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Study on the Tensile Properties and Application of Gravelly Soil Reinforced by Polypropylene Fiber

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ABSTRACT

Incorporating fibers into gravelly soil is an effective method to prevent the core wall of high earth core rockfill dams (ECRDS) from cracking. In this study, a new type of soil tensile device was used to carry out tensile tests on gravelly soil with different gravel contents and fiber contents. The test results show that as the gravel content increases from 0% to 50%, the improvement in tensile strength decreases from 48.9% to 6.4%, which means the increase in gravel content reduces the improvement in tensile strength significantly. The ultimate tensile strain, tensile strength, and post-peak tensile strength of fiber-reinforced gravelly soil are positively correlated with the fiber content. Combined with the Scanning electron microscopy (SEM) results, the reinforcement effect of the three types of fiber interfaces on the gravel soil is qualitatively analyzed, and the microscopic mechanism of the improvement of the tensile strength of fiber-reinforced gravelly soil is revealed. The energy absorption capacity (EAC) results showed that the lower the gravel content in the soil, the higher the degree of improvement in the EAC value. In practical application, it is recommended to use gravel soil with low gravel content and high fiber content. Finally, a regression model considering the gravel content and fiber content was proposed for fast predicting the tensile strength of the soil. The related results can provide references for the anti-cracking design of the core wall of high ECRDS.

1. Introduction

Earth-rock dams (ECRDs) are the oldest type of dam. The construction technology of modern ECRDs has been developed since the 1950s. At present, ECRDs are the most widely used and fastest growing type of dams in the world.

Gravelly soil is often used as the core material of high ECRDs to increase the deformation modulus of the core. According to statistics, in nearly 70% of the ECRDs taller than 100 m, gravelly soil is used as the core material constantly. Almost all of the extra-high ECRDs over 200 m which are under construction or have been built use gravelly soil as the core material. Although the incorporation of gravel reduces difference of the deformation modulus between the core and the rockfill, it also decreases the tensile strength of the soil significantly (Ji et al., 2019; Ji et al., 2020). Thus the risk of cracking in the core zone is about to increase.

From the perspective of dam safety prevention and control, the crack resistance of gravelly soil needs to be improved. At present, researchers have adopted various methods to improve the crack resistance of the soil. Some of these researchers use the method of adding chemical stabilizers (lime, cement, fly ash, etc.) to the soil (Consoli et al., 2011; Das et al., 2011). As a consequent, the tensile strength of the soil can be improved via chemical stabilization between soil particles. However, the above method tends to reduce the plasticity index and ductility of the soil, leading to an increase in the probability of brittle fracture, which is not conducive to its stability control. In recent years, fiber-reinforced methods have been widely used for soil improvement and reinforcement. Researchers conducted extensive research on the mechanical properties of soil mixed with fibers through laboratory experiments, and obtained many meaningful conclusions. Studies have shown that the incorporation of fibers improves the shear strength parameters (C and φ) (Consoli et al., 1998; Prabakar and Sridhar, 2002; Akbulut et al., 2007), unconfined compressive strength (Kaniraj and Havanagi, 2001; Deng et al.,

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2017), crack resistance and seepage resistance properties (Mesbah et al., 2004; Miller and Rifai, 2004; Harianto et al., 2008; Tang et al., 2016; Liang et al., 2018) of the soil. Previous studies have also shown that in addition to the type and content of fibers, the length of fibers (Santoni et al., 2001; Mesbah et al., 2004; Divya et al., 2014) is also an important factor affecting the tensile properties of fiber-reinforced soils. Although mixing discrete and randomly distributed fibers in conventional soils can improve the cracking resistance to a certain extent, for gravelly soil (soil mixed with gravel), the influence of fiber on its cracking resistance is less studied. The authors previously carried out tests on fiber-reinforced gravelly soils and came to some conclusions (Zhang et al., 2021), but the variation pattern and mechanical mechanism of the tensile properties of this type of reinforced soil are still unclear.

Based on the abovementioned research background, this paper aims to study the tensile properties of fiber-reinforced gravelly soil. By developing a new type of soil tensile device, 20 sets of tensile tests were performed to analyze the variation pattern of the stress-strain relationship, crack resistance and energy absorption capacity (EAC) of the specimens. Additionally, the microscopic reinforcement mechanism of fiber-reinforced gravelly soil was revealed through scanning electron microscopy (SEM) combined with test results. Further, recommendations in field applications of fiber-reinforced gravel soil are given. Finally, a regression model considering fiber content and gravel content was proposed to directly predict the tensile strength of the soil. The related results can provide references for the anti-cracking design of high ECRDs core wall.

2. Materials and Methods

2.1 Materials

The clayey soil used in the tensile test is from the core material of Lianghekou ECRD. According to the standard Proctor test (ASTM D2488, 2000), the sieving method and the densitometer method are used to conduct particle analysis of the soil. Fig. 1 showns the particle size distribution curve. The basic parameters of the soil according to the standard Proctor test (ASTM D2487, 2000) are shown in Table 1. Rockfill material from Lianghekou

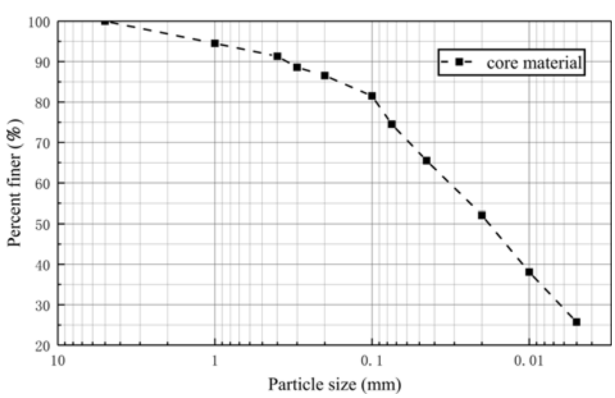


Fig. 1. Clay Particle Size Distribution Curve

Table 1. Basic Parameters of the Soil

Soil physical properties		Value
Specific gravity		2.75
Consistency limit	Liquid limit (%)	28.1
	Plastic limit (%)	16.3
	Plasticity index (%)	11.8
Standard compaction test	Optimum moisture content (%)	13.11
	Maximum dry density (g/cm^3)	1.89

Table 2. Common Physical and Mechanical Indicators of the PP Fiber

Property	Value
Density (g/cm^3)	0.91
Average diameter (mm)	0.033
Breaking tensile strength (Mpa)	469
Modulus of elasticity (Mpa)	4236
Ultimate elongation (%)	28.4
Melting point (°C)	169

ECRD was crushed and screened to obtain the appropriate particle size in this test. Based on the standard Proctor test (ASTM D4767-02, 2000), the maximum gravel size should be less than 1/5 of the fracture zone length of the specimen. The maximum size and minimum size of gravel are set to 10 mm and 5 mm, respectively.

Due to the advantages of a low price, high strength and toughness, high chemical resistance and microbial resistance, polypropylene (PP) fiber was used in the test. Moreover, PP fiber has a high mixing degree with soil particles after antistatic treatment compared with other fibers. Its common physical and mechanical indicators are listed in Table 2.

2.2 Tensile Device

Previous studies have shown that tensile test of soils are mainly divided into two categories: direct tensile test and indirect tensile test. Indirect tensile tests include flexural beam tests (Leonards and Narain, 1963; Viswanadham et al., 2010), Brazilian tensile test (Narain and Rawat, 1970) and double punch test (Kim et al., 2012). It should be noted that the above indirect test methods usually have a certain degree of assumptions and limitations.

In order to visually observe the process of soil failure, a direct tensile test method was adopted in this test. Fig. 2 shows some common methods to conduct direct tensile test. The most conventional method is using a cementing material to bond the end of the specimen to carry out the test (Zhu et al., 2008; Zhang et al., 2015). However, for gravelly soil, the random distribution of gravel significantly reduces the adhesion between the soil and ends. Consequently, the method of holding the end of the specimen with a clamp (Tang et al., 2007; Azmatch et al., 2011; Bahadur et al., 2011; Divya et al., 2014; Tang et al., 2014; Tran et al., 2018; Tran et al., 2019) was used to perform the direct tensile tests. In addition, to reduce the stress concentration in the section

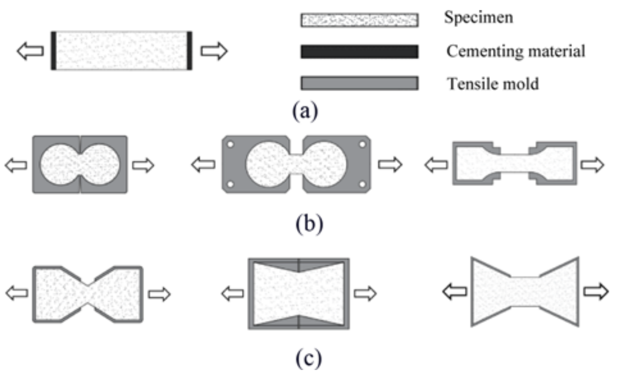


Fig. 2. Direct Tensile Tests: (a) Bonding Method, (b) Dumbbell Mold, (c) Horseshoe Mold

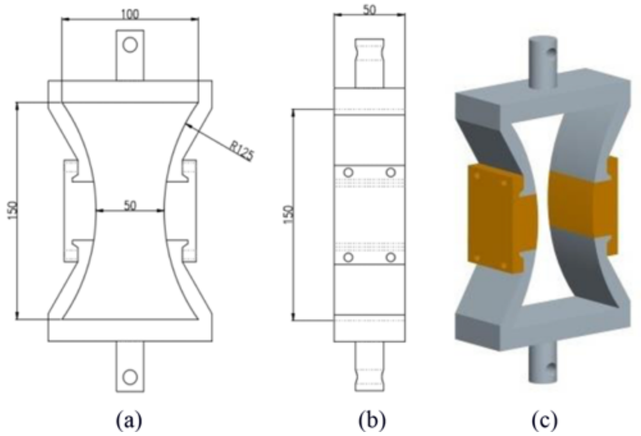


Fig. 3. Tensile Test Device of Zhang et al. (2021): (a) Front View, (b) Side View, (c) Schematic Diagram of Mold

connecting the clamp and the specimen, a dumbbell-shaped mold was designed in which the transition section is arc-shaped (Zhang et al., 2021). The mold size is shown in Fig. 3. The mold was used both to prepare the specimen and as a tensile device. After specimen preparation, the middle connecting section of the mold can be removed to carry out the tensile tests.

2.3 Testing Scheme

According to numerous tests and practical experience in dam engineering, it is recommended that the gravel content of core material is 30% – 50% (Zhang et al., 2006; Gao and Wu, 2012) for high ECRDs. As a consequent, four gravel contents of 0%, 30%, 40% and 50% are used in this paper. Considering that the experimental study should follow the principle from simple to complex, the length of the fibers was fixed in this study. To avoid fiber agglomeration during specimen preparation, the fiber content is controlled to within 0.2%, specifically 0%, 0.05%, 0.1%, 0.15% and 0.2%. According to the controlled variable method, the testing scheme is designed by combining different gravel contents and fiber contents. In line with different fiber contents, there are 5 test groups and a total of 20 specimens, each of which contains three parallel specimens. The specific testing scheme is shown in Table 3.

Table 3. Parameters of Testing Scheme

Test number	Fiber length l (mm)	Fiber content f (%)	Gravel content P (%)	
			Clay specimen	Gravelly soil specimen
T1	12	0	0	30, 40, 50
T2	12	0.05	0	30, 40, 50
T3	12	0.10	0	30, 40, 50
T4	12	0.15	0	30, 40, 50
T5	12	0.20	0	30, 40, 50

Table 4. ω_{op} and ρ_{dmax} of the Gravelly Soil

Gravel content P (%)	0%	30%	40%	50%
ρ_{dmax} (g/cm^3)	1.86	2.00	2.03	2.06
ω_{op} (%)	14.53	11.44	9.47	7.10

2.4 Specimen Preparation

Standard compaction tests were performed to obtain the maximum dry density (ρ_{dmax}) and optimal moisture content (ω_{op}) of the soil with different gravel contents before specimen preparation. Table 4 shows the values of ρ_{dmax} and ω_{op} of the specimens with different gravel contents. To keep in line with the actual, the dry density and moisture content of the specimens were set to the ρ_{dmax} and the ω_{op}.

The soil mixture with the specified moisture content is obtained by hand mixing procedure. In order to achieve satisfactory uniform mixtures, there are differences in the flow of hand mixing procedures. The hand mixing procedure in this paper refers to method suggested by Falorca et al. (2011). Before specimen preparation, soil and gravel were mixed uniformly in batches, and the bundled fibers were dispersed as fiber filaments. A certain amount of fiber filaments was randomly and evenly laid in each batch of soil. After stirring evenly, the soil mixture was then mixed with water to reach the optimal moisture content. After that, the soil mixture (Figs. 4(a) – 4(b)) was stored in sealed bags for 2 days to ensure a uniform moisture content within the soil. Finally, the soil mixture was placed into the mold coated with lubricant. The specimen was compacted in three layers, and each layer was shaved, as shown in Fig. 4(c).

2.5 Loading Apparatus

The specimen and the tensile device were fixed with a universal testing machine. The tensile tests of the soil was performed at a constant rate of 0.5 mm/min (Tang et al., 2014; Tang et al., 2016), and the data of the force sensor and the displacement sensor were recorded at the same time. The tensile stress of the specimen was calculated as follows:

$$\sigma = \frac{T}{A} = \frac{N - W_1 - W_2}{A}, \quad (1)$$

where T is the tensile force acting on the fracture surface of the specimen, A is the area of the fracture surface of the specimen,

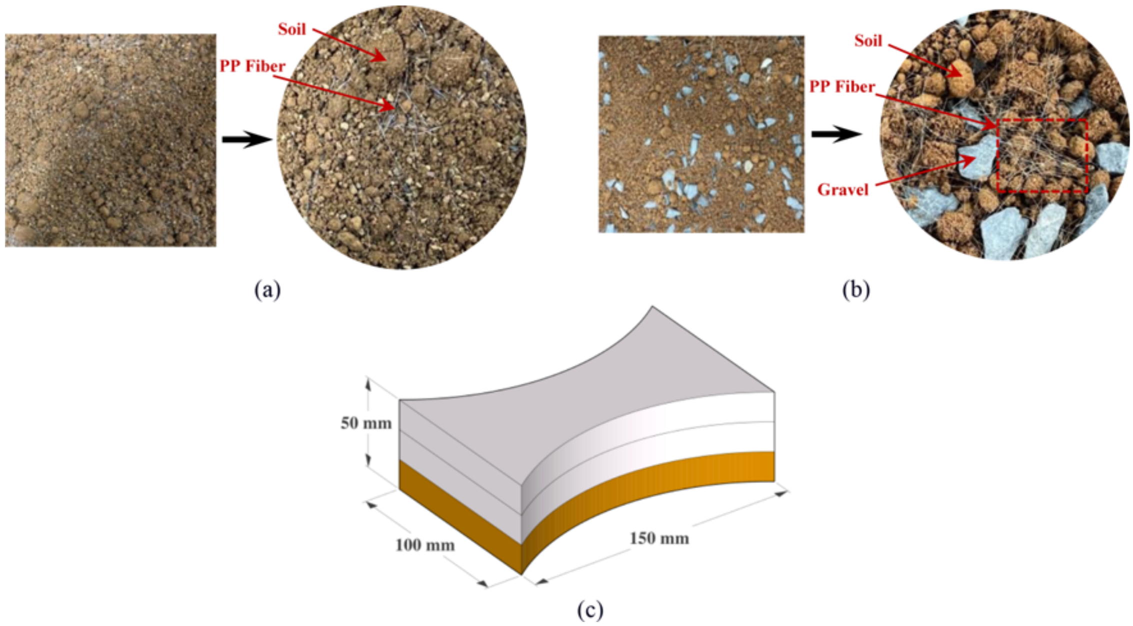


Fig. 4. Specimen Preparation: (a) Soil Mixture (f = 0.1%, P = 0%), (b) Soil Mixture (f = 0.1%, P = 30%), (c) Layered Compaction Specimen

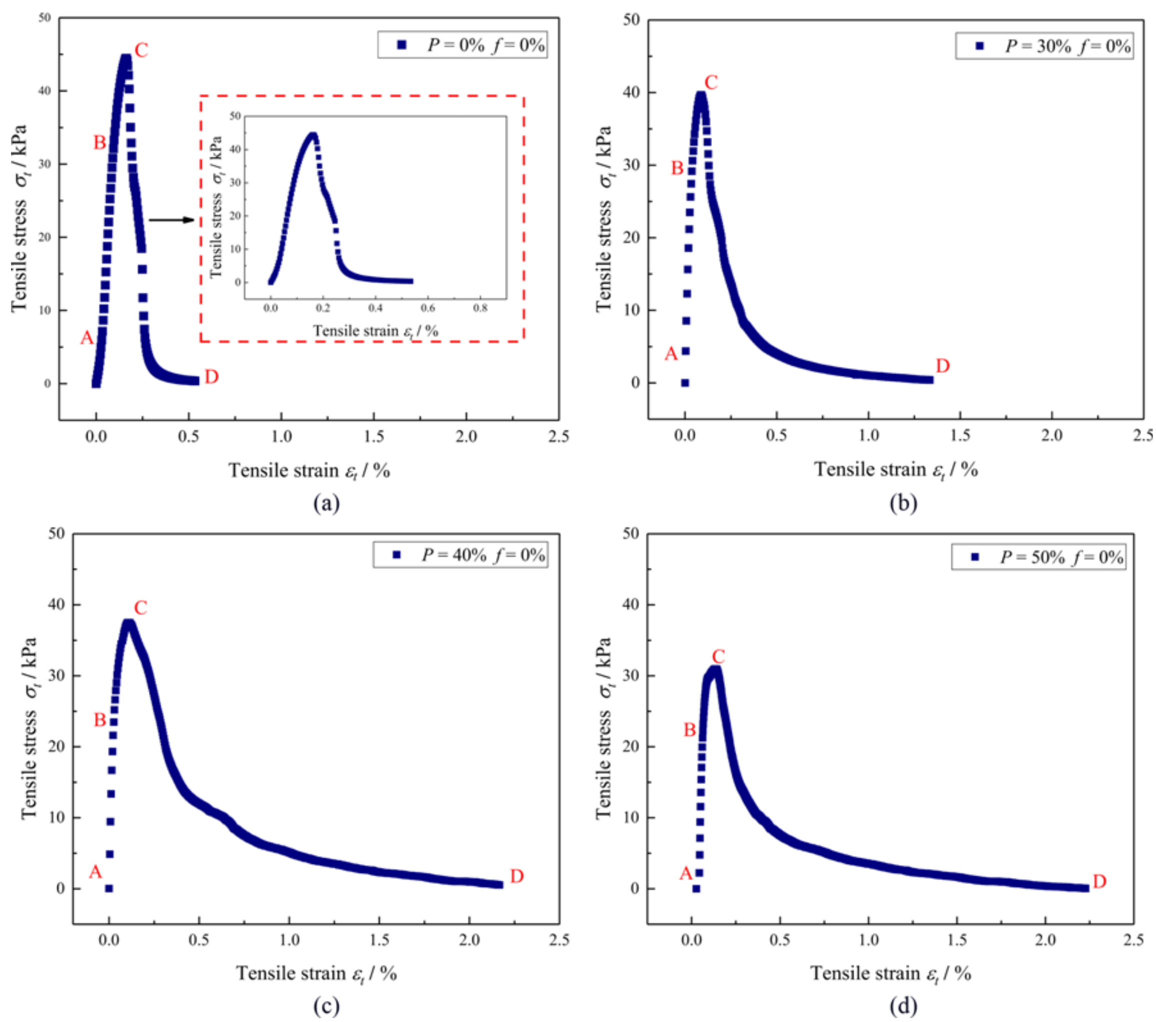


Fig. 5. The Stress-Strain Curves of the T1 Test Group: (a) P = 0% f = 0%, (b) P = 30% f = 0%, (c) P = 40% f = 0%, (d) P = 50% f = 0%

and N is the measured total axial force. W_1 and W_2 are the half-weights of the upper parts of the tensile mold and the specimen, respectively. The peak stress during the test is defined as the tensile strength (σ_t).

3. Results and Analysis

3.1 Stress-Strain Relationship

Figure 5 shows the stress-strain curves of the specimens in the T1 test group. As a whole, the curve can be divided into three loading stages: Several studies (Yuan et al., 2016; Zhang et al., 2021) have shown that the stress-strain curve of gravel soil can be divided into three loading stages, which are not repeated in this paper. The incorporation of gravel in the specimens leads to obvious differences in the softening stage. The difference in softening stages causes a change in the ultimate tensile strain of the soil. This part will be discussed in a later section.

Figure 6 shows the typical stress-strain curves of the T2 – T5 test groups. Compared with the results of the T1 test group, the stress-strain curves for both the pure clay specimens and gravelly soil specimens are significantly different. Incorporation of fibers results in an increase in the peak stress/tensile strength σ_t and ultimate tensile strain ε_{tmax} of the soil. Further, an obvious inflection point appears in the descending part of the curve after the peak, which indicates that the fiber bears part of the tensile stress at this moment.

3.2 Tensile Strength and Post-Peak Tensile Strength

The stress value σ_r at the inflection point in a curve is defined as the post-peak tensile strength of the specimen, which is used to evaluate the fiber-reinforcement strength after specimen cracking. Fig. 7 shows the curve of the stress value at the peak point and the inflection point in the stress-strain curve of the T1-T5 test groups. It can be seen that the incorporation of fibers increases the peak stress/tensile stress σ_t of the gravelly soil. Meanwhile, the post-peak tensile strength σ_r of the soil appeared.

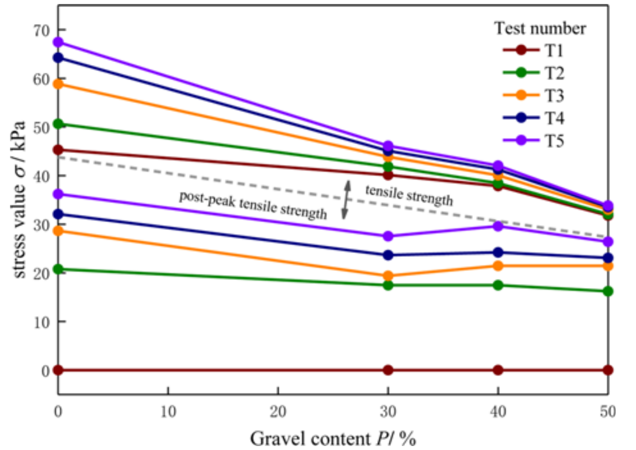


Fig. 7. The Curve of the Stress Value at the Peak Point and the Inflection Point in the Stress-Strain Curve of the T1-T5 Test Groups

Table 5. Tensile Strengths of the T1 – T5 Test Groups

Test number	Fiber content f (%)	Tensile strength (kPa)			
		Clay specimen	Gravelly soil specimen		
		$P = 0\%$	$P = 30\%$	$P = 40\%$	$P = 50\%$
T1	0	45.3	40.12	37.85	31.79
T2	0.05	50.64	41.85	38.45	32.05
T3	0.10	58.84	43.84	40.05	33.01
T4	0.15	64.25	45.08	41.25	33.52
T5	0.20	67.45	46.11	42.05	33.83

3.2.1 Tensile Strength

According to the test results, the mean value of the tensile strength of the 20 specimens is shown in Table 5. In general, the tensile strength of gravelly soil increased continuously with the increase of fiber content. The relationship between the tensile strength and gravel content as well as fiber content of different

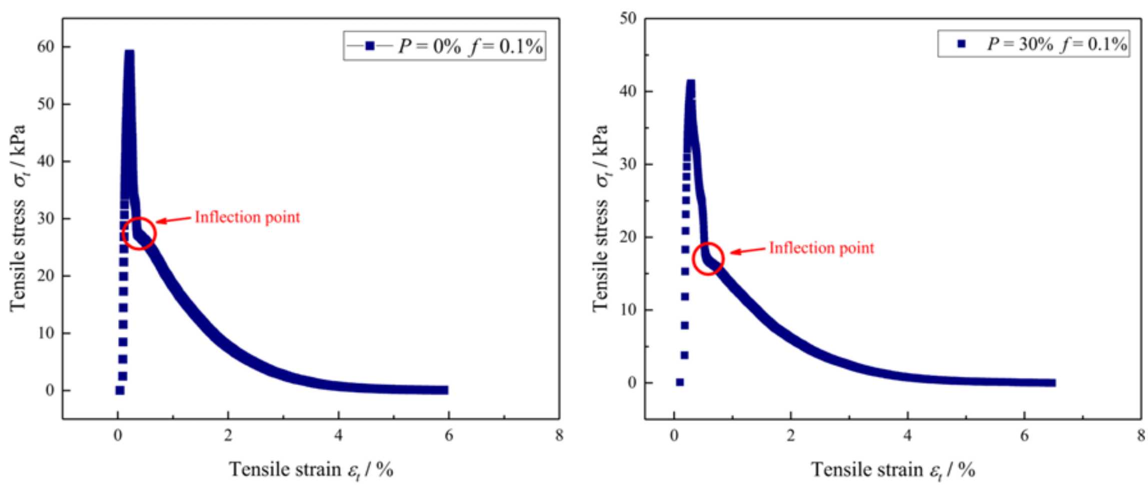


Fig. 6. The Stress-Strain Curves of the T2 – T5 Test Groups: (a) P = 0% f = 0.10%, (b) P = 30% f = 0.10%

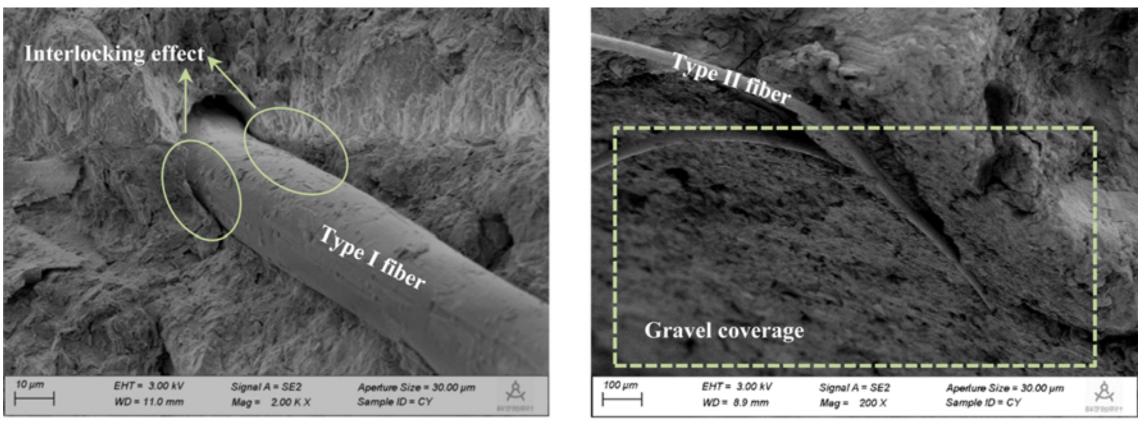
test groups is analyzed below.

For the T1 test group with a fiber content of 0, it can be seen from Fig. 7 that the tensile strength of the gravelly soil decreases with the increasing gravel content. The variation of tensile strength is consistent with the findings of previous research (Ji et al., 2019). The main reasons for the decrease in tensile strength are as follows: the tensile strength of the gravelly soil is provided by the tension and suction between the clay particles. On the one hand, due to the increasing gravel content, the content of the clay particles decreases. Consequently, the specific surface area of the gravel increases, resulting in a decrease in the effective area of the clay particles on the fracture surface. On the other hand, the gaps between gravel and gravel are not easily filled by clay particles, resulting in larger pores in the soil. There is insufficient contact between the clay particles, resulting in less force between the clay particles. Therefore, there exhibits a macroscopic decrease in the tensile strength of soil.

It can be seen from Fig. 7 that for pure clay specimens, the tensile strength was increased by up to 48.9% with the incorporation of 0.2% fiber. For gravelly soil specimens, the highest growth is 14.9%, 11.1% and 6.4% for the gravel content of 30%, 40% and 50%, respectively. In general, with the increase of fiber content, the tensile strength of the soil increases. However, with the increasing gravel content in the soil, the effect of fiber incorporation on the improvement of its tensile strength is significantly reduced.

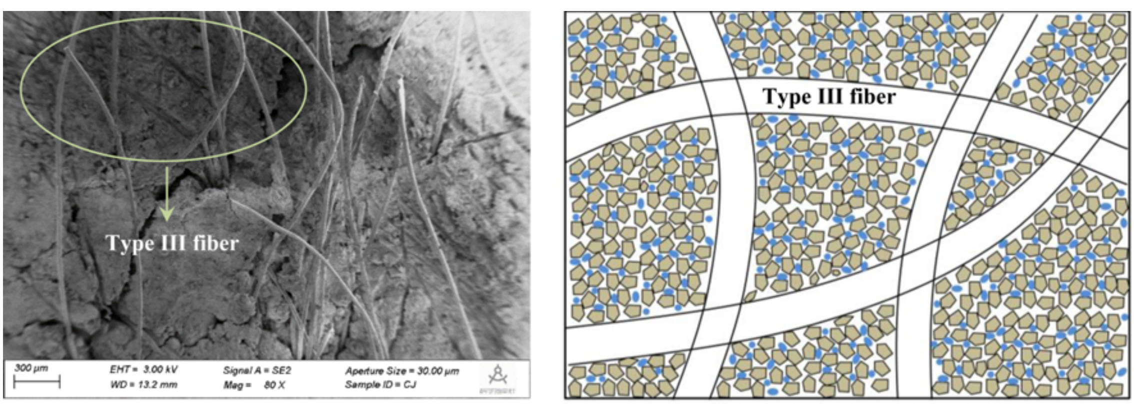
Considering that gravelly soil is a soil-gravel mixture composed of fine-grained clay and coarse-grained gravel, studying the micromechanical behavior of fibers, soil particles, and gravel can reveal the abovementioned mechanism of the improvement in the tensile strength. After the test, the fracture surfaces of specimen was scanned by electron microscopy. In the gravelly soil specimen, a part of the fibers are completely wrapped by soil particles to form a fiber-soil particle interface. The fibers in the fiber-soil particle interface are defined as type I fibers. In addition, some fibers are intermingled between gravel and soil particles to form a fiber-soil particle-gravel interface. And the above fibers are defined as type II fibers. A Sketch drawing of interfacial mechanical interactions of the above two types of fibers can be found in the literature (Zhang et al., 2021).

Figure 8 shows the SEM results of the specimen containing type I/II fibers in the fracture surface. It can be seen that due to the interlocking effect (Fig. 8(a)) between the fiber and the soil particles, when the fiber is gradually pulled out, the hard particles leave obvious scratches on the surface of the fiber. The above



(a) (b)

Fig. 8. SEM Photomicrograph of Type I/II Fibers: (a) Type I Fibers, (b) Type II Fibers



(a) (b)

Fig. 9. Type III Fibers: (a) SEM Photomicrograph of Type III Fibers, (b) Sketch Drawing of Type III Fibers

phenomenon shows that the friction generated by the interface between the fiber and the soil particles is one of the reasons for the increase in the tensile strength of the specimen. The surface of a type II fiber is generally smooth in areas of gravel coverage (Fig. 8(b)). The above phenomenon indicates that the existence of the gravel interface reduces the interlocking effect between the fibers and soil particles. Due to the weakened interfacial shearing effect, the fibers are easily pulled out. Therefore, the hard particles are difficult to leave scratches on the fiber surface. It can be seen that the type II fibers are not effective in improving the tensile strength.

In addition to the above two fiber types, there are still network fiber types in the soil, which we define as the type III fibers. Fig. 9(a) presents the SEM photomicrograph of the type III fibers. Its sketch drawing is shown in Fig. 9(b). It can be seen that the three-dimensional network structure formed by the overlap between fibers has a restrictive effect on soil particles. Because the reinforcement mechanism of type III fibers is relatively complex, we did not do in-depth research in this study. It is certain that such fibers have a non-negligible effect on the improvement of soil tensile strength. Further, we believe that the increase of gravel content will hinder the formation of such fibers, thereby affecting the improvement of soil tensile strength.

The above SEM results clearly reveal the microscopic reinforcement mechanism of fiber-reinforced gravelly soil. The test results show that when the gravel content is 50%, the fiber-soil particle-gravel interface becomes the dominant interface of the specimen. The significant increase in the proportion of type II fibers and a decrease in the proportion of type III fibers resulted in an increase of merely 6.4% in the tensile strength of the soil. However, compared with that of the clay specimens, the tensile strength of the specimens increases by 48.9% due to the presence of type I and type III fibers.

3.2.2 Post-Peak Tensile Strength

As shown in Fig. 7, the post-peak tensile strength of the specimen is positively correlated with the fiber content, which owing to the increasing fibers per unit area as the fiber content increases. After tensile cracks exist, more fibers can bear the tensile stress, which limits the decrease in the tensile stress to a certain extent. In previous studies, in order to explain the behavior of soil after cracking, Divya et al. (2014) proposed to use the post-cracking improvement index to assess the ability of fiber-reinforced soils to ductility. In this paper, I_c is used to represent the post-cracking improvement index, which is defined as

$$I_c = \frac{\sigma_r}{\sigma_t}. \quad (2)$$

The above metrics help to quantify the relative contributions of soils with different fiber and gravel contents to post-cracking behavior. An I_c value closer to zero indicates a greater contribution of fibers to soil ductility behavior. Fig. 10 shows the relationship between I_c and fiber content.

It can be seen from Fig. 10 that the higher the content of gravel content, the more obvious the improvement of the soil ductility behavior. For pure clay specimens, the effect of fibers can increase the I_c to 0.49. When the gravel content and fiber content of the soil are the highest, the I_c can reach 0.22, which indicates that the fiber has a significant effect on improving the stress-strain characteristics of the gravelly soil.

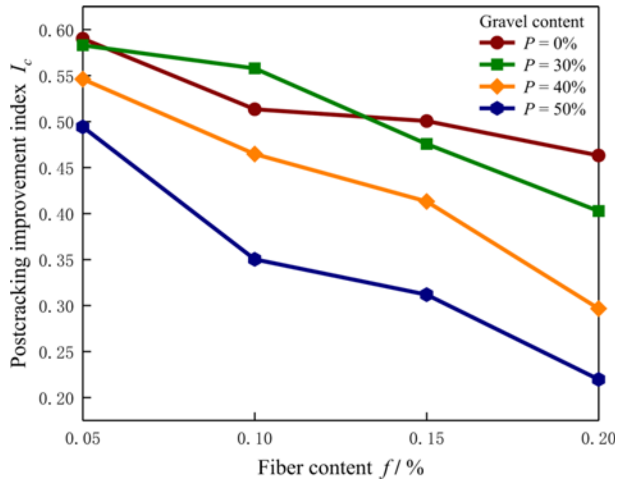


Fig. 10. Relations between the I_c and Fiber Content

3.3 Ultimate Tensile Strain

Figure 11 shows the curve of the ultimate tensile strain ε_{tmax} in the stress-strain curve of the T1-T5 test groups.

During the softening stage of pure clay specimens in the T1 test group, the tensile stress decreases rapidly with the increase of tensile strain, and the ultimate tensile strain is only 0.53% when the specimen exhibit complete failure. With the gradual increase of gravel content, the softening stage of the gravelly soil specimens gradually becomes longer. At the same time, the ultimate tensile strain increases significantly. When the gravel content reaches 50%, the ultimate tensile strain is 2.23%, which

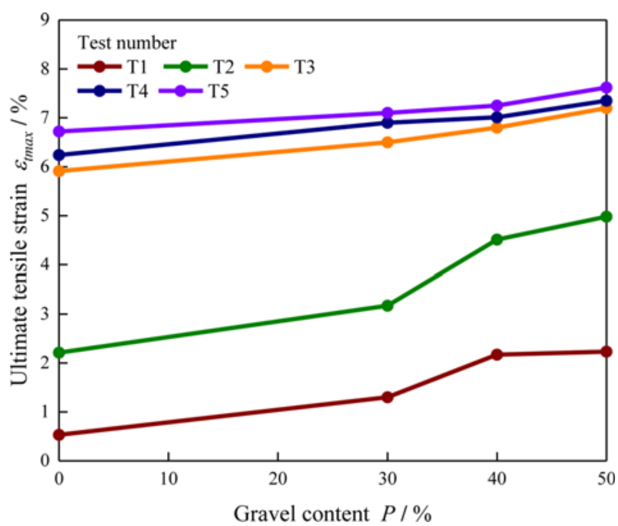


Fig. 11. The Curve of the Ultimate Tensile Strain in the Stress-Strain Curve of the T1-T5 Test Groups

is 4.2 times that of the pure clay specimens. The main reason for the above phenomenon is that after the formation of macroscopic cracks, the gravel and the clay gradually separate, and the cohesive force on the soil interface gradually decreases. However, there remains a certain friction between the gravel and the clay, which delays the failure process. It is proved that the higher the gravel content, the slower the process of soil failure.

For the T2 – T5 test group, the ultimate tensile strain of the specimen is positively related to the fiber content, and the fiber greatly enhances the resistance to plastic deformation of the gravelly soil. When the fiber content is 0.2%, the ultimate tensile strain of the specimens with gravel contents of 0%, 30%, 40% and 50% is 12.7, 5.5, 3.3, and 3.4 times that without reinforcement.

The typical soil failure pattern were presented in our previous study (Zhang et al., 2021). When the pure clay specimens complete failure, a relatively tortuous and irregular fracture path is formed in the middle of the specimen. However, the fracture path of the gravelly soil usually follows the outer contour of the gravel. For gravelly soil specimens, the crack propagation must overcome the obstacle of gravel interface, which delays the crack propagation to a certain extent. The above effects are also one of the reasons for the increase of the ultimate tensile strain of the soil. With fiber reinforcement, the fracture path of gravelly soil still follows the outer contour of the gravel, while that of pure clay specimens is almost a straight line in the middle of the specimen. The explanation for this phenomenon is that the incorporation of fiber further increase the uniformity of the pure clay specimens.

3.4 Analysis of Energy Absorption

The energy required for structural failure is defined as the energy absorption capacity (EAC). This parameter can be used to evaluate the role of fibers in clay reinforcement. EAC is the integrated value of the area under the stress-strain curve of the soil. Fig. 12 shows the calculated EAC values of the T1 – T5 test group.

The energy absorption capacity is positively correlated with the fiber content, as shown in Fig. 12. Therefore, the incorporation of fibers enhances the ability of the specimens to absorb energy during the fracture process. When the fiber content is 0.20%, the EAC value of the pure clay specimens exhibits the largest increase, which is 11.6 times of that without fiber. For the gravelly soil specimens, as the gravel content increases, the strengthening effect of the EAC value gradually decreases. In this test, when the fiber content is 0.2%, the EAC value of gravelly soil specimens with gravel content of 30%, 40% and 50% can be increased by 6.0, 3.0 and 2.8 times, respectively. The improvement effect of fiber on the energy absorption capacity also represents the reinforcement effect of fiber on soil to a certain extent. Clearly, the lower the gravel content of the soil, the better the fiber reinforcement effect.

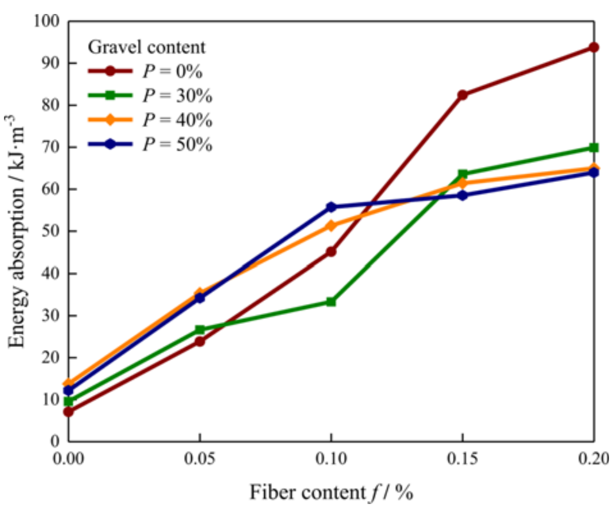


Fig. 12. Energy Absorption Curves of Fiber-Reinforced Gravelly Soil

3.5 Field Application Recommendations

Based on the tensile test results, the crack resistance of gravelly soil in this paper is evaluated by analyzing the variation in the tensile strength and ultimate tensile strain of gravelly soil. During field application, the generation of cracks will weaken the anti-seepage effect of the core wall. From the perspective of preventing soil cracking, the effect of fibers on improving the tensile strength is more important than increasing the ultimate tensile strain. Since the increase in gravel content reduces the improvement in tensile strength significantly, the authors recommend using lower gravel content and higher fiber content.

3.6 Prediction Model of Tensile Strength of Fiber-Reinforced Gravelly Soil

The tensile strength calculation model was obtained using the multiple regression analysis. The form of the multiple regression model is assumed as follows:

$$\sigma_t = \sigma_0 + k_0 \times P + k_1 \times f + k_2 \times P^2 + k3 \times f^2 + k_4 Pf\ , \tag{3}$$

where σ_t is the tensile strength of the specimen, σ_0 is the tensile strength of the specimen when the fiber content is 0%. P and f are the gravel content and fiber content, respectively. The k_0 to k_4 are regression coefficients. According to the results of 60 specimens, a regression model based on the basic parameters P and f is obtained to directly predict the tensile strength. The model expression is as follows:

$$\sigma_t = \sigma_0 - 0.14 \times P + 130.844 \times f + 0.003 \times P^2 - 84.918 \times f^2 - 2.241 Pf,\quad R^2 = 0.984. \tag{4}$$

The above models can be found in our previous study (Zhang et al., 2021). Fig. 13 gives the distribution of regression surface and the test results. The R^2 value of the fitting curve is 0.984, indicating a fine relationship between the experimental data and the model prediction data. Based on the model, the tensile strength of specimens with different gravel contents and fiber contents can be quickly predicted.

To evaluate the effectiveness of the parameters P and f, the

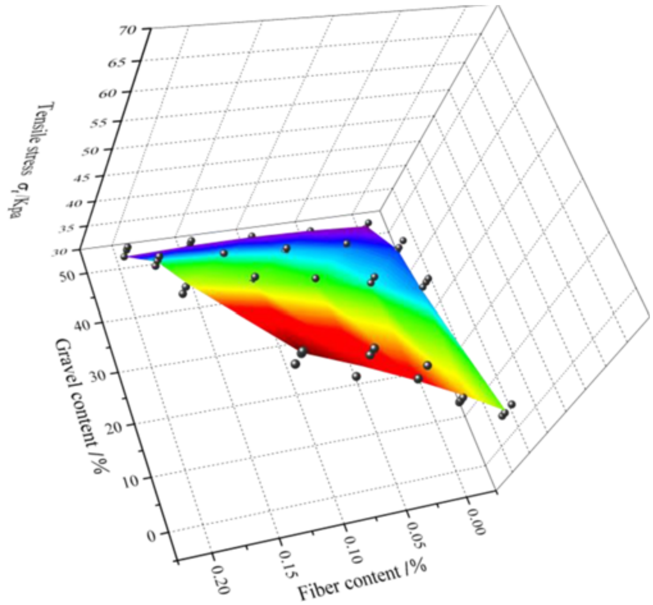


Fig. 13. Distribution of Regression Surface and the Test Results

Table 6. The Sensitivity of Input Parameters

Input parameters	Gravel content P (%)	Fiber content f (%)
Effective degree (%)	60.28	39.72

sensitivity of the parameters (Gandomi et al., 2013) was calculated using Eqs. (5) and (6), as shown below:

$$N_i = f_{\max}(x_i) - f_{\min}(x_i)\ , \tag{5}$$

$$S_i = \frac{N_i}{\sum_{j=1}^{n} N_j} \times 100\ , \tag{6}$$

where $f_{max}(x_i)$ and $f_{min}(x_i)$ are the predicted minimum and maximum values of the i-th parameter, and the other variables are equal to their average values. n is the number of variables. S_i is the effective degree of the two variables. Table 6 lists the sensitivity analysis results of the model parameters.

Table 6 shows that the sensitivity of P and f to the tensile strength is 60.28% and 39.72%, respectively. In predicting the tensile strength, the effectiveness of the gravel content is slightly higher than that of the fiber content. In other words, the gravel content affects the clay particles content of the gravelly soil directly, however the reinforcement effect of different fiber content depends to a large extent on the clay particles content in the gravelly soil. Therefore, the gravel content is a more effective parameter for predicting tensile strength.

4. Conclusions

Based on a new type of soil tensile device, this paper carried out an experimental study on the tensile properties of gravelly soil reinforced with polypropylene fiber. The relevant conclusions are as follows:

1. The tensile strength, post-peak tensile strength, and ultimate tensile strain of fiber-reinforced gravelly soil are positively correlated with the fiber content. However, as the gravel content in the gravelly soil increases, the effect of fiber incorporation on its tensile strength is significantly reduced. In practical application, it is recommended to use gravelly soil with low gravel content and high fiber content.
2. The reinforcement effect of the fiber on the gravelly soil originates from the micromechanical behavior of the interfaces between the fibers, soil particles and gravel. Among the three fiber types, type II fibers at the fiber-soil particle interface has the least effect on improving the tensile strength of gravelly soil.
3. The energy absorption capacity is positively correlated with the fiber content. When the gravel content is 30%, 40% and 50%, the EAC value can be increased by 6.0, 3.0 and 2.8 times, respectively. The lower the gravel content of the soil, the higher the degree of improvement in the EAC value, and the better the fiber reinforcement effect.
4. A multiple regression model is proposed to quickly predict the tensile strength of gravelly soil under different gravel contents and fiber contents. The sensitivity analysis of this model shows that the gravel content is the parameter that most affects the tensile strength, followed by the fiber content.

In the follow-up research, it is urgent to take technical measures to improve the threshold of fiber agglomeration. In addition, the effect of fiber length on the tensile properties of gravel soil needs to be considered.

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