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Research Article

Dynamic Mechanical Properties and Fractal Characteristics of Polypropylene Fiber-Reinforced Cement Soil under Impact Loading

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This paper aims to study the dynamic mechanical properties, failure patterns, fractal behaviors, and energy dissipation of polypropylene fiber-reinforced cement soil under impact loading. Dynamic compression tests for reinforced cement soil with different polypropylene fiber contents of 0%, 0.4%, 0.8%, and 1.2% were conducted using a 50 mm diameter split Hopkinson pressure bar (SHPB) device. The static and dynamic stress-strain curves, dynamic strength increase factor (DIF), fractal behaviors, and energy dissipation properties of polypropylene fiber-reinforced cement soil were investigated and analyzed. The experimental results indicated that the dynamic strength increase factor (DIF) of cement soil increases firstly and then decreases with the increase of polypropylene fiber content from 0% to 1.2%. The maximum dynamic compressive strength of cement soil was obtained with adding 0.8% polypropylene fiber. With the increase of polypropylene fiber content, the average particle size of cement soil fragments has an increasing trend, whereas the fractal dimension presents a decreasing trend. Besides, the fragmentation degree of cement soil decreases correspondingly with the increase of polypropylene fiber content. The fractal dimension value has a linear relationship with the polypropylene fiber content and a decreasing exponential relationship with the average particle size. The absorbed energy per unit volume of cement soil presents an increasing trend firstly and a decreasing trend subsequently as the polypropylene fiber content increases from 0% to 1.2%. When the fractal dimension of cement soil is kept in the range of 2.04 to 2.15, the absorbed energy per unit volume of cement soil increases first and then decreases. The absorbed energy per unit volume of cement soil has a quadratic parabola relationship with polypropylene fiber content and fractal dimension, respectively. At last, the relationship of the absorbed energy per unit volume, fractal dimension, and polypropylene fiber content can be established, which can be used in the studies of dynamic behaviors and fractal properties of the fiber-reinforced cement soil under impact loading.

1. Introduction

Polypropylene fiber has many advantages as high strength, low elongation, durability, impermeability, freezing resistance, and impact resistance. Adding appropriate dosage of polypropylene fiber into ordinary cement soil can effectively improve the strength and plastic deformation capacity of treated soil. Recently, many researchers concentrated on the soil stabilization with cement and fiber mixtures. In practical engineering, the polypropylene fiber-reinforced cement soil has been widely used in dams, subgrades, highways, buildings, and other engineering constructions [1–4]. In recent years, several investigators have performed a series of research for soil stabilization with polypropylene fiber inclusion and obtained so many useful achievements. Consoli et al. [5] conducted a series of laboratory tests to evaluate the influence of many parameters on the compressive strength of soil and found that the fiber content of fiber-reinforced cement soil is an important parameter to control the increase in compressive strength. The research results of Cai et al. [6] have shown that the unconfined compressive strength of treated soil can be improved with the addition of polypropylene fiber into soil, and the unconfined compressive strength of treated soil increases with increase in polypropylene fiber content. Moreover, with the combination of fiber reinforcement technology and the chemical agent stabilization, the treated soil presents a further improvement in strength behaviors. As Tang et al. [7] reported, the inclusion of polypropylene fiber into cement soil can not only enhance the compressive strength of cement soil but also improve the toughness of cement soil. Besides, Wang et al. [8] also found that the polypropylene fiber-reinforced cement soil has a significant increase in strength compared with the cement soil without polypropylene fiber. At the same time, it is observed that the stress-strain curve of polypropylene fiber-reinforced cement soil has typical strain hardening characteristics and the principal stress difference increases with increase in fiber content [8]. What's more, the proper dosage of polypropylene fiber is helpful to enhance the compressive strength of cement soil after freezing-thawing cycles. The experimental results of Ding et al. [9] indicated that the cement soil reinforced with 0.2% polypropylene fiber exhibits a higher unconfined compressive strength than other fiber contents. The achievements obtained above are mainly focused on the static mechanical properties of polypropylene fiber-reinforced cement soil. Nevertheless, there is relatively few investigation reported on dynamic behaviors of polypropylene fiber-reinforced cement soil under impact loading. In practical engineering, fiber-reinforced cement soil was also subjected to the impact loading; for example, the fiber-reinforced cement soil as the filling material of base course of the runway in a simple airport. The filling materials of base course are subjected to the severe impact loading when the airplane lands on the runway [10]. In addition, fiber-reinforced cement soil is also subjected to blasting and impact in national defense engineering [11]. The process that the material was subjected to external load till its final instable failure is an energy dissipation process in essence [12]. The macroscopic failure was displayed with different amounts, sizes, and particle distribution of fragments. Therefore, it is important and valuable to investigate the dynamic behaviors of cement soil. The study of dynamic properties and fractal characteristics of polypropylene fiber cement soil under impact loading can be used to evaluate the impact resistance and absorption ability of polypropylene fiber-reinforced cement soil.

It can be seen from the literature [13] that the higher strain rate does not significantly improve the dynamic impact strength of cement soil. Accordingly, in this paper, 0.45 MPa impact loading pressure (strain rate is approximately 170~180 s^{-1}) and a 50 mm diameter split Hopkinson pressure bar test device were adopted to research the dynamic behaviors of cement soil with different polypropylene fiber contents. The fractal dimension of impact broken fragments of polypropylene fiber-reinforced cement soil is obtained by the sieving tests, fractal theory, and statistics method. The effect of polypropylene fiber addition on dynamic mechanical properties, fractal characteristics, and energy absorption ability was considered as the main work in this study. In the following sections of this study, the difference between dynamic mechanical properties and static mechanical properties was analyzed and discussed. In addition, the influence of polypropylene fiber content on dynamic strength increase factor (DIF), fractal dimension, and absorbed energy per unit volume of fiber-reinforced cement soil was analyzed, respectively. The relationship between fractal dimension and absorbed energy per unit volume was also analyzed.

2. Experimental Procedure

2.1. Experimental Materials. The silty clay used in this study was obtained from a construction site located in Huainan, Anhui Province. The physical properties and the particle size distribution of silty clay used in this study were measured according to GB/T 50123-1999 [14]. The test results of the physical properties and particle size distribution of original silty clay are shown in Tables 1 and 2.

The cement used in this investigation is P·O42.5 ordinary Portland cement with a qualified stability. The fineness of the cement reaches 2%.

Polypropylene fiber is a synthetic fiber, which has good tensile strength, elastic modulus, and other mechanical properties. As a fiber reinforcement material, polypropylene fiber was widely used in the fields of building materials, filling materials, and so on. The polypropylene fiber used in this paper was purchased from Huixiang company in Shandong, and its physic-mechanical properties are shown in Table 3.

2.2. Specimens Preparation and Experimental Methods. According to the previous studies [13, 15], the soil sample used in the present work was prepared with a water-cement ratio of 0.5 and the cement content of each specimen was selected at 15% by weight of dry soil. In the present study, the different polypropylene fiber contents of cement soil were designated as 0%, 0.4%, 0.8%, and 1.2%. The dimensions of all the soil specimens used in SHPB test are $\phi 50\,mm \times 25\,mm$. The detailed preparation process of soil specimens is as follows: (1) the natural soil was crushed and passed through a 2 mm sieve, then removed the size of soil particles bigger than 2 mm; (2) the left soil particles were put in a dry oven at 105°C for about 24 hours; (3) the dried soil, cement, and polypropylene fiber were fully mixed, then the required distilled water was added into the mixtures; (4) the mixtures were uniformly stirred and mixed, then the mixtures were placed in a closed container for 24 hours; (5) the prepared mixtures were placed into a compacting mold and were compacted at least three times; (6) all the soil specimens prepared in this study need to satisfy the optimum moisture content of 21.52% and the maximum dry density of 1.71 g/cm^3; (7) the prepared soil samples were placed in a standard curing room with a

Table 1: Physical properties of silty clay.

Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Maximum dry density (g/cm^3)	Optimum moisture content (%)
34.80	22.97	11.83	1.71	21.52

Table 2: Particle size distribution of silty clay.

Grain size (mm)	Percent finer by weight (%)
$1 < d \leq 2$	2.20
$0.5 < d \leq 1$	8.87
$0.25 < d \leq 0.5$	15.05
$0.075 < d \leq 0.25$	10.51
$0.005 < d \leq 0.075$	43.23
$d \leq 0.005$	20.14

temperature of (20 ± 2)°C and a relative humidity of 95% and cured for 28 days.

For each polypropylene fiber dosage, the dynamic compression test (namely, SHPB test) was performed with 4 parallel soil samples. In order to ensure the validity of the experimental results, the soil specimen with bigger experimental errors would be discarded.

As shown in Figure 1, a 50 mm diameter split Hopkinson pressure bar (SHPB) device was adopted in this study to perform the dynamic compression tests. The SHPB device is mainly composed of a striker bar, an incident bar, a transmitted bar, a launch device, a buffer device, a dynamic data acquisition system, and a data processing system. In this study, two types of strain gauges were selected for SHPB test. Because of the low wave impedance of the cement soil, the transmitted signal is relatively weak. Thus, it is difficult for the ordinary foil-type resistance strain gauge to accurately record the transmitted strain signal. Based on the previous research [16], the sensitivity coefficient of semiconductor strain gauge is 110, which is about 50 times than that of the ordinary foil-type resistance strain gauge. Consequently, the application of semiconductor strain to capture the transmitted strain signal of cement soil in dynamic compression tests is a feasible method. Finally, the transmitted strain signal was collected by the semiconductor strain gauge on the transmitted bar, and the incident strain signal and the reflected strain signal were recorded by the ordinary foil-type resistance strain gauge on the incident bar.

The principle of SHPB test is based on the assumptions of one-dimensional stress wave and stress uniformity [17], that is, without considering the strain rate effect of the pressure bar, and the two-dimensional dispersion effect of the stress wave propagates between the pressure bar and specimen. In addition, when the stress wave has at least two transmission-reflection processes through the sample, the stress can be regarded as equal everywhere inside the sample. In order to reduce the dispersion effect and the friction effect [18], some measures were adopted in this test as follows: (1) adjusting the position of the striker bar, incident bar, and transmitted bar to make the soil sample in the same axial position with the three pressure bars; (2) reducing the waveform shocking phenomenon and dispersion effect by using the wave shape technique; (3) smearing the sufficient vaseline on both ends of soil sample to reduce the friction effect. After adopting the above measures, the original waveforms collected from SHPB tests are shown in Figure 2. Based on one-dimensional wave propagation theory, the stress, strain, and strain rate of soil sample can be obtained from the following equations:

$$\begin{cases} \sigma(t) = \dfrac{E_0 A_0}{2A_1}\left(\varepsilon_{\mathrm{I}}(t) + \varepsilon_{\mathrm{R}}(t) + \varepsilon_{\mathrm{T}}(t)\right), \\ \varepsilon(t) = \dfrac{c}{l_1}\displaystyle\int_0^t \left(\varepsilon_{\mathrm{I}}(t) - \varepsilon_{\mathrm{R}}(t) - \varepsilon_{\mathrm{T}}(t)\right)dt, \\ \dot{\varepsilon}(t) = \dfrac{c}{l_1}\left(\varepsilon_{\mathrm{I}}(t) - \varepsilon_{\mathrm{R}}(t) - \varepsilon_{\mathrm{T}}(t)\right), \end{cases} \tag{1}$$

where $\sigma(t)$, $\varepsilon(t)$, and $\dot{\varepsilon}(t)$ are stress, strain, and strain rate, respectively; E_0, A_0, and c are Young's modulus, cross-sectional area, wave velocity of pressure bar, respectively; A_1 and l_1 are the cross-sectional area and length of soil specimen; $\varepsilon_{\mathrm{I}}(t)$, $\varepsilon_{\mathrm{R}}(t)$, and $\varepsilon_{\mathrm{T}}(t)$ represent the incident, reflected, and transmitted strain pulse collected from SHPB tests.

The longitudinal wave velocity of the soil sample was measured about 1850 m/s, and the time for the stress wave to complete a transmission-reflection process in the axial direction of soil specimen is about 27.0 μs. It can be observed from Figure 2 that the time of rising edge of the stress wave is about 100 μs and the stress wave generates about 4 transmission-reflection processes in the axial direction of the soil specimen. Therefore, the collected stress wave meets the condition of stress uniformity [19].

3. Dynamic Mechanical Properties of Cement Soil

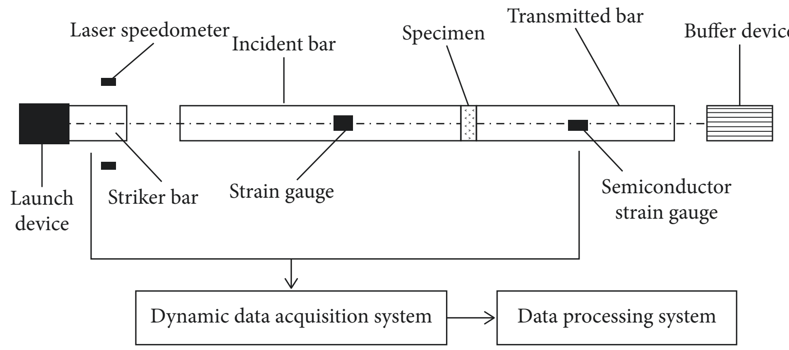
3.1. Dynamic Stress-Strain Curve. At 0.45 MPa impact loading pressure, the dynamic stress-strain curves of cement soil reinforced with different polypropylene fiber contents are shown in Figure 3. In order to further investigate the difference between dynamic mechanical behaviors and static mechanical behaviors, the static unconfined compression tests were performed with the uniaxial compression testing machine and the loading rate of static compression test was set at 1 mm/min. The cement soil specimen used in static compression test has a length of 100 mm and a diameter of 50 mm. Figure 4 presents the static stress-strain curves of the cement soil with various polypropylene fiber contents.

From Figure 3, it can be easily observed that the dynamic stress-strain curves of cement soil can be divided into three stages, namely, approximately elastic deformation stage, plastic deformation stage, and failure stage. In the approximate elastic deformation stage, the stress increases linearly with the increase in strain. During the plastic deformation stage, the growth rate of stress slows down with

Table 3: Physic-mechanical properties of polypropylene fiber.

Average length (mm)	Diameter (μm)	Tensile strength (MPa)	Elastic modulus (MPa)	Density (g/cm^3)	Elongation at break (%)
9	18–48	≥460	≥2500	0.91	5–20

(a)



(b)

Figure 1: The split Hopkinson pressure bar (SHPB) device and its schematic diagram: (a) SHPB device; (b) schematic diagram.

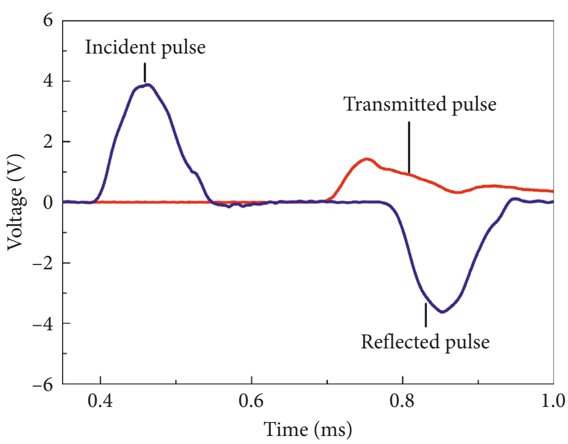


Figure 2: Original waveform diagram.

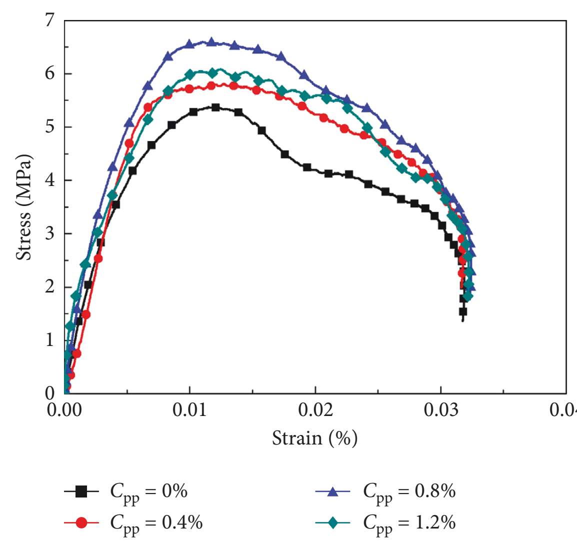


Figure 3: Dynamic stress-strain curves of polypropylene fiber-reinforced cement soil.

the increase of strain until the stress obtains its peak value. In the last stage, namely, failure stage, there is a sudden drop in stress with the slight increase of strain. Figure 3 also shows that with the increase of the polypropylene fiber content, the corresponding peak stress of the cement soil increases firstly and decreases subsequently. When the fiber content is 0.8%, the peak stress reaches its maximum value, which indicates a good dynamic compressive capacity of polypropylene fiber-reinforced cement soil compared with unreinforced cement soil. Moreover, the variation trend of ultimate strain of cement soil with various polypropylene fiber contents is not remarkable. It is directly found from Figure 3 that all the ultimate strains of cement soil with various polypropylene fiber contents are approximately converged on 3.20×10^{-2}.

It can be seen from Figure 4 that the inclusion of polypropylene fiber has an obvious influence on the static stress-strain curves of cement soil. The static stress-strain curves are different under various polypropylene fiber dosages, which show different compressive ability in static condition. For the cement soil without polypropylene fiber inclusion (polypropylene fiber dosage of 0%), the stress increases briskly until the peak stress is obtained. After that, a sharp reduction in stress can be observed. This phenomenon indicated the strain softening and brittle properties of cement soil without polypropylene fiber. The stress of cement soil reinforced with polypropylene fiber presents a slightly decreasing trend after the peak stress point, indicating that the inclusion of fiber plays an important role in changing the failure behavior of treated soil. The polypropylene fiber-reinforced cement soil shows a strain hardening behavior, which is a characteristic of the ductile trend. This experimental result of fiber reinforcement is similar to the research achievements of Jamsawang et al. [20]. When the polypropylene fiber content is in the range of 0%~1.2%, the peak stress and the failure strain increase firstly and then decrease with increase in fiber content.

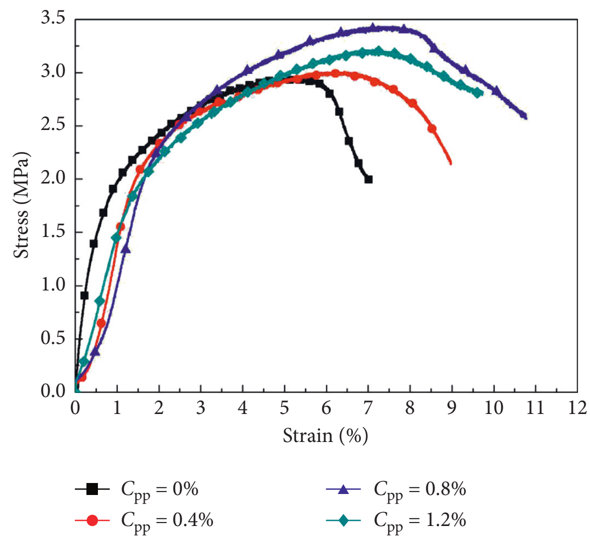


FIGURE 4: Static stress-strain curves of polypropylene fiber-reinforced cement soil.

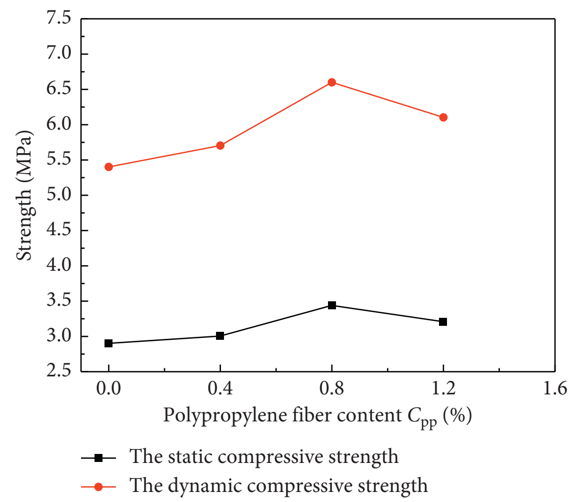


FIGURE 5: The dynamic and static compressive strength of cement soil with different polypropylene fiber contents.

Under the fiber content of 0.8%, the peak stress and the failure strain reach their maximum values of 3.43 MPa and 7.53×10^{-2}, respectively. It is easily found that the inclusion of fiber can directly change the sudden failure behavior and improve the static compressive strength of cement soil.

The peak stress of static and dynamic stress-strain curves is defined as static and dynamic compressive strengths, respectively. Figure 5 compares the results of dynamic compressive strength with the static compressive strength of cement soil under different polypropylene fiber contents. The static and dynamic compressive strengths presented in Figure 5 are the average values of several specimens for the same polypropylene fiber dosage. It can be seen from Figure 5 that the dynamic compressive strengths of cement soil reinforced with different polypropylene fiber contents of 0.4%, 0.8%, and 1.2% are 5.70 MPa, 6.60 MPa, and 6.10 MPa, respectively. The dynamic compressive strength increases firstly and then decreases with the increasing polypropylene fiber content. With the polypropylene fiber content of 0.8%, the dynamic compressive strength reaches its maximum value, which is 22.22% higher than that of ordinary cement soil (the polypropylene fiber content is 0%). In addition, the static compressive strengths of cement soil are 3.00 MPa, 3.43 MPa, and 3.20 MPa corresponding to the polypropylene fiber dosages of 0.4%, 0.8%, and 1.2%. The static compressive strength of cement soil reaches its maximum value under the condition of 0.8% polypropylene fiber inclusion, which is 18.41% higher than that of cement soil without polypropylene fiber.

The reasons of the enhancement in dynamic and static compressive strength can be explained as follows: the reinforcement effect has a certain influence on the improvement of strength of cement soil [21]. With the inclusion of polypropylene fiber into cement soil, a stable three-dimensional internal structure was gradually formed [22]. When the polypropylene fiber content is 0.8%, enough fibers intersect with each other inside cement soil. The surfaces of polypropylene fiber were fully wrapped and connected with hydration products and soil matrix, resulting in high interfacial bonding [13, 22]. The three-dimensional internal structure reaches its optimization, namely, the best stable three-dimensional internal structure was formed [22]. Accordingly, the corresponding compressive strength has been enhanced significantly. Besides, the addition of polypropylene fiber into cement soil can prevent the movement of the cement-soil particles and alleviate the development of cracks [20], so the strength of cement soil has been improved correspondingly. From another point of view, when the specimens are subjected to static loading or impact loading, the “bridge” effect of fiber can efficiently impede further extension of microcracks and the deformation of the cement soil [7]. However, when the fiber content excesses its optimum value, excessive polypropylene fibers aggregated and accumulated inside cement soil. Thus, a large number of fiber-fiber weak surfaces formed inside soil specimens, which have a trend to slide and damage under external loading [13]. With the polypropylene fiber of 1.2%, the static and dynamic compressive strength of cement soil have a common behavior of the downward trend.

What’s more, it can be easily found that the dynamic compressive strength of cement soil is much larger than the static compressive strength at the same dosage of polypropylene fiber. The explanations of this phenomenon are presented in the following section of the analysis of dynamic strength increase factor.

3.2. Relationship between Dynamic Strength Increase Factor and Polypropylene Fiber Content. In order to effectively analyze the influence of different polypropylene fiber contents on the static and dynamic compressive strength of cement soil, the dynamic strength increase factor (DIF) was introduced for the comparison between static and dynamic compressive strength, the calculated equation as follows:

$$\mathrm{DIF} = \frac{\sigma_d}{\sigma_s}, \tag{2}$$

where σ_d is the dynamic compressive strength of polypropylene fiber-reinforced cement soil, MPa, and σ_s denotes the static compressive strength of polypropylene fiber-reinforced cement soil that has the same fiber content with the dynamic compression tests, MPa.

The DIF values of polypropylene fiber-reinforced cement soil under four types of fiber dosage conditions are listed in Table 4. For each group of static and dynamic compression test, the soil specimens with smaller data errors were selected for next analysis. The average value of DIF was calculated by the DIF values of three soil samples. Subsequently, the average value of DIF has been chosen as the final DIF value used for analysis and discussion. The larger the DIF value, the greater the increase of strength of the cement soil under impact loading [23, 24].

It can be seen from Table 4 that with the polypropylene fiber content of 0.8%, the average value of DIF reaches its biggest value compared with other fiber dosages. This phenomenon indicates that the dynamic compressive strength of cement soil with 0.8% polypropylene fiber content has the most obvious enhancement in strength. Moreover, the dynamic compressive strength of fiber-reinforced cement soil is notably greater than the static compressive strength under the same polypropylene fiber content. Thus, all the DIF values in Table 4 are over 1. This could be explained by the situation where the cement soil is approximately under a condition of confining pressure in the SHPB test and the deformation of cement soil was constrained [23, 25]. Under the restraining action, the propagation and extension of the microcracks inside cement soil are limited, and the frictional force and bonding force among soil particles have been enhanced significantly [7]. As a result, the dynamic compressive strength of cement soil has been improved correspondingly.

In addition, the dynamic strength increase factor of cement soil increases firstly and then decreases as the polypropylene fiber content increases from 0% to 1.2%. The relationship between the average value of DIF and polypropylene fiber content is exhibited in Figure 6. From Figure 6, the correlation coefficient of fitting equation is 0.993. It is clearly observed that there is a quadratic parabolic relationship between the average value of DIF and polypropylene fiber content.

4. Fractal Characteristics of Cement Soil Fragmentation

4.1. Distribution of Impact Broken Fragments. The failure modes of polypropylene fiber-reinforced cement soil under impact loading are shown in Figure 7.

Figure 7 shows the size and quantity of the impact broken fragments of cement soil with different polypropylene fiber contents are significantly different. After the unreinforced cement soil is destroyed by impact loading, the size of fragments around the broken sample is small and many powdery particles appear in broken sample. With the polypropylene fiber increasing from 0.4% to 1.2%, the number of fragments gradually decreases and the grain size of fragments becomes bigger directly. It can be found that the degree of damage for specimens decreases gradually as the polypropylene fiber content increases. From the perspective of failure mode, when the impact loading pressure is constant, the cement soil fragments gradually change from powdery particles to massive particles and the grain size of cement soil fragments gradually increases with increasing polypropylene fiber content. Therefore, the addition of polypropylene fiber can change the failure mode of cement soil to some extent.

In order to quantitatively analyze the influence of polypropylene fiber content on the impact damage degree of cement soil, the average particle size D of impact broken fragments is introduced for the following comparison and analysis, and the corresponding equation is as follows:

$$D = \frac{\sum_{r=1}^{10} r_i d_i}{\sum_{i=1}^{10} r_i}, \tag{3}$$

where d_i is the average of the largest particle size and the smallest particle size of the fragments in different grades of standard sieve; r_i is the percentage of the mass of the fragments corresponding to d_i as a percentage of the total mass of the fragments.

After the dynamic compression test, the 0–0.15 mm, 0.15–0.3 mm, 0.3–0.6 mm, 0.6–1.18 mm, 1.18–2.36 mm, 2.36–4.75 mm, 4.75–9.5 mm, 9.5–16 mm, 16–26.5 mm, and 26.5–31.5 mm standard sieves of 10 grades were used to screen the impact broken pieces of polypropylene fiber-reinforced cement soil. The weight of crushed pieces in each grade standard sieve was measured by the high-sensitivity electronic scale. The screening results and the average particle size D are shown in Table 5.

Table 5 shows that with the increase of polypropylene fiber content, the percentage of smaller-size fragments (the size of fragments below 2.36 mm) to the total mass of the fragments gradually decreases from 21.74% to 16.95%. The percentage of bigger-size fragments (the size of fragments above 26.5 mm) to the total mass of the fragments gradually increases from 21.63% to 26.13% with the increase in polypropylene fiber content. Besides, the percentage of medium-size fragments (the size of fragments between 2.36 mm and 26.5 mm) to the total mass of the broken fragments shows a slight increasing trend with the increase of polypropylene fiber content. Furthermore, it is easily found that the average particle size of cement soil broken fragments gradually increases as the polypropylene fiber content increases from 0% to 1.2%. The reason is that with the inclusion of polypropylene fiber, the bite force and friction force between the polypropylene fiber and cement soil have a significant improvement [26]. Moreover, the polypropylene fibers interweaved inside cement soil to form a space structure system, which also has resulted in the enhancement of integrality of cement soil [13, 26]. When the cement soil is subjected to the impact loading, the bite force, friction force, and the stable space structure system can work together to effectively restrict the generation and expansion of microcracks inside cement soil. As a result, with the increase of polypropylene fiber content, the large-size and medium-size fragments present an increasing trend, and the small-size fragments show a reducing

Table 4: DIF values of cement soil with different polypropylene fiber contents.

Polypropylene fiber content		0%			0.4%			0.8%			1.2%	
σ_d (MPa)	5.30	5.40	5.50	5.70	5.60	5.70	6.50	6.60	6.70	6.10	6.10	6.20
σ_s (MPa)	2.88	2.91	2.90	3.02	2.95	3.00	3.39	3.43	3.47	3.21	3.20	3.24
DIF	1.84	1.86	1.87	1.89	1.90	1.90	1.92	1.92	1.93	1.90	1.91	1.91
Average value of DIF		1.86			1.90			1.92			1.91	

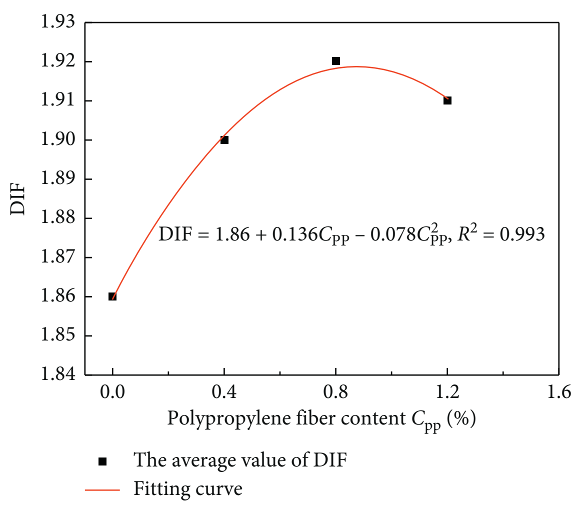


Figure 6: Relationship between DIF and polypropylene fiber content.

trend. Thus, the average particle size of impact broken fragments also increases gradually.

4.2. Calculation of Fractal Dimension. Fractal dimension is a quantitative description of the impact broken fragments of polypropylene fiber-reinforced cement soil, which can directly reflect the failure degree of polypropylene fiber-reinforced cement soil under impact loading [27]. The distribution equation of cement soil broken fragments can be obtained by G-G-S distribution function model [28] and mass-frequency relationship [29]:

$$y = \frac{M_r}{M_T} = \left(\frac{r}{r_m}\right)^b, \tag{4}$$

where r is the particle size of the broken fragments; r_m is the maximum particle size of the broken fragments; and b is the distribution parameter, which is numerically equal to the slope of the $\ln[M_r/M_T]-\ln r$ curve.

Based on the fractal dimension D_b of the broken fragments, the particle size r of the broken fragments, and the number of the broken fragments (N), which are larger than the particle size r, the formula of the fractal dimension can be obtained as follows:

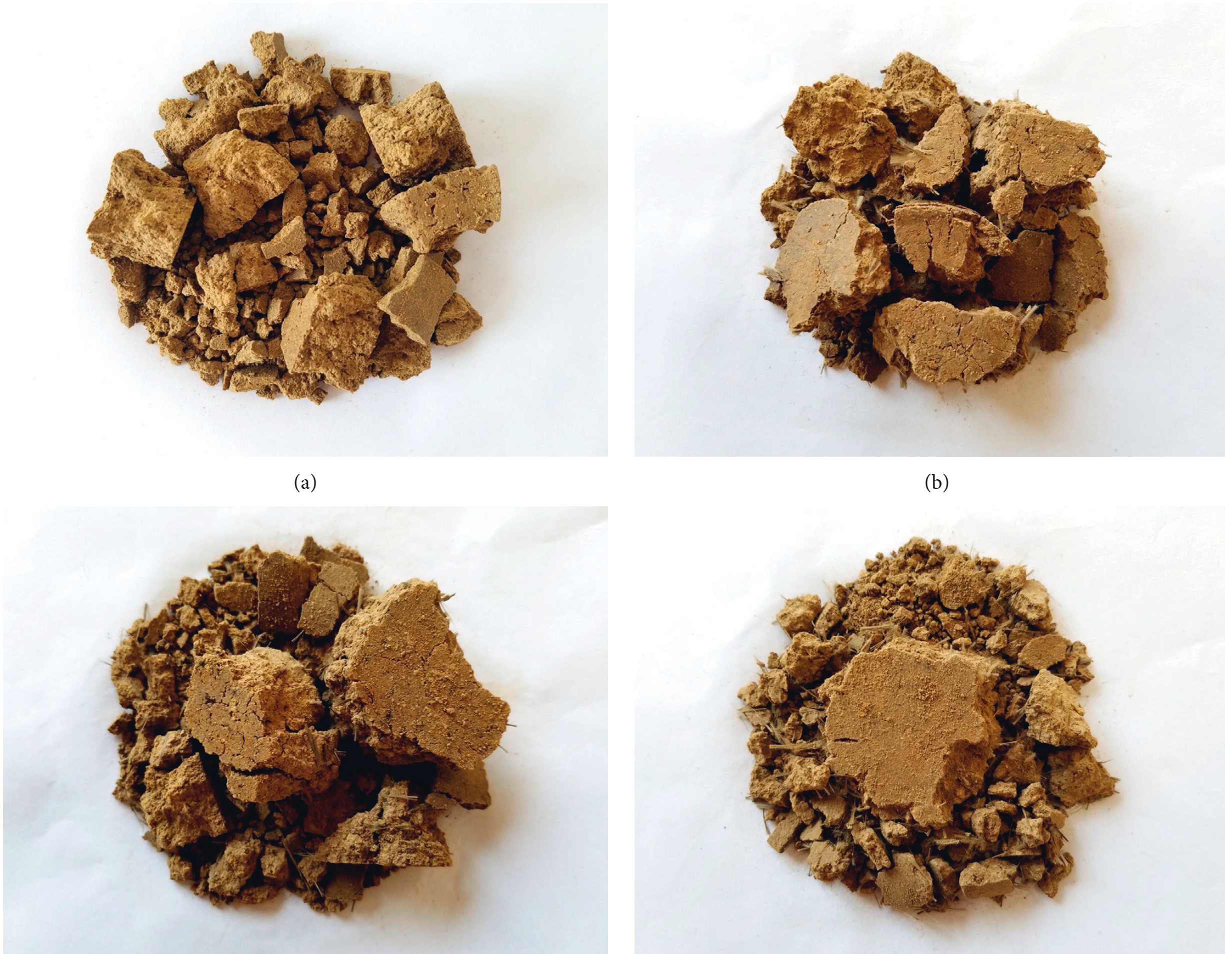
$$N = r^{-D_b}. \tag{5}$$

Considering the relationship between the number of fragments and the mass increment of fragments ($dM \propto r^3 dN$), the fractal dimension D_b of the fragments can be calculated by the mass-grain method [30], that is $D_b = 3-b$. Therefore, the fractal dimension of the broken fragments can be obtained by calculating the slope of the $\ln[M_r/M_T]-\ln r$ curve. Figure 8 exhibits the $\ln[M_r/M_T]-\ln r$ curve of cement soil reinforced with different polypropylene fiber contents.

It can be intuitively seen from Figure 8 that the linear fitting of experimental data presented under double logarithmic coordinate is very well. The fitting results showed that after SHPB tests, the distribution of crushed fragments of polypropylene fiber-reinforced cement soil has the fractal characteristics. A large number of inner damages (such as microcracks and defects) with self-similarity are randomly distributed inside cement soil within a certain range. These inner damages gradually develop under impact loading and finally evolve into the macroscopic breakage. The changing process of inner damages has a fractal property from the view of geometric statistics. From the fitting results, it is easy to calculate the fractal dimension. When the polypropylene fiber dosages of cement soil are 0%, 0.4%, 0.8%, and 1.2%, the slopes of the corresponding fitting straight lines are 0.87, 0.89, 0.93, and 0.96, respectively. According to the formula of $D_b = 3-b$, the corresponding fractal dimension values are 2.13, 2.11, 2.07, and 2.04, respectively. It can be found that the fractal dimension values decrease with the increase of polypropylene fiber content.

4.3. Relationship between Fractal Dimension and Polypropylene Fiber Content. According to the analysis of experimental data, there is a certain correlation between the polypropylene fiber content and fractal dimension of cement soil. The experimental data of the fractal dimension value under different polypropylene fiber contents and the fitting results are shown in Figure 9.

It can be observed from Figure 9 that the fractal dimension has a negative correlation with the polypropylene fiber content. The fractal dimension of impact fragments decreases obviously as the polypropylene fiber content increases from 0% to 1.2%. Given a reasonable explanation, the addition of polypropylene fiber can improve the toughness of cement soil due to the good bridging ability of fiber [20, 22]; thus, the degree of impact fragmentation for cement soil reduces correspondingly. With the increase of polypropylene fiber content, the number of impact fragments decreases, the particle size of impact fragments increases, the uniformity of impact fragments reduces, and the corresponding fractal dimension of fiber-reinforced cement soil decreases. What's more, using the fractal dimension values of impact fragments to analyze the impact fragmentation is consistent with the analysis results of the particle size distribution of impact fragments.



(a) (b) (c) (d)

Figure 7: Failure patterns of polypropylene fiber-reinforced cement soil in SHPB tests. (a) $C_{PP} = 0\%$, (b) $C_{PP} = 0.4\%$, (c) $C_{PP} = 0.8\%$, and (d) $C_{PP} = 1.2\%$.

Table 5: The screening result and the average particle diameter D.

C_{PP} (%)	Sieve size (mm)										Total mass (g)	D (mm)
	0	0.15	0.30	0.60	1.18	2.36	4.75	9.50	16.00	26.50		
0	0.55	0.97	2.06	3.15	6.09	7.13	5.06	15.17	31.73	19.85	91.76	16.56
0.4	0.43	0.87	2.02	3.13	5.94	5.88	4.86	12.76	34.11	22.52	92.52	17.41
0.8	0.37	0.61	1.97	2.82	5.38	5.16	4.54	12.56	35.31	23.34	92.06	17.94
1.2	0.29	0.59	1.87	2.60	5.47	4.83	4.23	12.77	35.56	24.13	92.34	18.18

4.4. Relationship between Fractal Dimension and Average Particle Size. Figure 10 shows the relationship between average particle size D and fractal dimension of polypropylene fiber-reinforced cement soil.

It is clearly observed from Figure 10 that the average particle size gradually reduces with the fractal dimension varying in the range of 2.04 to 2.15. The correlation coefficient of fitting result reaches 0.987. It can be easily found that there is a decreasing exponential relationship between average particle size and fractal dimension of impact broken fragments. That is to say, the average particle size decreases significantly with the increase of fractal dimension. The average particle size can intuitively express the distribution of impact fragments. From another point of view, the fractal dimension can quantitatively describe the degree of impact fragmentation. It can be concluded that the average particle size of cement soil has a certain negative correlation with the fractal dimension. In other words, the larger the average particle size, the smaller the fractal dimension, the fewer the number of fragments, and the larger the size of fragments.

5. Energy Dissipation Analysis of Cement Soil under Impact Loading

From the thermodynamic point of view, the work done by the external loading on the materials is not only used to

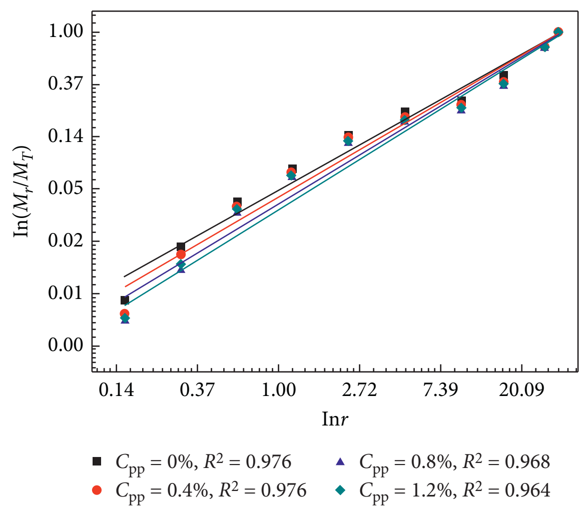


Figure 8: The ln[M_r/M_T]−ln$r$ curve of cement soil with different polypropylene fiber contents.

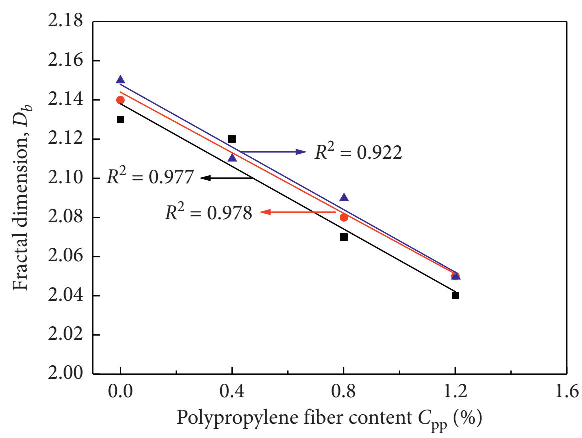


Figure 9: Relationship between fractal dimension and polypropylene fiber content.

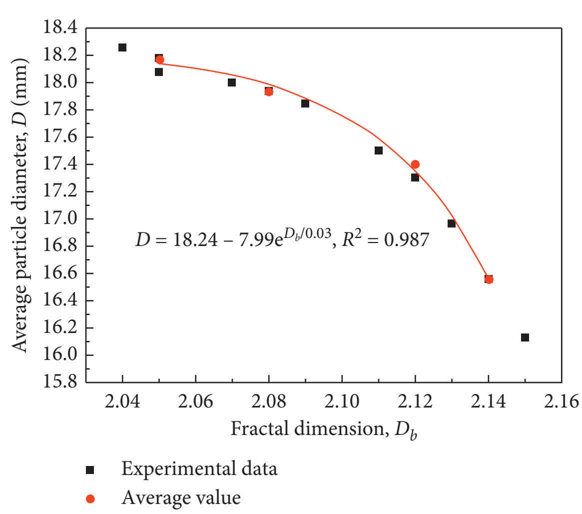


Figure 10: Relationship between average particle size and fractal dimension.

change the stress-strain state of the materials, but part of the work is also used for dissipated energy. The final result is the variation of the damage state of materials. The variation of damage state will further affect the change of stress-strain state. Actually, the deformation and damage of materials are the results of energy dissipation [31]. Therefore, the analysis of the energy dissipation of polypropylene fiber-reinforced cement soil under impact loading can accurately describe the essential characteristics of the dynamic mechanical behaviors and macroscopic failure patterns.

5.1. Energy Calculation in SHPB Tests. Based on the law of conservation of energy, the absorbed energy W_S, the incident energy W_I, the reflected energy W_R, and the transmitted energy W_T can be calculated by the following equation:

$$W_S = W_I - W_R - W_T. \quad (6)$$

The calculation formulas of incident energy W_I, reflected energy W_R, and transmitted energy W_T are as follows:

$$W_i = E_0 c A_0 \int_0^t \varepsilon_i^2 (t) dt, \quad i = I, R, T, \quad (7)$$

where $\varepsilon(t)$ represents the strain time history of stress wave; A_0, c, and E_0 represent the cross-sectional area, longitudinal wave velocity, and Young's modulus of the pressure bar, respectively.

Figure 11 indicates the energy-time variation curves of cement soil with different polypropylene fiber contents during impact loading.

From Figure 11, the whole energy-time variation curve can be divided into four stages. At the initial stage, the incident energy and absorbed energy of polypropylene fiber-reinforced cement soil increase lightly as time goes on. For the second stage, the incident energy and absorbed energy increases quickly compared with the initial stage. In the third stage, the growth rates of incident energy and absorbed energy slow down, which are similar to the growth rates of the initial stage. In the last stage, the incident energy and absorbed energy reach their maximum value, respectively; then the incident energy and absorbed energy maintain at a constant value. In addition, the absorbed energy values of cement soil reinforced with different polypropylene fiber contents are different, indicating the polypropylene fiber content has a certain influence on the energy absorption ability of fiber-reinforced cement soil.

In order to further analyze the relationship between polypropylene fiber content and absorbed energy, the time-history curves of absorbed energy are plotted in Figure 12. It can be found that the absorbed energy of fiber-reinforced cement soil is approximately ended at a constant value. The absorbed energy of ordinary cement soil (without polypropylene fiber inclusion) is 6.15 J, and the absorbed energy of cement soil with polypropylene fiber contents of 0.4%, 0.8%, and 1.2% are 7.11 J, 7.98 J, and 7.32 J, respectively. The absorbed energy of cement soil reinforced with polypropylene fiber is higher than that of ordinary cement soil. Moreover, with the increase of polypropylene fiber content, the absorbed energy of fiber-reinforced cement soil increases

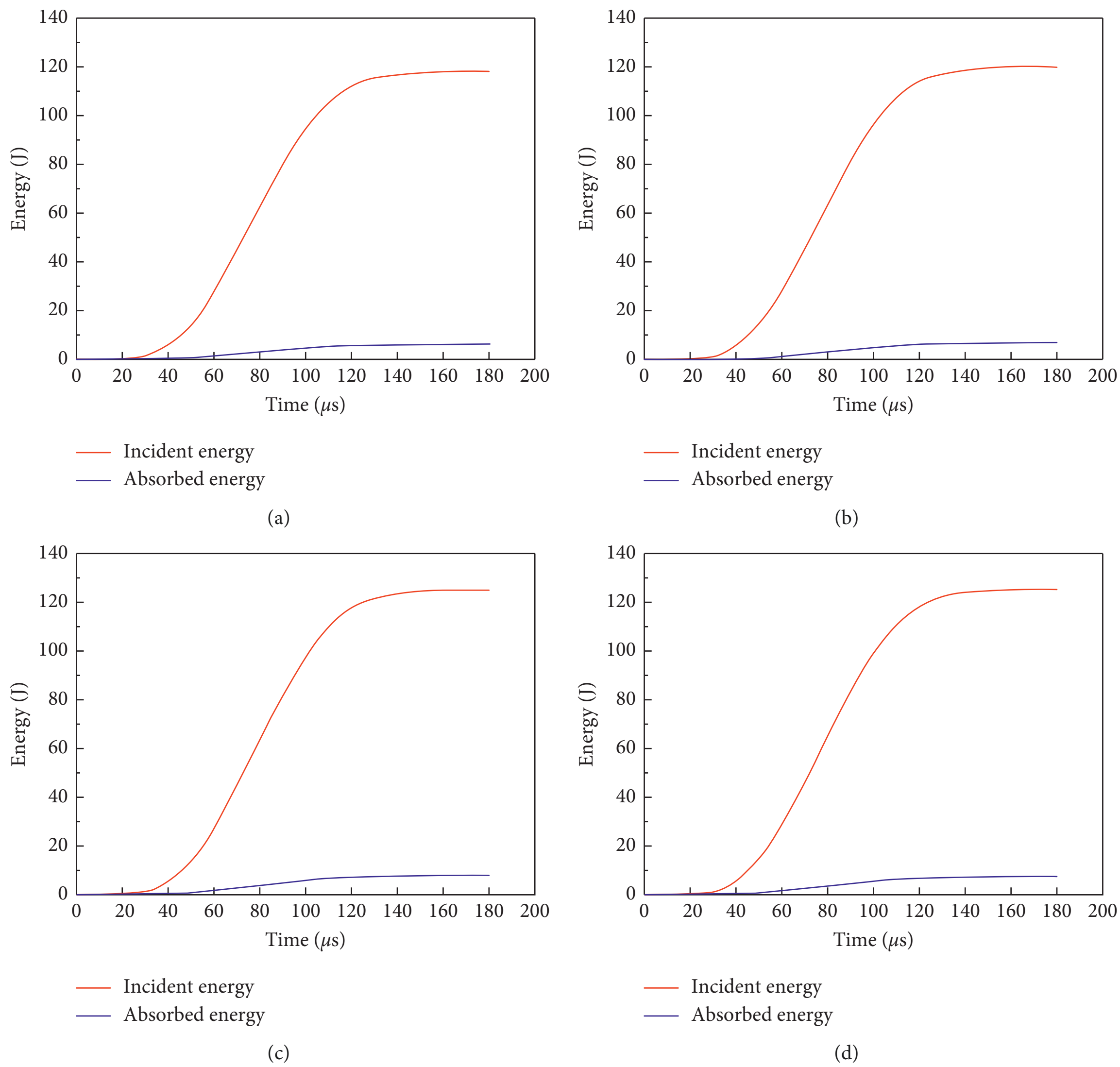


Figure 11: Energy-time variation curves of cement soil with different polypropylene fiber contents. (a) Polypropylene fiber content of 0%, (b) polypropylene fiber content of 0.4%, (c) polypropylene fiber content of 0.8%, and (d) polypropylene fiber content of 1.2%.

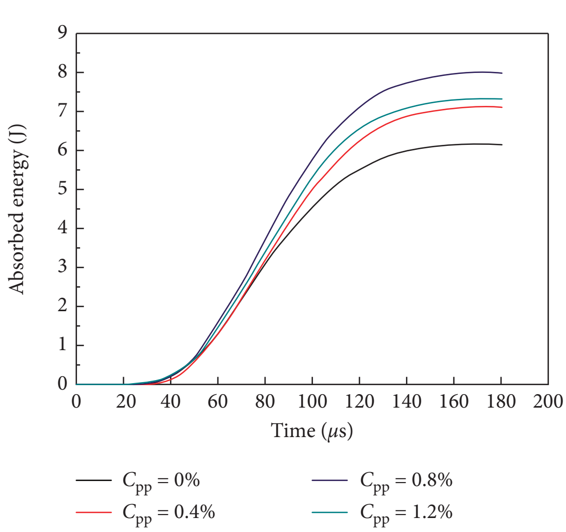


Figure 12: Time-history curve of absorbed energy.

firstly and decreases subsequently. The absorbed energy of cement soil reinforced with 0.8% polypropylene fiber reaches its maximum value, which is about 29.76% higher than that of unreinforced cement soil.

5.2. Relationship between Polypropylene Fiber Content and Absorbed Energy per Unit Volume. Under impact loading, the absorbed energy W_S is mainly composed of energy consumed by the expansion and penetration of the original cracks and new cracks, the kinetic energy of the impact fragments, and the energy dissipated by other forms such as acoustic energy, thermal energy, and so on. According to related studies [32], in the case of relatively low loading rate, the kinetic energy of the impact fragments and other forms of energy dissipation are considerably small components of the total absorbed energy. Therefore, it can be considered that the absorbed energy W_S of cement soil is equal to the energy consumed by the propagation and connection of original cracks and the new crack inside cement soil.

The absorbed energy per unit volume U is introduced to eliminate the errors of specimen size. The corresponding formula is as follows:

$$U = \frac{W_S}{A_1 l_1}, \quad (8)$$

where A_1 represents the cross-sectional area of soil sample and l_1 is the initial length of soil sample.

Figure 13 presents the relationship between absorbed energy per unit volume and polypropylene fiber content. It can be seen from Figure 13 that with the fiber content in the range of 0% to 0.8%, the absorbed energy per unit volume of cement soil increases remarkably. The cement soil reinforced with 0.8% polypropylene fiber has acquired a maximum value in absorbed energy per unit volume. However, the absorbed energy per unit volume of cement soil decreases gradually when fiber content increased from 0.8% to 1.2%. The reason of these observations is that the added fibers were closely wrapped by the cementitious compounds and soil matrix due to the increase of polypropylene fiber content. Besides, the integrality of internal structure of cement soil has been improved significantly [7, 13]. With the polypropylene fiber content of 0.8%, the polypropylene fiber has the best connection state with the cement soil matrix. When the fiber-reinforced cement soil is subjected to impact loading, the polypropylene fiber can fully exert its reinforcement effect and inhibit the extension of internal microcracks. Finally, because of the insufficient bonding force of the interface between the fibers and cement soil, the fibers present an obvious pull-out failure pattern. In addition, the process of the fibers being pulled out from the cement soil matrix will consume a large amount of energy [33]. Thus, the more strong the connection between fibers and cement soil matrix, the more dissipated energy of the fiber pull-out process. With the addition of excessive polypropylene fiber ($C_{pp} = 1.2\%$), too much fibers will cause the overlap phenomenon and form a fiber-fiber interface. The fiber-fiber interfaces are easy to damage as the cement soil under impact loading because the fiber-fiber interfaces inside cement soil are regarded as the weak interfaces [33]. The failure process of weak interfaces has lacked the pull-out phenomenon of fibers, so the absorbed energy per unit volume shows a decreasing trend.

5.3. Relationship between Fractal Dimension and Absorbed Energy per Unit Volume. The process of internal microcracks of cement soil generation, development, and connection has consumed a large amount of energy. In addition, the internal damages (microcracks and flaws) of cement soil gradually developed and eventually evolved into the macroscopic breakage, and this process has a statistical fractal property. In other words, the deformation and damage of cement soil under impact loading accompany with the energy dissipation. Therefore, the absorbed energy per unit volume has a substantial connection with the fractal dimension. The relationship between absorbed energy per unit volume and fractal dimension is shown in Figure 14.

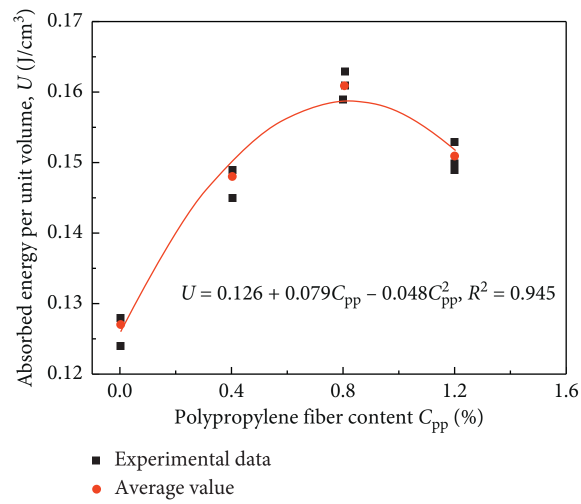


Figure 13: Relationship between absorbed energy per unit volume and polypropylene fiber content.

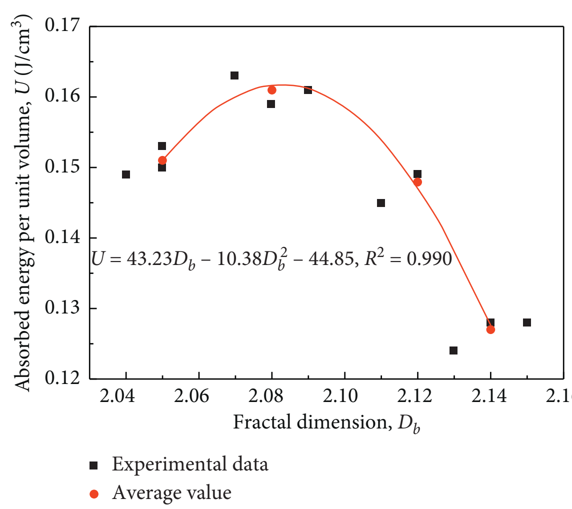


Figure 14: Relationship between absorbed energy per unit volume and fractal dimension.

From Figure 14, it can be easily found that the average values of absorbed energy per unit volume with different fractal dimension values of 2.04, 2.08, 2.12, and 2.14 are 0.151 J/cm^3, 0.161 J/cm^3, 0.147 J/cm^3, and 0.127 J/cm^3, respectively. The average value of absorbed energy per unit volume keeps an increasing trend with the increase of fractal dimension value until the fractal dimension value reaches 2.08. Furthermore, when the fractal dimension value of cement soil is 2.08, the average value of absorbed energy per unit volume reaches its maximum value of 0.161 J/cm^3, which is 26.77% higher than that of cement soil with the biggest fractal dimension value of 2.14. However, as the fractal dimension value exceeds 2.08, the average value of absorbed energy per unit volume decreases gradually as the fractal dimension shows an increasing tendency. Meanwhile, it can be observed that the average value of absorbed energy

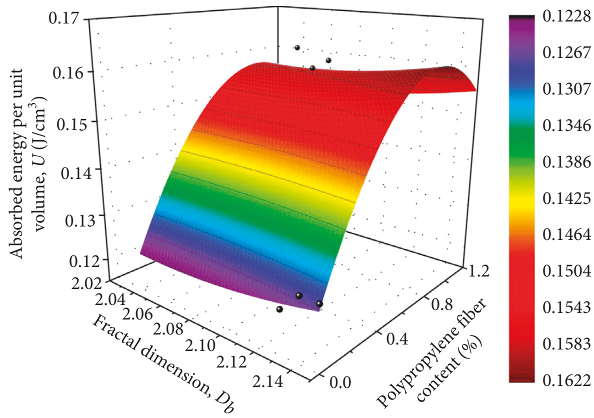


Figure 15: Relationship of absorbed energy per unit volume with fractal dimension and polypropylene fiber content.

per unit volume has a quadratic parabola relationship with the fractal dimension value through the curve fitting.

5.4. Relationship of Absorbed Energy per Unit Volume with Fractal Dimension and Polypropylene Fiber Content. The relationship of fractal dimension (D_b), polypropylene fiber content (C_{PP}), and absorbed energy per unit volume (U) is fitted in Figure 15. With the polypropylene fiber content varying in the range of 0% to 1.2% and the fractal dimension varying in the range of 2.04 to 2.15, the fitting equation is as follows:

$$U = 2.100 - 1.920D_b + 0.085C_{\mathrm{PP}} + 0.466D_b^2 - 0.051C_{\mathrm{PP}}^2,$$
$$R^2 = 0.94. \tag{9}$$

The above fitting relationship can provide a reference for further studies of the energy absorption behaviors and fractal phenomenon of the fiber-reinforced cement soil under impact loading. Because the energy absorption ability and fractal behaviors can be considered as the important indices to reflect the impact properties of materials, the investigation of this test can become a valuable base for the further research in practical engineering. The inclusion of polypropylene fiber into cement soil can effectively enhance the impact resistance and energy absorption ability; thus, the polypropylene fiber-reinforced cement soil can be used as filling material in base/subbase layers of airport runway. Moreover, the combination of fiber and cement can be regarded as a good reinforcement method in national defense engineering or other practical engineering.

6. Conclusions

In the present study, the dynamic mechanical properties and fractal characteristics of reinforced cement soil with different polypropylene fiber dosages were investigated using a 50 mm diameter SHPB device system. The following conclusions can be drawn:

(1) Under impact loading, the dynamic strength increase factor (DIF) increases firstly and then decreases with an increase in polypropylene fiber content from 0 to 0.8%. The maximum value of DIF is 1.92 with the polypropylene fiber content of 0.8%. The polypropylene fiber content and DIF value present a quadratic parabola relationship.

(2) The distribution of impact broken fragments of polypropylene fiber-reinforced cement soil under impact loading has a good fractal characteristic. With the polypropylene fiber content increasing from 0% to 1.2%, the average particle size of impact broken fragments increases directly and the fractal dimension decreases gradually. There is a good linear relationship between fractal dimension and polypropylene fiber content. In addition, it is easily found that there is a decreasing exponential relationship between fractal dimension and average particle size.

(3) The polypropylene fiber dosage has a certain influence on the absorbed energy per unit volume of cement soil. With enhancing polypropylene fiber content from 0% to 1.2%, the absorbed energy per unit volume increases firstly and decreases subsequently. When adding 0.8% polypropylene fiber into cement soil, the absorbed energy per unit volume of cement soil reaches its maximum value of 0.161 J/cm^3. The absorbed energy per unit volume and the polypropylene fiber content have a secondary parabola relationship.

(4) The absorbed energy per unit volume increases firstly and then decreases with the fractal dimension varying in the range of 2.04 to 2.15. There is a quadratic parabola relationship between absorbed energy per unit volume and fractal dimension. Finally, the relationship among the absorbed energy per unit volume, fractal dimension, and polypropylene fiber content can be expressed by an empirical equation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

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