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Research paper

Study on uniaxial impact compression characteristics of basalt fiber cement soil

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Abstract: In order to study the dynamic mechanical properties of cement soil, uniaxial impact compression tests with different strain rates of cement soil with no fiber and with 0.2% basalt fiber were carried out by using a 50 mm steel split Hopkinson pressure bar device. The test results show that the impact compressive strength, dynamic increase factor and peak strain increase with the increase of strain rate under the same basalt fiber content, showing obvious strain rate effect. The dynamic stress-strain curve of basalt fiber cement soil underwent elastic deformation stage, plastic deformation stage and failure stage. With the increase of strain rate, the degree of fracture of cement soil samples gradually increases, which shows that the number of fragments increases, the size decreases and tends to be uniform. After adding basalt fiber in cement soil, the crack can be delayed, the degree of fracture is smaller than that without fiber and the plasticity of the samples is enhanced. It shows that basalt fiber can improve the impact compressive strength of cement soil.

Keywords: cement soil, basalt fiber, SHPB experiment, impact compressive strength, strain rate effect

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1. Introduction

Cement soil is a material made by mixing soil, cement and other materials in a certain proportion. Cement soil is widely used in soft foundation treatment, slope reinforcement and stability, deep foundation pit support and other engineering fields due to its low compressibility, low permeability and other superior characteristics [1, 2]. However, the strength of cement soil is relatively low and often fails to meet the designed strength requirements. Therefore, how to improve its strength has become a hot topic in cement soil research. The incorporation of fiber into cement soil is an effective method [3–6]. Nilo Cesar Consoli [7] found that the addition of fiber improved the compressive strength of cement soil through the unconfined compression test of fiber cement soil. Hamidi [8] studied the influence of polypropylene fiber on cement soil strength through conventional triaxial compression test and shear test. Kutanaei [9] added polyvinyl alcohol fiber to cement soil and found that the fiber could absorb energy generated by external load and thus improve the strength of the sample. Chen feng [10] concluded that basalt fiber can effectively improve the tensile strength and plastic deformation capacity of cement soil. Tang Chaosheng [11] proposed to use the physical reinforcement effect of polypropylene fiber combined with the chemical reinforcement effect of cement to discuss the influence of the content and length of polypropylene fiber on the strength of cement soil. He Wenxiu [12] used glass fiber and fly ash to improve the mechanical properties of cement soil.

However, most of the above researches focused on the static properties of fiber cement soil, and there were few researches on the dynamic characteristics of fiber cement soil under impact load. In practical engineering, cement soil bears not only static load, but also dynamic load such as wave and vehicle. Basalt fiber have advantages such as good waterproof, corrosion resistance, high elastic modulus, high temperature resistance, high tensile strength, low price and environmental protection, and so on [13]. Therefore, this article selects the basalt fiber cement soil as the research object and impact compression test was carried out on cement soil with different basalt fiber content, using the ∅ 50 mm variable cross-section SHPB experiment device by adjusting the impact pressure. The effects of basalt fiber content and strain rate on impact compressive strength, dynamic increase factor, dynamic stress-strain curve and failure pattern of cement soil were analyzed.

2. Experimental procedure

2.1. SHPB test device and principle

The impact bar, incident bar and transmission bar used in the impact dynamics laboratory ∅ 50 mm steel Hopkinson (SHPB) test system are all made of the same high-strength alloy steel material. The length of the impact bar is 0.6 m, and the length of the incident bar and transmission bar is 2.4 m and 1.2 m respectively. The elastic modulus of the steel rod was 210 GPa, the density was 7.8 g·cm^{-3}, and the longitudinal wave velocity was 5190 m·s^{-1}. During the test, the specimen is placed between the incident bar and the transmission bar, as shown in Fig. 1. The impact bar strikes the incident bar with a certain impact velocity, and an incident pulse is generated in the incident bar. When the stress wave propagates to the surface of the specimen, a reflection pulse and a transmission pulse are generated. The incident and reflected pulses are collected through the strain gauge on the incident bar, and the transmitted pulses are collected through the strain gauge on the transmission bar. The distance between the strain gauge on the incident bar and the transmission bar and the specimen is 1.2 m and 0.6 m respectively.

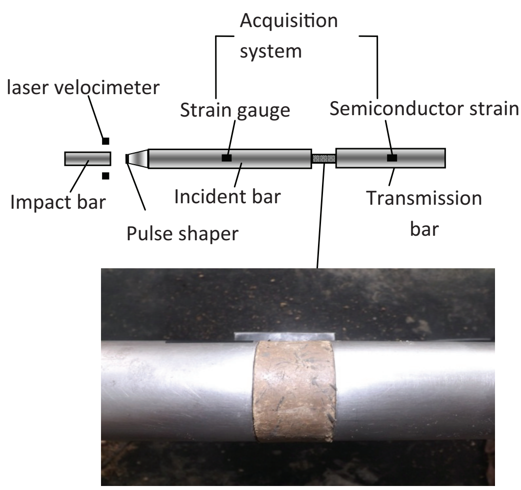


Fig. 1. Impact compression test device

In order to solve the problem of stress uniformity in SHPB test, vase line should be evenly applied to the contact surface of the incident bar, transmission bar and specimen before the test to minimize the impact of friction on the stress distribution of the specimen. The axes of the incident bar, transmission bar and specimen should be in the same straight line [14]. Due to the relatively low wave impedance of cement soil, effective data cannot be collected by ordinary resistance strain gauge, so semiconductor strain gauge is used to collect transmission signal in the test.

2.2. Sample making and test design

The test soil sample was taken from the foundation pit of a construction site in Huangshan city. The liquid limit was 34.50%, the plastic limit was 21.76%, the optimal moisture content was 20.60%, and the maximum dry density was 1.71 g·cm^{-3}. Particle distribution of test soil is shown in Table 1. P·O 42.5 ordinary Portland cement is used.

The physical and mechanical properties of basalt fiber produced by a company in Shanghai are listed in Table 2.

Undisturbed soil was dried and crushed in 2mm sieve, and the soil sample with an moisture content of 20.60% was prepared by adding water. After mixing, it was sealed

Table 1. Particle distribution of test soil

Particle sized mm	Content %	Particle sized mm	Content %
$d \leq 0.005$	19.07	$0.005 < d \leq 0.075$	36.38
$0.075 < d \leq 0.25$	14.82	$0.25 < d \leq 0.5$	17.15
$0.5 < d \leq 1$	10.05	$1 < d \leq 2$	2.53

Table 2. The physical and mechanical properties of basalt fiber

Filament diameter m	Length mm	Elongation at break %	Tensile strength MPa	Density g·cm^{-3}	Tensile modulus GPa
15	12	3.2	3800–4800	2.65	90~110

with a plastic bag and stood for 24 h. Cement is added at 20% of dry soil weight. The ratio of water to cement is 0.5. The cylinder specimen was prepared by layering compaction method. In the SHPB test, when the length-diameter ratio of the specimen is about 0.5, the inertia effect and friction effect are small [15]. Therefore, the samples were made into a cylinder with a diameter of 50 mm and a height of 25 mm. The cement soil samples were packed into self-sealing bags and finally moved to the curing room for 28 days. The curing temperature was (20 ± 2))°C and the curing humidity was 95%. The static compressive strength of cement soil is 2.95 MPa.

Different strain rates were obtained by changing the impact pressure. The strain rates were determined to be about 120 s^{-1}, 140 s^{-1}, 160 s^{-1} and 180 s^{-1} through multiple tests. Basalt fiber content is 0 and 0.2% respectively. Three parallel samples were prepared for each set of tests. The specific test scheme is shown in Table 3.

Table 3. SHPB test design of cement soil

Test object	Basalt fiber content %	Strain rate s^{-1}
Cement soil	0, 0.2	120, 140, 160, 180

3. Results and discussion

3.1. SHPB test results

Basalt fiber cement soil impact compressive strength refers to the maximum stress of cement soil material under impact load, which reflects the ability of cement soil to resist impact damage. The impact compression performance of cement soil on the condition of different basalt fiber content (0 and 2%) and different strain rates was considered in the test. Data processing was carried out by using the three-wave method [16], and the impact compressive strength of cement soil was obtained as shown in Table 4.

Table 4. SHPB test dates of cement soil

Basalt fiber content %	Strain rate $\dot{\varepsilon}$ s^{-1}	Impact compressive Strength σ MPa	Dynamic increase factor (DIF)
0	116	4.23	1.43
	121	4.32	1.46
	117	4.25	1.44
	138	4.55	1.54
	136	4.61	1.56
	142	4.57	1.55
	165	4.98	1.69
	161	5.02	1.70
	157	4.95	1.68
	182	5.52	1.87
	175	5.61	1.90
	184	5.49	1.86
0.2	125	5.15	1.75
	120	5.21	1.77
	117	5.18	1.76
	143	5.68	1.93
	140	5.72	1.94
	137	5.61	1.90
	168	6.12	2.07
	157	6.21	2.11
	162	6.18	2.09
	186	6.52	2.21
	184	6.58	2.23
	176	6.48	2.20

The expressions of the stress $\sigma(t)$, strain $\varepsilon(t)$ and strain rate $\dot{\varepsilon}(t)$ of the specimen are as follows:

$$\sigma(t) = \frac{E_0 A_0}{A_s} \varepsilon_T(t) \tag{3.1}$$

$$\varepsilon(t) = \frac{C_0}{l_s} \int_0^{\tau} [\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)]\, \mathrm{d}t \tag{3.2}$$

$$\dot{\varepsilon}(t) = \frac{C_0}{l_s}\left[\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)\right] \tag{3.3}$$

where: $\varepsilon_I(t)$, $\varepsilon_R(t)$, and $\varepsilon_T(t)$ are the corresponding incident, reflected and transmitted stress waves at time t respectively; E_0, A_0, C_0 and A_s are the elastic modulus, cross section area, longitudinal wave velocity and cross section area of the test block, respectively. $C_0 = \sqrt{E_0/\rho_0}/\rho_0$ is the density of the bar material; l_s is the height of the specimen; τ is the duration time of stress wave.

Dynamic increase factor (DIF) is the ratio of dynamic impact compressive strength and static compressive strength, which reflects the increase of compressive strength of materials under impact load. It can be seen from Table 4 that the dynamic increase factor increases with the increase of strain rate, which shows a strong strain rate effect. When the strain rate is about 180 s^{-1}, the maximum increase of dynamic increase factor of basalt fiber cement soil is 27.4% when the strain rate is about 120 s^{-1}.

3.2. Influence of strain rate

It can be seen from Table 4 that the impact compressive strength of cement soil shows a strong strain rate effect. Whether or not basalt fiber is mixed in cement soil, its impact compressive strength increases with the increase of strain rate. The impact compressive strength of cement soil under high strain rate is higher than that under low strain rate. The fitting curve between impact compressive strength and strain rate was established by analyzing the test data, as shown in Figure 2.

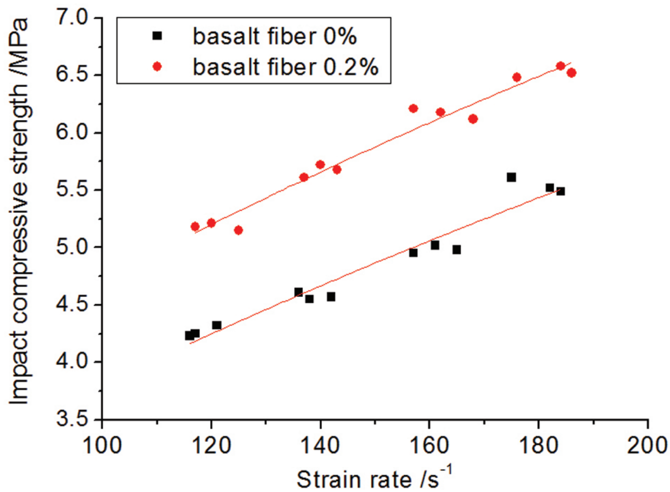


Fig. 2. The dependence of impact compressive strength on the strain rate

The fitting curve equations in Figure 2 are:

– when the content of basalt fiber is 0%,

$$\sigma = 0.233\dot{\varepsilon}^{0.607}, \quad R^2 = 0.941 \tag{3.4}$$

– when the content of basalt fiber is 0.2%,

$$\sigma = 0.379\dot{\varepsilon}^{0.547}, \quad R^2 = 0.963 \tag{3.5}$$

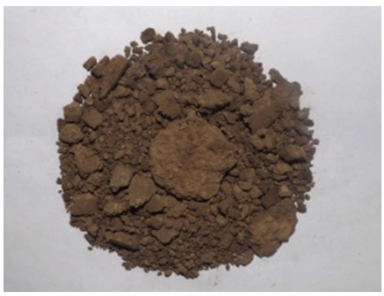
σ represents the impact compressive strength of cement soil, and the unit is MPa. $\dot{\varepsilon}$ represents the strain rate, and the unit is s^{-1}. It can be seen that there is a power function relationship between the impact compressive strength and strain rate of cement soil, and the correlation between them is good, with the correlation coefficient reaching 0.941.

The effect of strain rate on dynamic mechanical properties of cement soil is also reflected in the failure pattern of specimens. When the strain rate increases successively from 120 s^{-1}, 140 s^{-1}, 160 s^{-1} and 180 s^{-1}, the degree of fracture of cement soil samples gradually increases, showing that the number of fragments increases, the size decreases and tends to be uniform, as shown in Figure 3 and Figure 4. The reason is that the larger the strain rate is, the less time it is for the micro-cracks inside the cement soil sample to expand, so they expand simultaneously in all local areas, and the energy absorption is exactly reflected in the number of the extended cracks [17], so the peak strength of cement soil is improved.

$\dot{\varepsilon}$ = 121 s^{-1}

$\dot{\varepsilon}$ = 138 s^{-1}

$\dot{\varepsilon}$ = 165 s^{-1}



$\dot{\varepsilon}$ = 182 s^{-1}

Fig. 3. Failure pattern of cement soil sample unmixed basalt fiber

To investigate the impact of strain rate on the performance of cement soil impact compression, the dynamic stress-strain curves of cement soil at strain rates of about 140 s^{-1} and 160 s^{-1} are analyzed, as shown in Figure 5. From the typical dynamic stress-strain

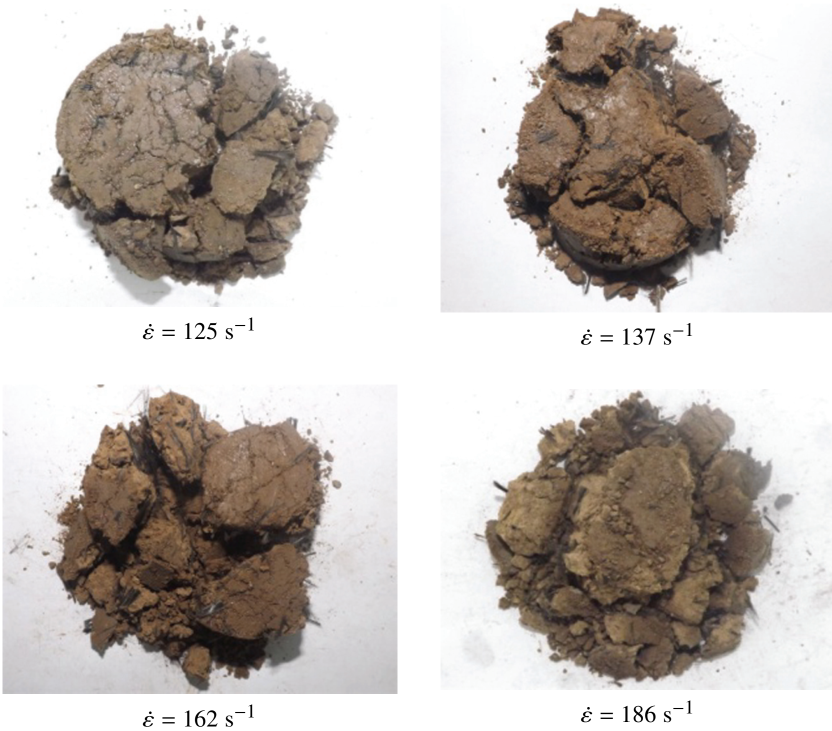


Fig. 4. Failure pattern of cement soil sample with the 0.2% content of basalt fiber

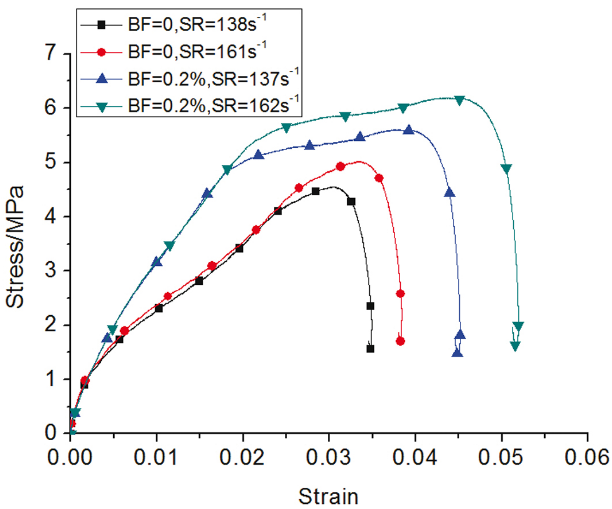


Fig. 5. Dynamic stress-strain curve of cement soil under different strain rate (BF represents the basalt fiber, SR represents the strain rate)

curve of cement soil, the dynamic stress-strain curve can be divided into elastic deformation stage, plastic deformation stage and failure stage. In the early stage of loading, due to the small dynamic load applied, the stress-strain curve of cement soil are approximately linear and in the elastic deformation stage. With the further increase of dynamic load, the dynamic stress-strain curve of cement soil gradually changes from elastic stage to plastic stage. Due to the large void ratio of cement soil, the voids of the test pieces are gradually eliminated under the action of dynamic load, making the test pieces gradually compressed and the voids gradually smaller, showing obvious ductility. It can also be seen from Figure 5 that there is an obvious inflection point in the elastic deformation stage and the plastic deformation stage, which is the boundary point between the elastic deformation stage and the plastic deformation stage. The elastic deformation stage is from the beginning of loading to the inflection point, and after the inflection point it enters the plastic deformation stage. When the dynamic load continues to increase, the cement soil void age decreases continuously and gradually reaches the compaction state. When the stress reaches the limit value, the stress-strain curve turns sharply downward, the stress decreases sharply, and the strain increases only a little, showing obvious brittleness.

As shown in Fig. 5 and Table 4, the dynamic peak stress and peak strain of the cement soil samples increase with the increase of strain rate under the condition of mixed basalt fiber or not. When no fiber was added, the strain rate increased from 138 s^{-1} to 161 s^{-1}, the corresponding peak stress increased from 4.55 MPa to 5.02 MPa, and the peak strain increased from 0.0305 to 0.0336. When 0.2% basalt fiber was added, the strain rate increased from 137 s^{-1} to 162 s^{-1}, the peak stress increased from 5.61 MPa to 6.18 MPa, and the peak strain increased from 0.0394 to 0.0452, with an increase of 10.16% and 14.72% respectively. Meanwhile, as the strain rate increases, the dynamic elastic modulus of cement soil increases significantly, indicating that cement soil has a strong strain rate effect.

3.3. Influence of basalt fiber content

As shown in Table 2, the DIF of cement soil without fiber content is significantly lower than that with 0.2% basalt fiber content cement soil. When the strain rate is about 120 s^{-1}, the DIF of the specimens without fiber is 1.43, 1.46 and 1.44, and the average DIF is 1.443. The DIF of specimens with 0.2% basalt fiber were 1.75, 1.77 and 1.76, and the average DIF was 1.76. The DIF of specimens with 0.2% basalt fiber is 1.22 times that of the specimens without fiber. Similarly, when the strain rates were about 140 s^{-1}, 160 s^{-1} and 180 s^{-1}, the DIF of specimens with 0.2% basalt fiber is 1.24 times, 1.24 times, 1.18 times that of the specimens without fiber respectively.

As shown in Table 2 and Fig. 2, at the same strain rate, the impact compressive strength of cement soil specimens mixed with 0.2% basalt fiber was significantly higher than that without fiber. When the strain rates were about 120 s^{-1}, 140 s^{-1}, 160 s^{-1} and 180 s^{-1}, respectively, the impact compressive strength of cement soil mixed with 0.2% basalt fiber increased by 21.4%, 23.9%, 23.8% and 17.8% respectively compared with that without fiber. It shows that basalt fiber can improve the impact compressive strength of cement soil.

The main reason is that when basalt fiber is mixed into cement soil, discrete fiber form a spatial network of cushioning effect on the interior of cement soil. It inhibits the emergence and development of cracks in cement soil under impact load, improves its ability to resist impact damage, and improves the strength of cement soil.

As shown in Fig. 4, at the same strain rate, the ordinary cement soil is broken to a large extent after being compressed by impact, and most of the samples are small scale fragments or even crushed. When basalt fiber are added, the plasticity of the samples is enhanced, which is manifested in that the breaking degree gradually decreases, and large scale fragments are in the majority, and the number of fragments decreases.

Basalt fiber cement soil has certain plasticity, and the increase of pressure makes cement soil particles and the structure between particles and basalt fiber become more compact. Due to the spatial interlacing structure rearrangement and the development of tensile strength of basalt fiber at different positions, the occlusal friction between basalt fiber and soil mass and the spatial binding force formed by fiber interweave in soil mass continue to increase. It plays an effective role in load transfer and dispersion, and plays a limiting role in the generation of failure cracks, thus increasing the integrity of soil. It is indicated that the addition of basalt fiber can improve the failure toughness and reduce the brittleness of cement soil, which is beneficial to improve the safety and stability of the project.

4. Conclusions

Based on the impact compression test on cement soil with different basalt fiber content, the effects of basalt fiber content and strain rate on impact compressive strength, dynamic increase factor, dynamic stress-strain curve and failure pattern of cement soil were analyzed, and the main results are as follows:

1. In the uniaxial impact compression test, the impact compressive strength and dynamic increase factor of cement soil show strong strain rate effect. The impact compressive strength and dynamic increase factor of cement soil mixed with 0.2% basalt fiber are about 1.2 times of those without fiber.
2. The dynamic stress-strain relation curve of basalt fiber cement soil can be divided into three stages, namely elastic deformation stage, plastic deformation stage and failure stage, which show strong plasticity before reaching the peak stress, and then show obvious brittleness after a sharp decline in bearing capacity.
3. With the increase of strain rate, the degree of fracture of cement soil samples gradually increases, which shows that the number of fragments increases, the size decreases and tends to be uniform.
4. After adding basalt fiberin cement soil, the plasticity of the samples is enhanced, which is manifested in that the crack can be delayed, the breaking degree gradually decreases, and large scale fragments are in the majority, and the number of fragments decreases. It shows that basalt fiber can improve the impact compressive strength of cement soil.

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