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ORIGINAL PAPER

Strength assessment of sand stabilized with synthetic polymer and natural fibers

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Abstract
Soil stabilization using polymers and fibers has been widely investigated in recent years. This study introduces an innovative approach by integrating synthetic polymer (AH polymer) with natural fibers (sisal fiber) for sand stabilization. A comprehensive experimental framework was established to assess the impact of varying polymer content (1%, 2%, 3%, and 4%) and fiber content (0.2%, 0.4%, 0.6%, and 0.8%, by the mass of dry sand), and densities, on the mechanical properties of stabilized sand, including compressive strength (UCS), tensile strength (TS), and flexural strength (FS). The synergistic stabilization effects of the polymer and fibers were elucidated through SEM. The findings indicate that the synergistic application of AH polymer and sisal fibers significantly enhances the structural integrity of sand. Notably, the UCS, TS, and FS exhibited a well-linear relationship with both the polymer and fiber content. The strengthening effect of fiber was particularly pronounced in samples with higher polymer content. According to the strength increase rate, the optimal polymer content is 2%, and optimal fiber content is 0.6% for the UCS, 0.4% for the TS and 0.8% for the FS. An increase in density was observed to linearly augment the UCS and FS. For sand with 2% polymer and 0.8% fiber, the TS increased linearly with the increment in density, however, for sand with 4% polymer and 0.4% fiber, TS kept a non-monotonic relationship with density. The study also revealed that augmenting the content of polymer and fibers diminishes the brittleness of the stabilized sand, whereas an increase in density has the opposite effect. Furthermore, the incorporation of polymer and fibers resulted in an elevated deformation modulus. The polymer functions as an adhesive, binding fibers to sand particles, while the fibers create a network-like structure that amplifies the effective contact area among sand particles, thereby substantially improving the mechanical properties of the sand.

Keywords Sand · Polymer stabilization · Fiber reinforcement · Strength assessment · Combined stabilization mechanism

Introduction

Sand is one of the most common problematic soils during engineering construction, often resulting in dust storms, liquefaction, and soil erosion due to its low cohesion and loose structure. Soil stabilization is a significant method that can enhance the poor properties of problematic soils to meet the requirements of practical engineering by employing effective stabilization methods. Chemical and physical methods are the two main approaches to improving the properties of soil (Behnood 2018; Soltani et al. 2022; Yuan et al. 2021). The addition of chemical stabilization materials, such as cement, ash, and lime, can effectively improve the strength of the soil. However, brittle failure often occurs, resulting in significant strength loss. This phenomenon is more notable when the soil is mixed with more chemical materials and cured for a longer time (Jia et al. 2019; Shariatmadari et al. 2021). Additionally, some environmental threats, such as greenhouse gas emissions and the heat island effect, are closely related to the large quantities of traditional chemical stabilization materials used (Miles and Esau 2017; Wilberforce et al. 2019; Worrell et al. 2001). Therefore, innovative soil stabilization materials that are low-carbon and environmentally friendly during production and application processes are being investigated in recent years.

The use of polymers as innovative chemical materials for soil stabilization has become a prominent research topic.

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Polymers have demonstrated a lower environmental impact compared to traditional materials like cement and lime, with reduced greenhouse gas emissions, natural resource consumption, and energy use. Furthermore, these polymers are designed to biodegrade into carbon dioxide and water, leaving no lasting environmental effects (Huang et al. 2020a, 2020b; Huang et al. 2021). Numerous researchers have investigated the mechanical and hydraulic properties of polymer-stabilized soils. Their findings indicate that adding polymer enhances the compressive strength (Ghasemzadeh et al. 2021; Ghasemzadeh and Modiri 2020), tensile strength (Liu et al. 2018a, 2018b), flexural strength (Barani and Barfar 2021), shear strength (Judge et al. 2022), and hydraulic conductivity(Guler et al. 2018) of soils. Optimal polymer content and curing time were determined based on test results, varying with soil types and polymer characteristics. Scholars attribute the polymer's enhancement effect to the void-filling and particle-bridging effects of the polymer membrane, improving inter-particle bonding(Biju and Arnepalli 2020; Dubey et al. 2021; Yang et al. 2019; Almajed et al. 2022). Polymers also improve water stability and erosion resistance by forming macro-aggregates(Abrol et al. 2013). Soil particles can form a continuum through flexible bonds provided by polymer membrane elements coating the soil particle surface(Tingle et al. 2007). Despite the effective strength gain from polymer addition, its impacts on the surrounding environment and ecology should not be ignored. Many studies have investigated the effect of polymers on plant growth. Tian et al. (2021) found that polymer improves nitrogen uptake by plants, a key nutrient for plant growth. Additionally, polymers can adsorb and store large amounts of water in long polymer chains, creating a beneficial condition for plant growth (Zhou et al. 2021). The review of these literature indicates that polymers have an improving effect on strength of soil and the plant growth, however, the brittle failure also happened in the polymer-stabilized soil, and it is difficult to further improve the mechanical properties of soil without other stabilization materials.

The use of natural and synthetic fibers as the physical method for soil stabilization has become a rising trend due to their advantages of randomly discrete distribution, high strength, strong acid and alkali resistance, and easy mixing(Lv et al. 2021; Yilmaz 2015). By incorporating the effect of fibers, the toughness, ductility, and residual strength of soils can be effectively enhanced, as fibers provide extra tensile capacity and resistance to relevant large-scale deformation(Abioghli and Hamidi 2019; Zhang et al. 2021). The main reinforcement mechanism of fibers is that they not only can fill the voids in the soil but also act as a spatial three-dimensional network to interlock soil particles, leading to a reduction in the occurrence of potential weak planes and the dry-crack properties of the soil(Tang et al. 2007; Xue et al. 2014; Yuan et al. 2021). In addition, the fibers also act as the anchored and soil nailed systems, which can resist external stress and reduce post-peak strength loss(Chen et al. 2020; Zhang and Benmokrane 2002). The increase in the effective interface contact area between soil particles provided by fibers is also an important factor that leads to the strength gain of soils(Tang et al. 2010). As expected, the mechanical properties and stability of soils were significantly improved by the bonding network of fibers.

There are also many traditional chemical stabilization materials such as lime, cement, and fly ash, and their combination with synthetic fibers such as polypropylene fiber, has been proven to be effective for soil stabilization(Ng et al. 2020; Shen et al. 2021; Tan et al. 2021). However, some environmental concerns still remain during the production and application of such stabilization materials and their combination. Therefore, the combination of polymers and fibers, as one of the promising methods recently applied to soil stabilization, has also been well investigated (Liu et al. 2020a, 2020b, 2020c; Mirzababaei et al. 2018). Natural fibers (e.g., coconut fiber, sisal fiber, palm fiber, jute fiber, etc.) originated from plants; in contrast, synthetic fibers are produced by the chemical industry. Most synthetic fibers applied in soil stabilization are more difficult to degrade by biological and natural processes compared to natural fibers (Zhao et al. 2019), which may cause secondary pollution to the surrounding environment. Therefore, the utilization of natural fibers in soil stabilization is more environmentally friendly, more economical, and non-toxic compared to that of synthetic fibers. Some studies indicate that sisal fibers produced in Tanzania and Brazil are characterized by minimal consumption of non-renewable energy and low greenhouse gas emissions. Moreover, the the sisal residue disposal from sisal fiber production can be repurposed as organic fertilizers, resulting in negligible environmental impact (Broeren et al. 2017).

Although the application of polymers and synthetic fibers has shown promise in soil stabilization(Mirzababaei et al. 2018; Yuan et al. 2022), limited research has been undertaken to evaluate the effect of polymers and their combination with natural fibers on the mechanical behavior of incohesive soil. In addition, there is limited research focusing on the comprehensive evaluation of compressive, tensile, and flexural strengths of stabilized sand, especially for flexural strength, which is only a few literature mentioned about this mechanical properties of stabilized soil. Additionally, there is a quite rare research that comprehensively evaluates the compressive, tensile, and flexural strengths of the synthetic polymer and natural fiber stabilized sand, especially regarding the flexural strength, only a small number of studies have addressed this mechanical property in stabilized soils. Therefore, in this study, the effect of sisal fiber (SF) and its combination with AH polymer on the mechanical properties of sand was investigated through a series of unconfined compressive strength (UCS), direct tensile strength (DTS), and flexural strength (FS) tests. Specifically, in this study, four different contents of sisal fibers (i.e., 0.2%, 0.4%, 0.6%, and 0.8%, by the weight of dry sand) were considered to evaluate the effect of fiber contents on the strength gain in different content of polymer (i.e., 1%, 2%, 3%, and 4%, by the weight of dry sand) stabilized sand. The relationships between fiber contents and the mechanical properties of polymer-stabilized sand are obtained. Finally, the polymer-fiber combined reinforcement mechanism was studied based on the obtained experimental data and scanning electron microscopy (SEM). Through this comprehensive analysis of the mechanical properties of the stabilized sand, the optimal polymer and fiber content for each strength index were identified. This information can serve as valuable guidance for the application of stabilized sand in different practical engineering areas.

Materials and methods

Materials

The sand used in this study was collected from a river bank in Changzhou, China. After air-dried and the sand was sieved with a 2-mm mesh. The particle size distribution curve of the sand is shown in Fig. 1. The mineral composition of the used sand is presented in Fig. 2. The specific gravity (G_s), coefficient of uniformity (C_u), coefficient of curvature (C_c), minimum and maximum dry density (ρ_{min} and ρ_{max}) of the sand were 2.65, 3.0, 1.23, 1.33 g/cm^3 and 1.69 g/cm^3, respectively. The internal frictional angle and cohesion of the used sand is 29°and 3 kPa, respectively.

The polymer used in this study is a polyurethane organic polymer (Fig. 3). It turns into a white solution after being mixed with a certain amount of water, and the polymer solution becomes an elastomer with high strength and toughness during the air-drying process. The elastomer acts as a

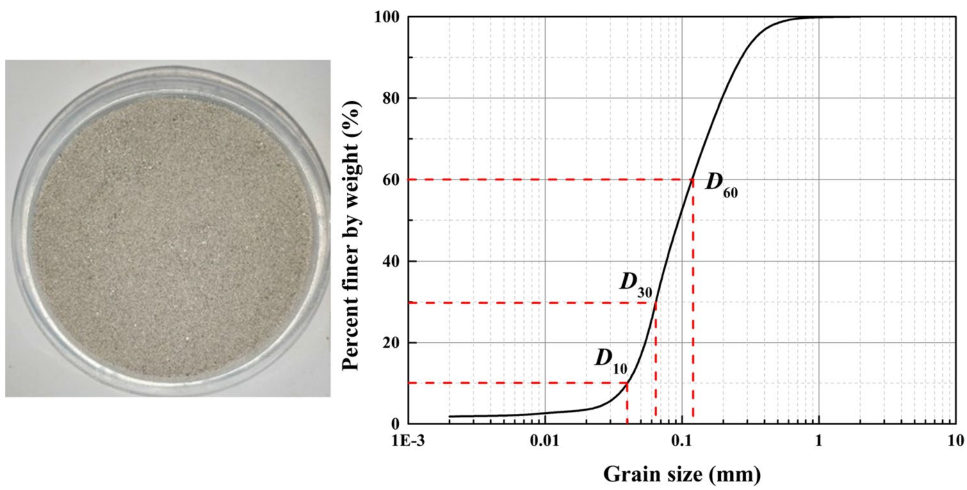


Fig. 1 The grain-size distribution of the sand

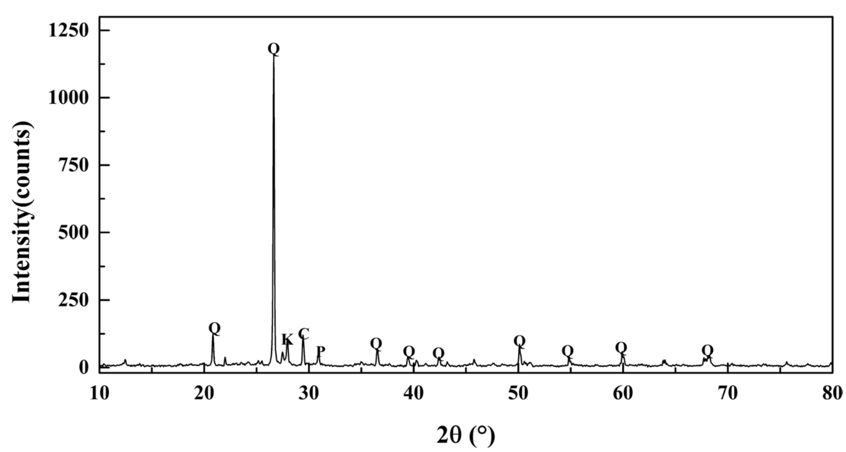


Fig. 2 The mineral composition of sand

network to interlock sand particles, leading to the improvement in the mechanical properties of the soil. The density, viscosity, solid content, and pH value of the polymer are 1.18 g/cm^3, 600–700 MPa·s, 85% and 7, respectively.

In previous studies, it was observed that the fiber with a length of less than 15 mm or greater than 25 mm has an ineffective reinforcement effect on the strength of soils(Babu and Vasudevan 2008). Hence, the 18-mm length of sisal fibers was selected in this study. The sisal fiber used to reinforce the polymer-stabilized sand was generated from the sisal and chemically treated with a solution of sodium hydroxide to increase the durability of the fibers and its has a rougher surface compared to synthetic fibers. The detailed physical properties of the sisal fiber were presented in Table 1. The treated sisal fiber (Fig. 4(a)) and the distribution of sisal fibers among sand particles is shown in Fig. 4(b).

Testing program

In this study, four contents of polymer (1%, 2%, 3% and 4%, by the total dry mass of sand) using) and their combination with 0.2%, 0.4%, 0.6% and 0.8% (the total dry mass of sand) content of sisal fibers were used to stabilize the sand. The 1.50 g/cm^3 dry density of the sand was selected in these tests. A series of unconfined compressive strength tests, direct tensile tests and flexural strength tests were carried out to investigate the mechanical properties of polymer-fiber-stabilized sand (PFSS). Considering the effect of density on the mechanical properties of PFSS, the densities of 1.40, 1.45, 1.50, 1.55 and 1.60 g/cm^3 were selected in the above-mentioned tests.

Three identical samples were prepared for each test group to enhance the precision and reliability of the test results. During the sample preparation, the oven-dried sand was uniformly mixed with different content of sisal fibers using a laboratory mixer prior to polymer solution inclusion. A certain amount of polymer was mixed with 10% water by manual stirring forming the polymer solution. Then, the polymer solution was incrementally added to the fiber-sand mixture and stirred by using the mixer, forming the PFSS mixture. The mixture was transferred into the mold corresponding to different types of tests and hydraulically compacted for about 2 minutes, forming samples of different sizes. Finally, the demolded samples

Fig. 3 The polyurethane organic polymer and its chemical formula

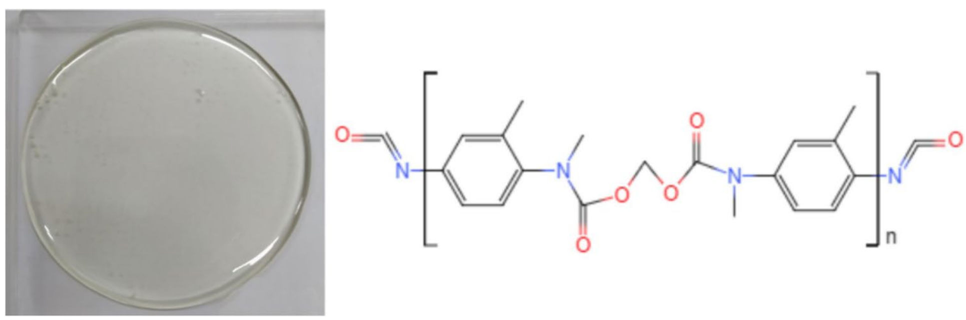
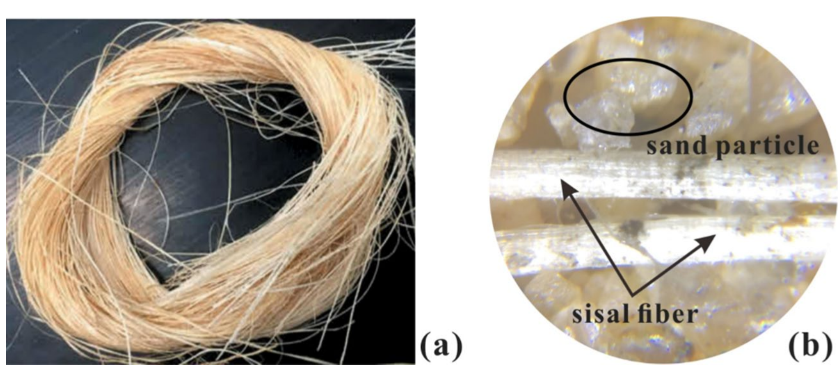


Table 1 Physical and mechanical indices of the sisal fiber

Length (mm)	Density (g/cm^3)	Diameter (mm)	Tensile strength (MPa)	Appropriate temperature (°C)	Elongation (%)	Elasticity modulus (MPa)	Optimal pH value range
18	1.45	0.2–0.3	670	≤100	3–5	2200	5–11

Fig. 4 The polymer elastomer and sisal fiber



were cured for 96 hours at indoor conditions to ensure complete setting during the air-hardening reaction of polymer in the sand. The 96-hour curing time was determined based on the negligible weight-loss of the sample after being cured for 96 hours, indicating that the air-hardening process of the polymer was almost completed.

Unconfined compressive strength test

In this study, the YYW-2 compressive strain control device was adopted for measuring the unconfined compressive strength (σ_c) of PFSS at varying contents of polymer and sisal fibers. The specimen with a diameter of 39.1 mm and a height of 80 mm was subjected to continuous loading at a constant strain rate of 2.4 mm/min (Liu et al., 2020a). In the test process, the axial stress and strain were recorded to draw the strain-stress curves, the unconfined compressive strength of samples was determined based on the peak value in the curves or the stress corresponding to 15% strain in the curves without peak value.

The energy absorption derived from the area beneath the strain-stress curve (at the strain corresponding to peak stress or at 10% strain), is a critical parameter that correlates positively with the soil's toughness characteristics (Mirzababaei et al. 2013; Alotaibi et al. 2022). A higher energy absorption value demonstrates a more ductile behavior of the stabilized sand sample. In this study, the energy absorption is specifically defined as the amount of energy required to reach the peak stress, providing valuable insights into its mechanical resilience and potential performance under stress.

Direct tensile strength test

Even though natural soil has a relatively low tensile strength compared to rock, it is still one of the important mechanical properties of soil, which is related to the soil shrinkage cracking failure and the slope instability when exposed to tensile force such as the gravity of the slope. The tensile strength of PFSS was tested by the direct tensile device, and the sample has a height of 25 mm, length of 80 mm and width of 60 mm. The sample was placed in the mold with a narrow middle section; therefore, the pullout force can be directly applied to the middle section of the specimen. The direct tensile strength (σ_t) is given by the following equation (Tang et al. 2016):

$$\sigma_t = \frac{2T + w_1 + w_2}{2S} \tag{1}$$

where T is the maximum tensile stress (N), w_1 is the weight of specimen (N), w_2 is the weight of the mold (N), and S is the cross-sectional area of the middle section (m^2).

Flexural strength test

Even though the flexural strength of natural sand is almost zero, the sand stabilized with polymer and its combination fibers will gain a significant flexural strength. The flexural strength of PFSS will play a significant role in the overall performance of pavements when it was used as the subgrade materials. The flexural strength test is carried out using a three-point bending flexural device for PFSS, which is designed independently for the flexural strength test for the stabilized soil. The flexural sample has a 160-mm length, 40-mm width, and 20-mm height and placed on two cylinders with a 100-mm span length. During the test, the bending of the sample was performed at a rate of 0.2 mm per minute, and the loading force was recorded at an interval of 0.02 mm displacement(Barani and Barfar 2021). Therefore, the flexural strength (σ_f) can be calculated utilizing the displacement-stress curves. The flexural strength was obtained from the following equation (Barani and Barfar 2021):

$$\sigma_f = \frac{3Fl}{2bh^2} \tag{2}$$

Where F is the maximum applied load, l is the length of the sample, b is the width of the sample, h is the height of the sample.

Scanning electron microscopy (SEM) test

In this study, the microstructure of inter-particle interaction was investigated by SEM. The size of the SEM sample is $1 \times 1 \times 1$ cm. Before the SEM test, the sample was oven-dried and then covered with gold powder.to get clear images.

Results and analysis

The unconfined compressive strength test

Stress-strain characteristic

Figure 5 presents the axial stress-strain curves of the sand stabilized with different polymer contents, fiber contents and densities. As shown in Fig. 5(a), the sand is stabilized only with different polymer contents, the axial stress first increased rapidly and then decreased slowly with the increment in strain. Based on the characteristics of curves, the deformation process can be divided into four stages, compaction stage, elastic deformation stage, plastic deformation stage and post-peak deformation stage, respectively. For sand stabilized with 1% polymer, the stress increased significantly with the increase in axial strain until strain reached 6%, then the stress behaved with the obvious loss after the peak value. In contrast, the curves of sand stabilized

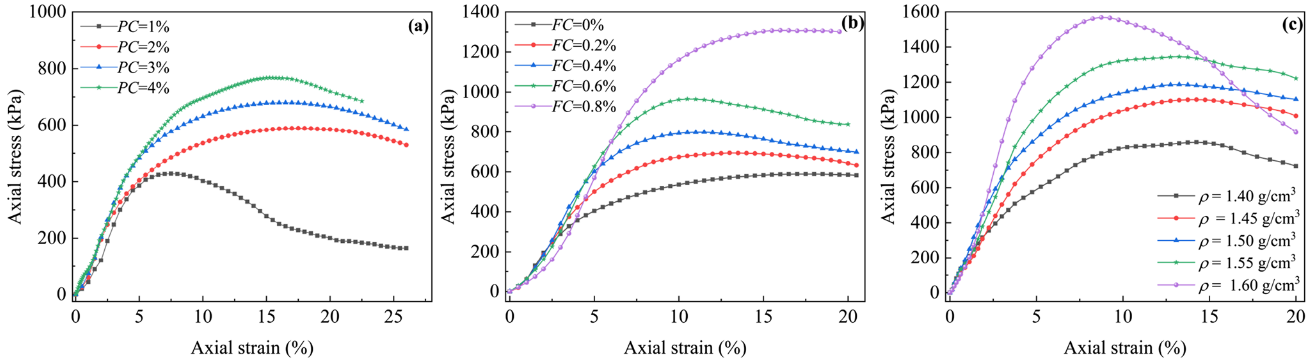


Fig. 5 The typical stress-strain curves of stabilized sand: (**a**) the effect of polymer content; (**b**) the effect of fiber content; (**c**) the effect of densities

with 2%, 3% and 4% share similar shapes of stress-strain curves, the post-peak stress drop during strain softening was also less pronounced with a higher polymer content, which indicated that the sand stabilized with more polymer shown more obvious ductile characteristic. This phenomenon also indicated that soil mixed with higher content fiber required more energy to deform the sample to a certain strain level, which is consistent with other type of soil stabilized with fibers (Mirzababaei et al. 2018; Zhang et al. 2021). Compared with the sudden strength loss of soil stabilized with conventional stabilization materials like cement and lime, it is also one of the advantages of flexible stabilization materials (Jia et al. 2019). In addition, for the sample with 2%, 3% and 4% polymer, the strains corresponding to the peak stress are about 15%, which is significantly higher than that of the sample with 1% polymer.

Figure 5(b) displays the axial stress-strain curves affected by sisal fiber contents. It is shown in Fig. 5(b) that the peak value of stress increased with the increase in fiber content. The strain corresponding to the peak stress increased as fiber content increased from 0% to 0.6%, however, for the sample with 0.8% fiber, no obvious peak value can be observed in the curves. Moreover, the stress drop of the sample after the peak value is less obvious with higher fiber content, which means the sand stabilized more fiber behaved with a more significant strain-hardening behavior. This can be explained that the addition of fibers can provide more tensile strength and restrict the deformation of the sample, thus, the strength and toughness of the sample were obviously improved by fibers.

The influence of density on the stress-strain characteristic can be noticed in Fig. 5(c). As can be observed, the shapes of curves were significantly affected by the increasing density, especially as density increased from 1.55 g/cm^3 to 1.60 g/cm^3. The detailed changes can be described as followed. The increase rate of axial stress gradually increases with the increase of density, indicating that the sample with higher density has experienced a shorter compaction stage. Additionally, the strains corresponding to the peak stress decrease with increasing of density. For example, the strains corresponding to the peak stress approximately increased from 15% to 8.5% as density increased from 1.40 g/cm^{3}to 1.60 g/cm^3, the stiffness was greatly improved. It can also be noticed that the denser sample has a more obvious stress loss after the peak value.

The UCS and energy absorption

The effect of polymer content, sisal fiber content and density on the UCS of sand are presented in Fig. 6. As observed in Fig. 6(a), the fiber addition significantly improves the strength of polymer-stabilized sand, and the strength kept a well-linear relationship with fiber content. For the sand stabilized with 1%, 2%, 3% and 4%, the unconfined compressive strength increased by 577.1 kPa, 823.7 kPa, 1096 kPa and 1589.7 kPa, respectively, when the fiber content increased by 0.2%,. This result indicated that for sand stabilized with more polymer, the enhancement effect of fiber was more significant. It can also be noticed in Fig. 6(a) that, for the samples with 1%, 2% and 3% polymer content, the increase of UCS decreased slightly when the fiber content reached 0.6%, while for the sand with 4% polymer, the increasing rate of UCS kept at a high rate with the increment in fiber content. Similarly, the UCS of sand was also greatly improved by infusion of polymer, and the enhancement effect of the polymer was more obvious when the samples with higher fiber content. It can be concluded that the combination stabilization of polymer and fiber can significantly increase the strength of sand. The polymer acted as a binder between the fiber and sand particles, increasing the contact area between fibers and sand particles, thereby improving the integrity of samples. In addition, the infusion of polymer makes the non-cohesive sand transform into cohesive soil, thus, the fiber can also play the role of reinforcement

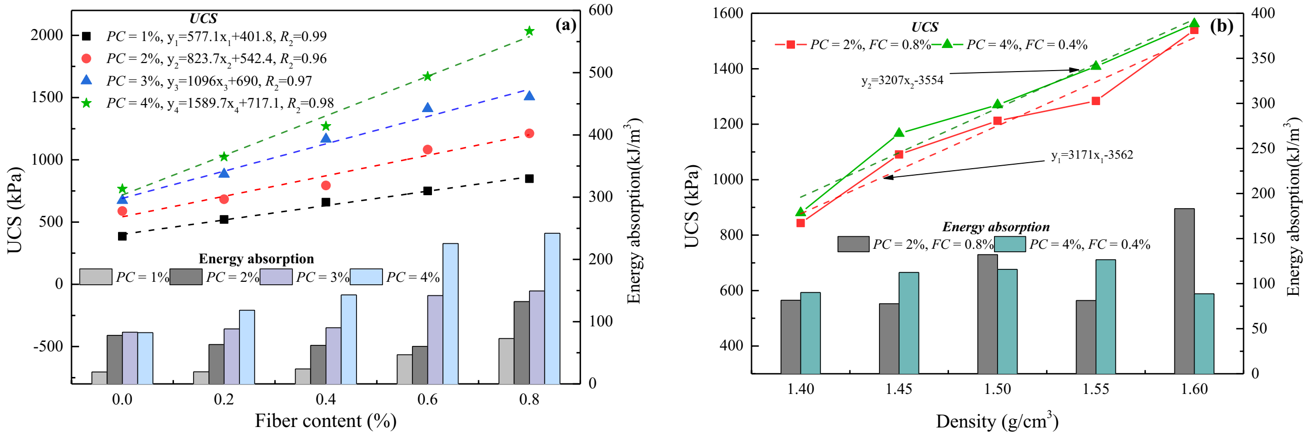


Fig. 6 The UCS and energy absorption of PFSS varying with polymer and sisal fiber content (**a**); and the UCS of PFSS varying with density (**b**)

and anchorage among sand particles. Eventually, the UCS of sand was greatly improved. Compared to sand stabilized with synthetic fibers, the UCS is significantly higher at equivalent fiber contents, as observed by Liu et al. (2020a). This enhancement can be attributed to the low density of natural fibers, which leads to a greater volume fraction and consequently, a more substantial distribution of fibers among the sand particles, thereby boosting the UCS of the sample.

The variation in UCS with density is illustrated in Fig. 6(b). The results indicate that the UCS increases linearly with the increase of density. Besides, the slope between the UCS and the density of the samples with different fiber and polymer contents is roughly same. At the same density, the compressive strength of sand stabilized with 4% polymer and 0.4% fiber content was always greater than that of sand stabilized with 2% polymer and 0.8% polymer. The anchorage effect of fiber can be fully realised as density increased, and under the action of polymer film, the effective contact area between fiber and sand particles will increase, improving the friction between particles (Liu et al. 2018a, 2018b). Besides, the voids among samples become smaller with the increment in density, which enhanced the interaction between sand and fibers. Moreover, fiber can also restrict the rearrangement of sand particles, increasing the ability of resisting deformation as exposed to the external force.

Figure 6(a) presented the energy absorption of the sand stabilized with polymers and fibers. As observed, an increase in both polymer and fiber content leads to enhanced energy absorption in the stabilized sand. Particularly, for samples with a higher fiber content, the presence of polymer plays a more substantial role in boosting energy absorption. Notably, the energy absorption observed in this study obviously surpasses that of sand stabilized with polymer and root, as reported by Liu et al. (2020a, 2020b, 2020c). In their research, the energy absorption was capped at a maximum of 70 kJ/m^3, whereas our findings indicate a substantially higher energy absorption. In contrast, for samples containing 3% and 4% polymer, there is a obvious increase in energy absorption as the fiber content rises from 0% to 0.6%. However, when the fiber content is further increased from 0.6% to 0.8%, the increment in energy absorption is relatively minor. This suggests that, with increasing fiber content, the bridging effect becomes more pronounced, requiring more energy to pull out the fibers, which in turn contributes to the enhanced toughness of the fiber-stabilized sand. This enhancement can also be ascribed to the polymers' ability to mitigate debonding, sliding, and fiber pull-out at the crack level, thereby improving the deformation resistance of the samples during both micro and macro crack propagation (Alotaibi et al. 2022). Furthermore, the research conducted by Hamidi and Hooresfand (2013) elucidates that the elongation of fibers when subjected to stress plays a vital role in enhancing energy absorption, particularly at equivalent levels of axial strain. The effect of density on the energy absorption of the stabilized sand is shown in Fig. 6(b). It is evident that energy absorption does not maintain a simple monotonic relationship with density. However, it can be generally concluded that samples with higher fiber content require greater energy absorption to reach peak stress. This phenomenon can be attributed to the fact that more densely compacted sand allows for the full realization of fiber reinforcement, enhancing the material's ability to absorb energy during deformation or failure processes.

The elastic modulus

As one of the important parameters of geotechnical mechanics, the elastic modulus is often used to evaluate the mechanical properties of stabilized soil. The elastic modulus adopted in this paper was replaced by the secant modulus, which is defined as the slope between the 50% peak stress and its corresponding axial strain in the stress-strain curve. Figure 7(a) displays the elastic modulus of sand stabilized with different content of polymer and fibers. Compared to the elastic modulus of sand treated with polymer and root, as reported by Liu et al. (2020a, 2020b, 2020c), which varied from 2 MPa to 6 MPa varying with the content of polymer and root, our results indicate a significant enhancement in the elastic properties of the treated sand. Overall, both polymer and fiber contributed to the elastic modulus development. Besides, the benefit of increasing fiber was more significant while at a high polymer content. For example, when fiber content increased from 0% to 0.8%, the elastic modulus of samples with 1% and 4% polymer increased by 39.3% and 209.8%, respectively. Additionally, when the fiber content is same, the increment in the polymer can also improve the elastic modulus of stabilized sand. For the samples with 0% and 0.6% fiber, the elastic modulus and polymer content kept a linear relationship. However, for the samples with 0.2%, 0.4% and 0.8% fiber, the increasing polymer leads to the exponential increase of elastic modulus.

The elastic modulus of samples with different densities was also evaluated, as shown in Fig. 7(b). As observed, an increment in density increases the elastic modulus. It can also be concluded that for the sample with 4% polymer and 0.4% fiber and 2% polymer and 0.8% fiber, the average elastic modulus increases by 3.65 MPa and 3.20 MPa when density increased by 0.05 g/cm^3, respectively. Moreover, the elastic modulus of the sample with 2% polymer and 0.8% fiber was slightly greater than that of the sample with 4% polymer and 0.4% fiber, which indicates that the benefit of fiber on the improvement of elastic modulus was more significant than polymer.

The results of direct tensile strength test

The direct tensile strength of samples with different content of polymer and fiber and density are presented in Fig. 8. As can be observed in Fig. 8(a), the tensile strength of samples with different content of polymer kept a well-linear relationship with fiber content. For samples with 1%, 2%, 3% and 4% polymer, the tensile strength increased by 3.4 times, 3.9 times 2.4 times and 2.4 times, respectively, when fiber content increased from 0% to 0.8%. The influence of polymer content on the tensile strength of samples can also be noticed in Fig. 8(a). The tensile strength of samples without fiber increased linearly with polymer content. However, after fibers were added to the sand, the tensile strength kept a non-linear relationship with fiber content. As the polymer increased from 1% to 2%, the tensile strength has a significant improvement, in contrast, the increase was the least when the polymer increased from 2% to 3%. Based on the test results, it can be concluded that polymer and fiber both played a beneficial role in improving the tensile strength of sand, with the increase of polymer, the effective connection between fiber and sand particles was enhanced, which led to the increase in tensile strength. The tensile strength obtained in this study is notably superior to that of sand reinforced with synthetic polymers and a variety of synthetic fibers, including polypropylene, basalt, and glass fibers, as reported by Liu et al. (2020a, 2020b, 2020c). This enhancement can be predominantly attributed to the rougher surface characteristics of sisal fibers, which are capable of providing higher tensile force compared with synthetic.

Figure 8(b) shows the relationship between tensile strength and density. As observed, for samples with 2% polymer and 0.8% fiber, the tensile strength increased

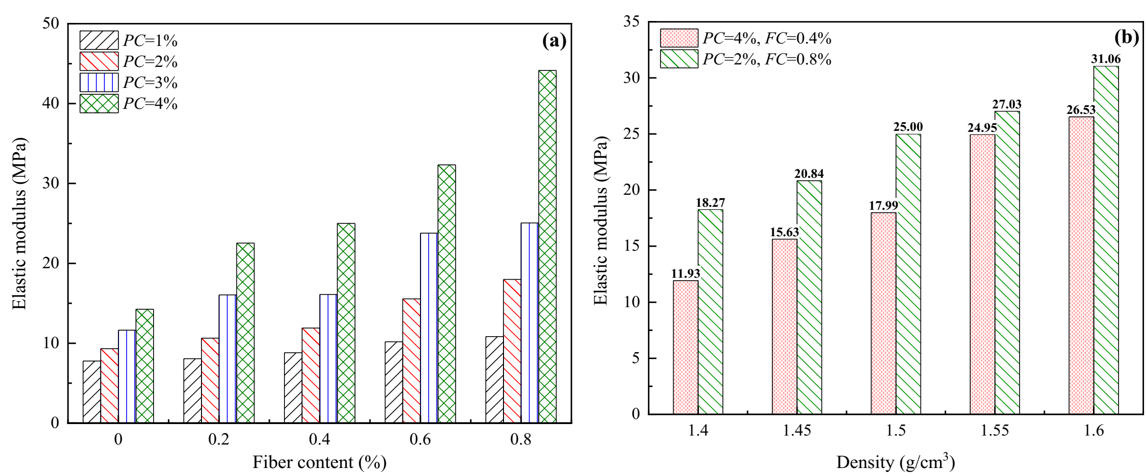


Fig. 7 The elastic modulus of PFSS (**a**) the effect of polymer content and fiber content; (**b**) the effect of densities

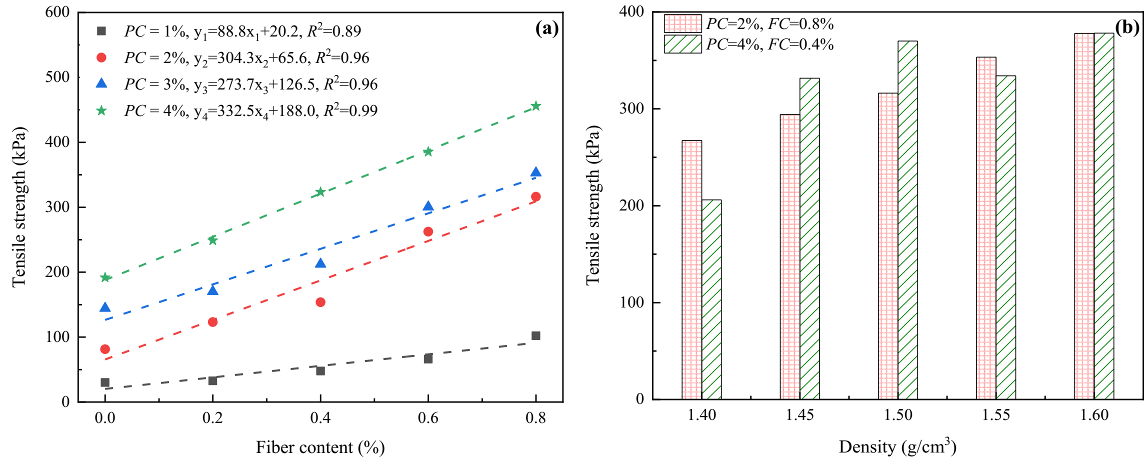


Fig. 8 The DTS of PFSS varying with polymer and sisal fiber content (**a**) and density (**b**)

with the increment in density. However, for samples with 4% polymer and 0.4% fiber, the tensile strength kept a non-monotonic relationship with density, which is consistent with the finding reported by Liu et al. (2018a, 2018b). For the sample with 1.40 g/cm^3 density, the tensile strength of the sample with 2% and 0.8% fiber is higher than that of samples with 4% polymer and 0.4% fiber. However, this phenomenon reversed as density ranged from 1.45 g/cm^3 to 1.50 g/cm^3. With the further increase of density, the difference in tensile strength between samples with 2% polymer and 0.8% and samples with 4% polymer and 0.4% fiber was weakened. The void ratio and pore-space were greatly reduced as density increased, therefore, the effective connection provided by polymer film was enhanced, which played a role in improving the tensile strength of stabilized silty sand.

The results of flexural strength test

The stress-displacement characteristic

Figure 9 shows the plots of stress-displacement of stabilized sand considering the variations of fiber content and density. The effect of fiber content on the stress-displacement curves of samples with 2% polymer can be noticed in Fig. 9(a). As observed, the stress increase rates were higher in samples stabilized with more polymer than in samples stabilized with fewer polymer. In addition, the stress drop after the peak value was less pronounced with higher fiber content. Furthermore, this study observed that the failure displacement, which corresponds to the peak stress, increases with the increment in fiber content. Notably, this failure displacement is significantly larger than that observed in xanthan gum-treated clay, where the displacement remains below

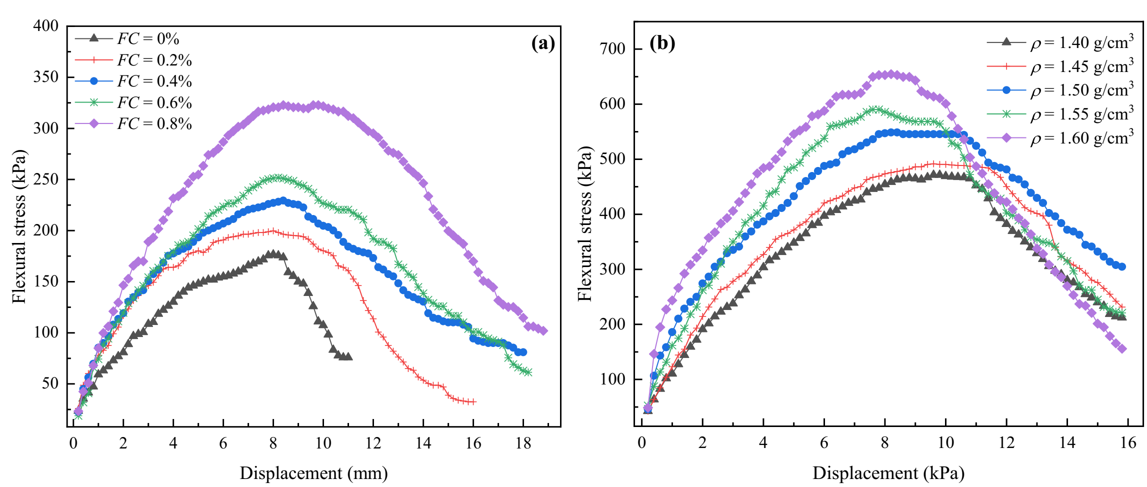


Fig. 9 The typical stress-displacement curves of samples varying with fiber content (**a**) and density (**b**)

1 mm, as reported by Barani and Barfar 2021, indicating synthetic polymer and sisal fiber stabilized sand behaves with more fracture Energy. After reaching the peak value, the stiffening effect of the fiber will improve the bending and deformation resistance of the sand, thus, although the polymer film between the sand particles is probably broken or detached from the surface of sand particles, fibers can still provide a certain tensile strength and reduce the stress loss.

The stress-displacement curves of samples with 4% polymer and 0.4% fiber varying with density were presented in Fig. 9(b). It illustrated that an increment in density promoted the stress increase rate before the peak value. Besides, the displacement corresponding to the peak stress decreased with the increase in density. Compared to the samples with low density, the strengthening effect of fiber on the interaction of sand particles with higher density was more significant. On the other hand, the gaps between sand particles become smaller with increasing densities, therefore, the connection between sand particles and fibers will be greatly improved.

The flexural strength

Figure 10 depicts the variation in the flexural strength with polymer content, fiber content and density. The results showed that the increase in both polymer and fiber caused an increase in flexural strength (Fig. 10(a)). Besides, the flexural strength of samples with different polymer content kept a well-linear relationship with fiber content, averagely, the flexural strength of the samples with 1%, 2%, 3% and 4% increased by 101.4 kPa, 166.6 kPa, 293.9 kPa and 620.2 kPa, respectively, as the fiber content increased by 0.2%, indicating that the effect of fiber on enhancing the flexural strength was more dramatical at high polymer content. Moreover, compared with samples without fibers, the flexural strength of samples stabilized with 0.8% fiber increased by 2.3 times, 1.8 times 1.9 times and 2.6 times, respectively. At high fiber content, the increase of polymer content results in a more significant enhancement of flexural strength, especially as polymer content increased from 3% to 4%. In comparison to clay stabilized with xanthan gum, the sand stabilized with AH polymer and sisal fiber exhibited significantly higher flexural strength, approximately tenfold that of xanthan gum-treated clay (Barani and Barfar (2021)). Nevertheless, it remains lower than that of soil stabilized with cement and polypropylene fibers (Pedroso et al. 2023). The middle section of the sample will first undergo bending deformation under vertical load, the fibers anchored between sand particles will provide tensile resistance and limit the further deformation of the sample until the fibers slide or break, meanwhile, the sample reached the maximum flexural stress, which is the flexural strength. Similarly, under the synergistic action of polymer, the reinforcement effect of fiber and the bonding effect of polymer play a joint enhancement effect, which greatly enhanced the flexural strength of sand.

Figure 10(b) shows the flexural strength with varying density for samples with 2% polymer and 0.8% fiber and 4% polymer and 0.4% fiber. As observed, the flexural was linearly increased with the increase in density, and the slope of samples with 2% polymer and 0.8% was higher than that of samples with 4% polymer and 0.4% fiber, which indicated the flexural strength increased by the increasing density was more pronounced for samples with higher fiber content. With the increase of density, the volume of polymer and fiber per unit increased, and the three-dimensional fiber network and polymer film network will become denser, which provided more connecting force in the midst of sand particles and restrict the movement of sand particles. Under the vertical load of the sample, the fiber is not easy to slip out, and the sand is also well-bound, so as to improve the flexural

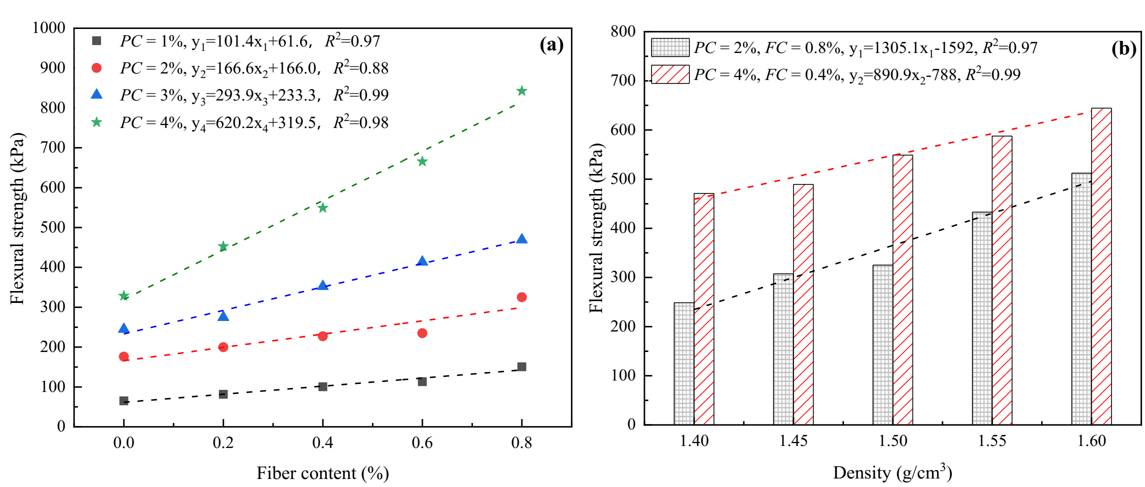


Fig. 10 The flexural strength of stabilized sand varying with polymer and sisal fiber content (**a**) and density (**b**)

strength of the sample. As a result, the fiber benefit to the flexural strength was enhanced by the increased density.

The determination of optimal content of polymer and fiber content

As mentioned in the previous analysis, the UCS, TS, and FS consistently maintained a linear correlation with the sisal fiber content. Nonetheless, upon analyzing the incremental strength of the stabilized sand with each 1% rise in polymer content and each 0.2% rise in fiber content (as illustrated in Fig. 11), it became evident that the incorporation of either polymers or fibers exerts a distinct influence on the stabilization of the sand's mechanical properties. Consequently, the optimal content levels can be determined by examining the rate of strength enhancement. It can be observed in Fig. 11 that the increase rate of UCS, TS and FS of the stabilized sand as polymer content increased from 1% to 2% is obviously higher compared to the increments from 2% to 3% and 3% to 4%. Across various fiber contents, the average increase rates for UCS, TS, and FS are found to be 194.54%, 235.56%, and 132.26%, respectively. Drawing upon this discernible pattern, it can be concluded that a polymer content of 2% represents the optimal level. Moreover, the solidification time decreases with the increasing content of polymer (Liu et al., 2019). Consequently, a 2% polymer content emerges as the ideal choice, combining significant enhancement effect of mechanical properties with a practical solidification time suitable for application. In contrast, the optimal fiber content is not a constant value based on the increase rate of UCS, TS and FS according to this determination pattern. Figure 11(a) illustrates that the peak increment in UCS occurs within the fiber content range of 0.4% to 0.6%. In comparison, the TS and FS exhibit their maximum increase rates at the intervals of fiber content increased from 0.2% to 0.4% and from 0.6% to 0.8%, respectively. Regarding different polymer contents, the peak average increase rates for UCS, TS, and FS are found to be 58.81%, 41.58%, and 28.51%, respectively. Consequently, the optimal fiber content is determined to be 0.6% for UCS, 0.4% for TS, and 0.8% for FS.

The analysis on sample failure modes

The failure modes of samples subjected to compressive, tensile, and flexural stresses are depicted in Fig. 12. As observed, for UCS test, it is evident that specimens with a lower fiber content ($FC \leq 0.4\%$) exhibit an "X" shaped failure pattern. As the fiber content increases, the central intersecting cracks gradually diminish, thereby reducing the "X" shaped configuration. The specimen sections separated by cracks do not completely disperse under the influence of the fibers, and the specimen remains intact as a whole. Compared to specimens with a fiber content of 0.2%, those with 0.4% fiber content show a significant reduction in the angle between the internal cracks and the horizontal direction, which also reduces the size of the separated sections on either side of the specimen. When the fiber content increases from 0.4% to 0.6%, the failure pattern of the specimens shifts from an "X" shape to a "Y" shape. A primary crack can be observed developing from the upper-middle part of the specimen, dividing into two secondary cracks at the center,

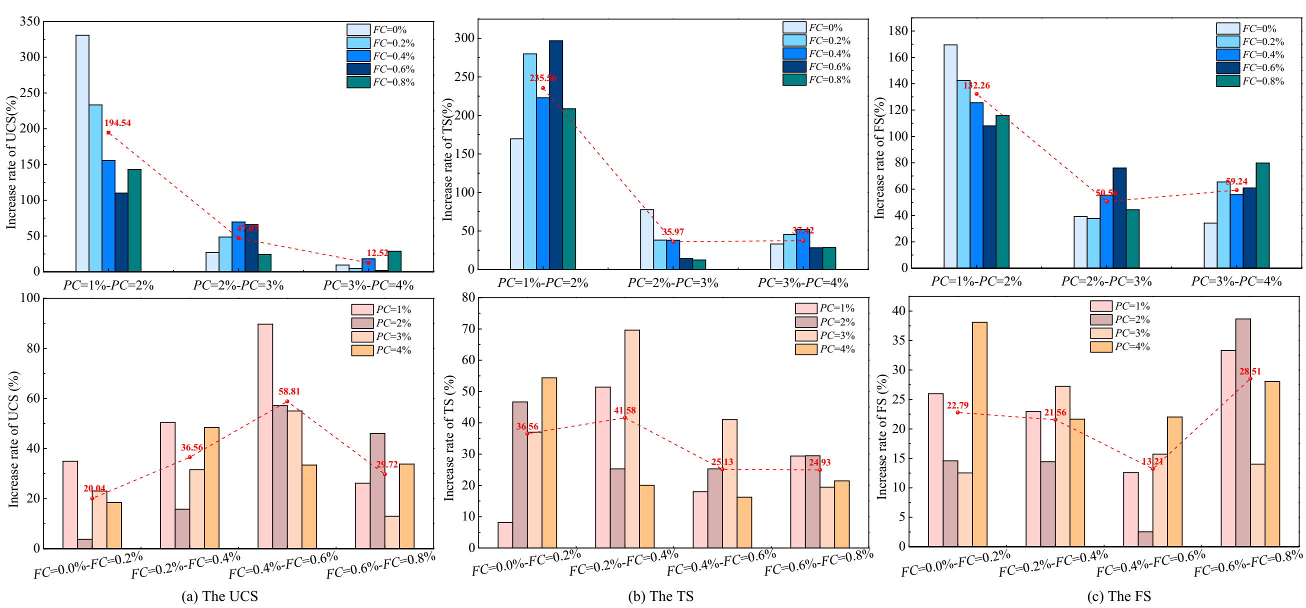


Fig. 11 The strength increase rate of the stabilized sand (**a**) The UCS, (**b**) The TS, (**c**) The FS

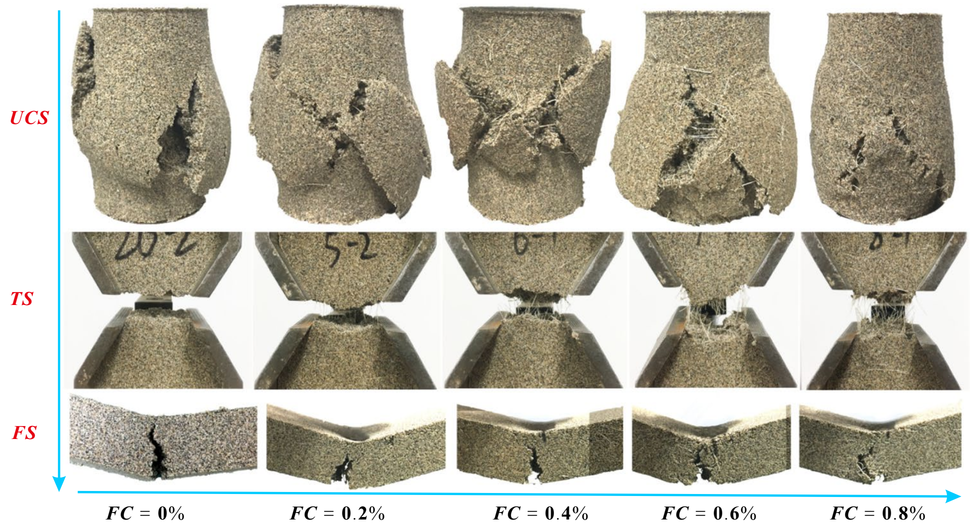


Fig. 12 The failure modes of sand stabilized varying with sisal fiber content

with the development of the cracks being restricted by the fibers, thus maintaining the overall integrity of the specimen. For specimens with a fiber content of 0.8%, the damage characteristics are even less pronounced; only two cracks originating from the middle-lower part of the specimen can be seen, and these cracks gradually heal under the action of the fibers after the external load is removed, nearly preserving the specimen's shape, indicative of significant ductile fracture characteristics.

In addition, for the tensile strength test, as the fiber content increases, the fracture surfaces become more undulating. At a fiber content of 0.2%, the fibers are almost isolated at the fracture surface, providing limited tensile strength. Consequently, the fibers are prone to being pulled out. However, in samples with higher fiber content, under the influence of the polymer, there is a more extensive entanglement and interconnection among the fibers, which can provide greater tensile strength. Typically, the fracture sites in these samples exhibit a phenomenon where the soil particles, enveloped by fibers, undergo cohesive fractures along weak planes. For the tensile strength samples, the inclusion of fibers significantly affects the bending failure pattern of the specimens. As the fiber content increases, the smoothness of the specimen's cross-section progressively decreases. Compared to specimens without fibers, those with fibers exhibit a fracture development that is notably constrained by the fibers under vertical loading. Additionally, the phenomenon of fibers being pulled out can be observed on the surface of the fracture plane. Due to the random distribution and intertwinement of fibers, the resistance to bending provided by the fibers among the sand particles is uneven, resulting in irregular fracture surfaces. These fractures develop preferentially in directions where fiber distribution is sparse or the bonding strength is lower. Furthermore, with an increase in fiber content, a denser network of fibers forms between the sand particles, enveloping them and effectively limiting the bending deformation of the specimens under three-point loading. It is apparent that the reinforcing effect of the fibers limits the deformation tendencies of the sand, and the three-dimensional fiber network formed by a high volume of fibers enhances the elastic properties of the polymer-reinforced soil, increasing its resistance to deformation under external forces and transitioning the material to one with favorable ductile characteristics.

Discussion

Stabilization mechanism of polymer

After the polymer solution was added into the sand, a series of reactions occurred between the polymer solution and the sand particles, including the wetting stage, adsorption stage, hardening and bonding stage. At the wetting stage, the gaps can be filled with the polymer solution, however, the distance of effective "polymer particles" was still large, the effective connection among sand particles has not formed yet (Fig. 13(a)). With the evaporation of water, the polymer solution entered into the second stage, the adsorption stage, at this stage the contact points between polymer and sand particles increased and the distance of "polymer particles" was shortened (Fig. 13(b)), thus, it is the key stage for the formation of the interaction between polymer and sand particles. Otherwise, the addition of polymer could potentially have a lubricating effect on the soil particles, which may not be desirable for the intended reinforcement (Ghasemzadeh et al. 2020). The hardening and bonding stage is the process of water loss and interrelated bonding of polymer films, at this stage, the distance of "polymer particles" was further decreased and jointed together, forming a chain structure

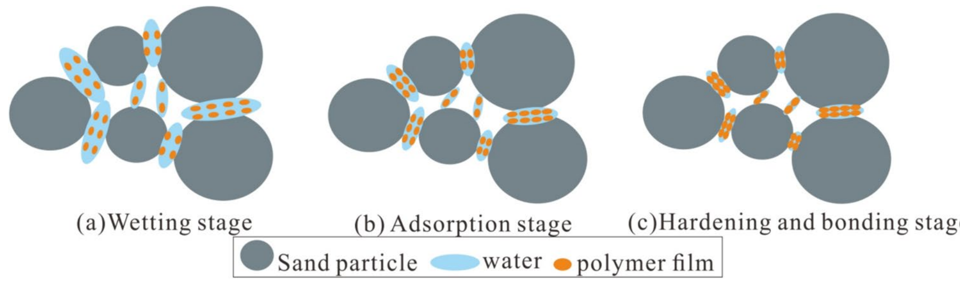


Fig. 13 Microscopic diagram of contact relationship between sand particles and polymer film at different curing stages

(Fig. 13(c)), thus, the connecting force among sand particles was significantly enhanced. Furthermore, as the polymer content increased, the gelatinous polymer elastomer became progressively thicker and more robust, this change resulted in a significant improvement in the mechanical properties of the sand, thereby augmenting its overall stability and resilience (Wang et al. 2022). Additionally, the polymer elastomer can also served as a buffer, enhancing the ductility of the system through its elastic deformation (Liu et al., 2020a). This characteristic effectively mitigated the further opening and propagation of cracks, thereby contributing to the overall structural integrity and durability. As can be visually observed from the SEM images of polymer-stabilized sand, the polymer film adhered to the surface of sand particles, acting as a "bridge" between two separate particles, which connected loose sand into a whole. Besides, the polymer bonding can also enhance the interparticle force by the filling, enwrapping and connecting effect of the polymer (Liu et al. 2018a, 2018b), resulting in the improvement of strength.

Combined stabilization mechanism of polymer and fiber

According to the results of strength tests, the addition of fiber can significantly enhance the mechanical properties of polymer-stabilized sand. For cohesive soils, the fiber-soil interaction was regarded as a combination of cohesion and friction. In contrast, the interaction between fiber and natural sand was mainly provided by friction. However, due to the presence of polymer, sand transformed into clay-like soil, polymer acted as a binder at the particle-particle and fiber-particle interface and hence provided a strong cohesion (Kang et al. 2019; Liu et al., 2020a). Therefore, the strengthening benefit of fibers on the polymer stabilized sand mainly depended on the connecting force, friction and locking force between fiber and sand. The stabilized sand can also be regarded as a three-phase composite material composed of sand, fiber and polymer. In this case, there is a good coupling interaction between fibers and sand particles, thus, fiber has the ability to generate the coordinated deformation with sand particles. In addition, the polymer adhered on the surface of fibers and sand particles can also increase the effective contact area between fibers and particles, which played a beneficial role in increasing the cohesion and interfacial friction between sand particles (Tang et al. 2007).

Considering the stress characteristics of fiber in soil, the orientation of fiber relative to the direction of principal stress will determine the fiber is pulled or compressed. As the fiber experienced tensile deformation, the enhancement effect of fibers on the strength is the most significant. It mainly relied on the interfacial friction between the fiber surface and the soil particles, which limited the deformation of the soil and provides a large tensile strength in the soil (Liu et al. 2020a, 2020b, 2020c), therefore, only fibers in the tensile state (called effective fibers) can play the true fiber reinforcement effect (Zornberg 2002). The schematic diagram of the polymer-fiber-sand interaction is shown in Fig. 14. Once the stabilized sand was subjected to external force, the rearrangement of sand particles happened in a limited space, thus, the fiber under the previously unstressed state will be subjected to pressure or tension. In this situation, the reinforcement effect of the fiber realised, which can provide tensile resistance between the sand particles. With the further increase of external force, the polymer film at the interface of sand particles and fibers may break or slip from the surface of sand particles. In contrast, due to the good tensile strength and ductility of the fiber, it can still provide a remarkable deformation resistance at a large strain, which also accounted for the sand stabilized with more fibers exhibiting better toughness characteristics. During the process of the test, it can be noticed that sliding out from the sand particles is the main failure form of fiber.

The microscopic mechanism of polymer-fiber-sand interactions can be analyzed from the SEM images shown in Fig. 15. As observed, the fibers distributed among sand particles interweaved and connected with each other forming a three-dimensional spatial fiber network (Liu et al. 2020a, 2020b, 2020c). In addition, the joints between fibers acted as anchorage points with the presence of polymer (Fig. 15(b)), which further enhances the anti-deformation ability of the three-dimensional spatial fiber network. Besides, sisal fiber has a rough surface and certain pores (Fig. 15(b)), behaving with good hydrophilicity. Therefore, when the polymer solution was added into the mixture of sand and fiber, with undergoing of the hardening process, the polymer film can

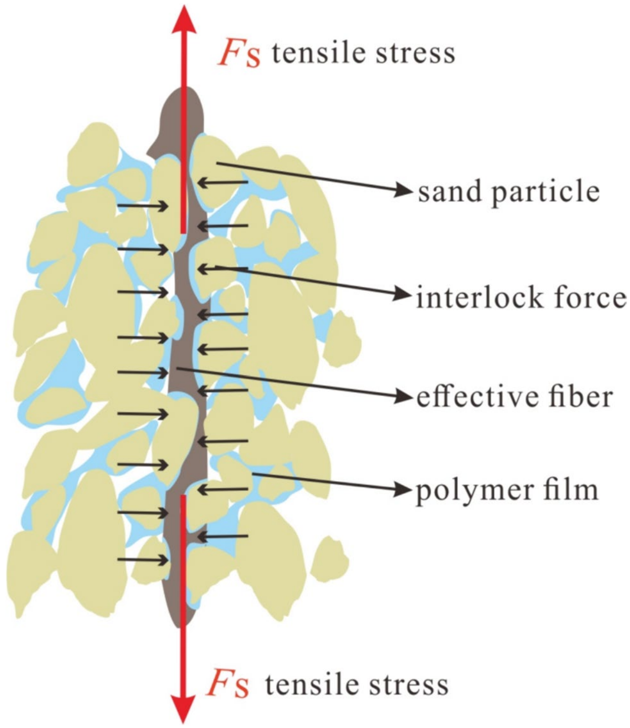
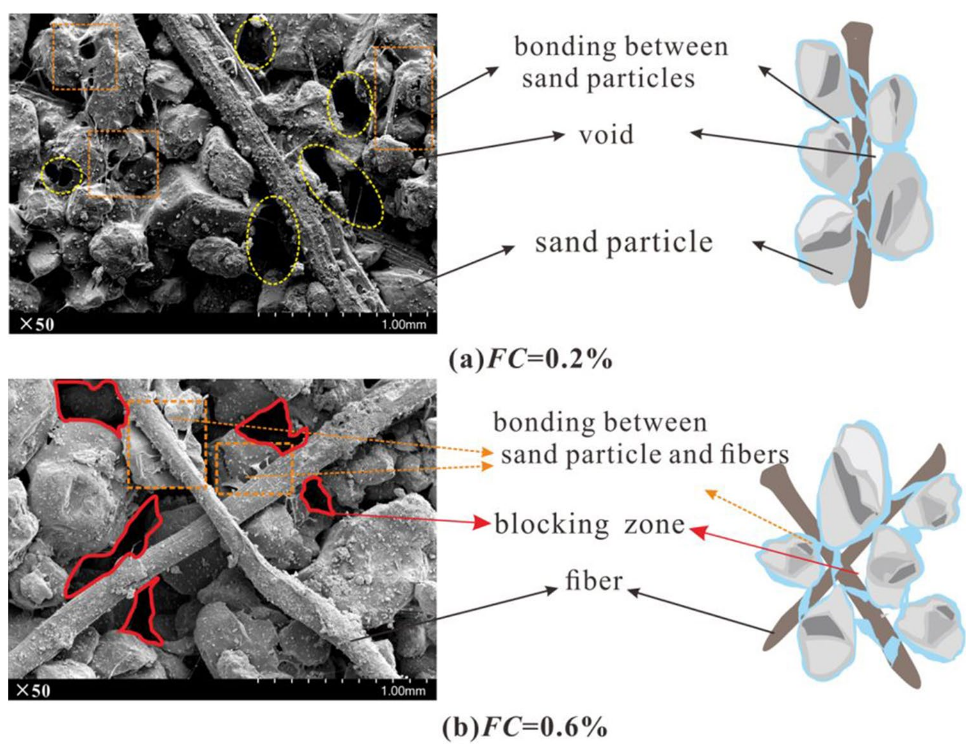


Fig. 14 The schematic diagram of polymer-fiber-sand interaction

effectively adhere to the surface of the fiber and enter its pores, forming an effective bonding and strengthening the interaction between the fiber and sand particles. With a higher polymer content, more binder formed between fibers and sand particles, which further improved the bonding strength. The addition of fibers can also fill the pores between sand particles, similar to the mechanism of reinforced concrete (Huang et al. 2020a, 2020b). With the increase in fiber content, the interwoven connections between the fibers became more significant, forming denser fiber networks. As a consequence, the role of fiber networks in restricting the movement of sand particles became more pronounced.

For samples with low density, it has a loose structure, more voids distributed among sand particles, which cannot be completely occupied with the polymer, thus, the bonding interaction between the sand particles and fibers is weak. As a consequence, the fiber will be easily pulled out from sand particles, and the enhancing effect of fibers was not completely realized. In contrast, with the increment in density, the numbers and sizes of voids became smaller, and the contact between sand-polymer-fiber is closer, the tensile strength of fibers can be fully mobilized. Therefore, the fiber provides greater locking force, which significantly improves the strength of the polymer-stabilized sand. Besides, the effective contact area between sand particles and fibers was greatly increased at well-compacted sand, the occlusal effect of fibers is more pronounced, which significantly improved the cohesion and internal friction angle of sand. In this case, the fiber has more potential to generate coordinated deformation due to the establishment of tight coupling and the greater

Fig. 15 The SEM images of polymer-fiber-sand interaction



effective contact area between fibers and particles with the presence of polymer (Liu et al. 2020a, 2020b, 2020c). As a result, the mechanical properties and the deformation resistance of sand were greatly enhanced.

Conclusion

In this study, a comprehensive series of mechanical properties tests were undertaken to assess the efficacy of utilizing AH polymer and sisal fiber in soil stabilization. The investigation examined the impact of polymer content, fiber content, and soil density on strength development. Drawing upon the findings and discussions, the following conclusions have been derived:

•The combined application of AH polymer and sisal fiber demonstrates considerable potential for enhancing the mechanical properties of sand. The UCS, FS, and TS exhibited linear increments with rising polymer and fiber content. Specifically, for sand containing 1%, 2%, 3%, and 4% polymer, the respective increases in the UCS were 577.1 kPa, 823.7 kPa, 1096 kPa, and 1589.7 kPa, while FS increased by 101.4 kPa, 166.6 kPa, 293.9 kPa, and 620.2 kPa, and TS increased by 88.8 kPa, 304.3 kPa, 273.7 kPa, and 332.5 kPa, respectively, with each 0.2% increment in fiber content. The reinforcing effect of fiber on sand strength is particularly pronounced in samples with higher polymer content. Through an analysis of strength increase rates, the optimal polymer content was determined to be 2%, and the optimal fiber content to be 0.6% for UCS, 0.4% for TS, and 0.8% for FS.

•The relationship between UCS and FS maintains a clear linearity with density. For sand with 2% polymer and 0.8% fiber, TS displayed a linear increase as density rose. Conversely, for sand with 4%polymer and 0.4% fiber, TS exhibited a non-monotonic relationship with density. The introduction of polymer and fiber reduced specimen brittleness, while higher density enhanced it. Additionally, more polymer and fiber content contributed to a higher deformation modulus of stabilized sand.

•Upon drying, the polymer solution within the soil matrix transformed into elastic membranes, serving to bridge and bond the sand particles, thereby establishing a stable structure. In the presence of polymer, the reinforcing effect of fibers was maximized, as the polymer acted as a binder between the fibers and sand particles, resulting in the formation of a 3D fiber network structure and an increase in effective contact area. Consequently, deformation was constrained by the fibers, leading to significant enhancements in the mechanical properties of sand.

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Data Availability Data will be made available on request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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