and adopts the absolute volume method. According to Equations (1) and (2), water consumption, cement and aggregate content per unit volume \( m_w, m_c \) and \( m_a \) can be obtained based on the known water cement ratio \( w \) and target density \( \rho \). In the equation, \( S_a \) is the mass coefficient determined by field tests. Finally, according to Formula (3), the amount of foam per unit volume of BFFC \( V \) is obtained, where \( K \) is the surplus coefficient determined by trial tests. \( \rho_c, \rho_m, \rho_a \) and \( \rho_w \) are the dry density of cement, admixture, aggregate and water respectively. Here, the influence of fibre incorporation is mainly considered through \( K \) and \( S_a \).

\[
\rho = S_a (m_c + m_m + m_a) \quad (1)
\]

\[
m_w = w(m_c + m_m) \quad (2)
\]

\[
V = K[1 - \left(\frac{m_c}{\rho_c} + \frac{m_m}{\rho_m} + \frac{m_a}{\rho_a} + \frac{m_w}{\rho_w}\right)] \quad (3)
\]

2.1.3. Preparation method. Using the physical foaming method to prepare BFFC: produce foam in advance through diluted foaming agent by compressed air, and then mix cement, admixtures, fine sand, basalt fibre and other dry materials in the mixer at a slow speed in another mixer, with water and liquid admixtures added by several times with the same quantity. When the concrete slurry in the mixing system is completely mixed, the foam is injected and carefully turned over. After the pouring, curing and demoulding of BFFC, the finished products are cut into desired shape for mechanical tests. Cylindrical BFFC specimens with diameter of 40 mm and a height of 80 mm are drilled for quasistatic test and diameter of 20 mm and a height of 100 mm are for dynamic tests.
2.2. Quasi-static test
A 300 kN electro-hydraulic servo testing machine is used to conduct uniaxial compression test. Lubricants were applied to the upper and lower surfaces of the specimen during the test. The test is displacement controlled, and the loading rate is 1 mm/min. The test system is shown in Figure 1.

![Figure 1. Quasi-static test system](image)

2.3. Dynamic mechanical test
Split Hopkinson Pressure Bar (SHPB) is an important technique to measure the constitutive behavior of materials under impact load. The fundamental principles of this test is to decouple the wave propagation and the strain rate effect of materials to obtain the dynamic stress-strain characteristics of materials.

2.3.1. SHPB apparatus. A schematic diagram of SHPB device is presented, see Figure 2. The device consists of a bar system, a loading system, and a data acquisition system. The specimen is sandwiched between input and output bar. After tests begun, the striker bar is launched by high pressure nitrogen. An elastic compressive pulse is thus generated in incident bar due to the impact. The compressive wave travel along the input bar towards the specimen. When the wave reaches the interface between input bar and specimen, part of the wave reflects into the input bar and the residual wave travel through specimen into the output bar. Laboratory tools, strain gauges, were used to record strain history during this process.

![Figure 2. Schematic diagram of SHPB device](image)

Two strain gauges are stuck at the midpoint of input and output bar radial symmetrically. The reason for put strain gauges radial symmetrically in this project is to eliminate strain caused by bending moment due to potential misalignment or Poisson effect. The self-built SHPB system is demonstrated in Figure 3.
2.3.2. Data Processing. According to the assumption of data equilibrium and constant loading strain rate, the strain rate $\dot{\varepsilon}$, strain $\varepsilon$ and stress $\sigma$ histories of the tested material in time domain can be expressed as:

$$\dot{\varepsilon}(t) = -2 \frac{c_b}{L_s} \varepsilon_r$$ (4)

$$\varepsilon(t) = -2 \frac{c_b}{L_s} \int_0^t \varepsilon_r dt$$ (5)

$$\sigma(t) = \frac{A_b}{A_s} E_b \varepsilon_r$$ (6)

where $c_b$, $A_b$, and $E_b$ denote the wave velocity, cross-sectional area and elastic modules of the loading bars, $L_s$ and $A_s$ represent the thickness and cross-sectional area of specimen, $\varepsilon_r$ and $\varepsilon_i$ are the time-history of reflected and transmit wave which are typically measured by strain gauges attached on the incident and transmit bars respectively.

3. Result and discussion

For all the stress strain curves examined, the dynamic stress-strain curves consist of an elastic portion, in which the stress directly proportional to strain, followed by an approximate plateau, see Figure 4(a) for example, which shows that BFFC demonstrates obvious brittleness under quasi-static loading but reveals strain hardening characteristic under high strain rate. This may due to the fibre connection between cementitious particles. The peak strength of BFFC under different strain rate are shown in Figure 4(b). As can be seen from the figure, peak strength increases with the increase of strain rate, and elevate with the rise of density under the loading condition. This suggests that BFFC is strain rate sensitive, the higher the compactness of the material is, the greater the inertia effect, the peak strength is thus becoming greater.
Figure 4. SHPB test results (a) Stress strain curve for BFFC of 900 kg/m³, 0.2 % fibre content. (b) Peak strength of BFFC

4. Conclusion
In this paper, dynamic mechanical properties of BFFC were tested using SHPB device, stress strain characteristics and peak strength of BFFC were investigated under different strain rate. The conclusions are as follows:

(1) BFFC demonstrates obvious brittleness under quasi-static loading but reveals strain hardening characteristic under high strain rate.

(2) The dynamic stress strain curves of BFFC comprises an elastic regime, in which the stress increases proportional to strain and an approximate plateau.

(3) BFFC is strain rate sensitive, the peak strength increases with the rise of strain rate.

(4) Peak strength increases with the increase of density under the same strain rate.

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