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Research Article

Studying Shear Performance of Flax Fiber-Reinforced Clay by Triaxial Test

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Laboratory triaxial tests were carried out to investigate the reinforcement mechanism, to study the characteristics of flax fiber-reinforced clay, and to discuss the effect on stress-strain relationship and shear strength parameters of flax fiber-reinforced clay in different flax fiber content and different confining pressure. Respectively, the ratio of fiber content to clay by weight is 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%, and the confining pressure is 100 kPa, 200 kPa, and 300 kPa in triaxial test. The test results show that, the shear strength of flax fiber-reinforced clay is greater than that of pure clay. Compared with the pure clay, the shear strength of flax fiber-reinforced clay increased as the cohesion and friction increased; while the increase of the friction is relatively small, the increase of cohesion is large. The shear strength firstly increased and then reduced with the increase of flax fiber content. When the fiber content was 0.8%, the shear strength reached a peak value, and the shear strength reduced with the further increase of fiber content.

1. Introduction

The strength and antideformation capacity of natural plain soil are often insufficient to meet engineering requirements of soil. The addition of reinforcement to soil can restrict the deformation and increase the strength of soil. At present, the normally used reinforcing materials in soil are fiber, metal bar, and geosynthetics. Among them, the fiber is beneficial to tensile and crack resistances, as it can be evenly distributed in soil, which makes the mechanical properties of fiber-reinforced soil approach to isotropy and effectively make up for the deficiency of traditional reinforced soil [1, 2]. Fiber reinforcement technology is always a hot topic in the research field of soil improvement [3–6]. The results of the previous studies show that the compression strength, the shear strength, the tensile capacity, and the bearing capacity of soil can be effectively improved by the reinforcement of polypropylene and other synthetic fibers. Besides, the strain of soil under failure can be also increased, and the loss of strength can be reduced, which makes the soil sample represent higher toughness [7, 8].

Shear failure of soil often cause disaster in geotechnical engineering. The shear strength of soil can be improved by adding certain amount of fiber. Prabakar and Sridhar [9] and Consoli et al. [10] compared the shear strength index of plain soil with that of fiber-reinforced soil by experiments; the results show that the addition of fiber can increase the shear strength of soil. Yetimoglu and Salbas [11] mentioned that fiber reinforcement had no significant effect on the peak shear strength, but the residual shear strength of sand increased. Zhu et al. [12] studied the interaction between fiber and surrounding soil through shear tests, and then analyzed the reinforcement process and its mechanism of short fiber. In general, direct shear tests and triaxial compression tests are carried out to investigate the shear strength characteristics of fiber-reinforced soil. In terms of direct shear tests, Garry and Ohashi [13] studied the effects of different fiber inclining angles on the working mechanism of fiber-reinforced sand. Welker and Josten [14] conducted a series of direct shear tests to study the shear strength properties of polypropylene fiber-reinforced soil, and the optimum fiber content was determined to be 0.2%. Tang et al. [15] studied the strength characteristics of the fiber-reinforced cement soil. In terms of triaxial compression tests, Gray and Alrefeai [16] carried out triaxial tests on the stress-strain performance of fiber-reinforced sand with

nondiscrete distribution, and the test results show that the fiber increases the axial strain of reinforced sand when it is destroyed, and reduces the loss of postpeak strength. Ranjan et al. [17] carried out triaxial tests on medium and coarse sand reinforced with fiber, and the results show that the peak strength of fiber-reinforced soil is enhanced with the increase of fiber content, and the residual strength is higher than that of plain soil. In addition, the shear strength of fiber-reinforced soil is linearly correlated with the content of fiber. Yetimoglu et al. [18] carried out triaxial tests on fiber-reinforced sand, and the results show that the shear strength of fiber-reinforced sand was obviously increased compared with that of nonreinforced sand. Botero et al. [19] put regenerated polyester resin (PET) fiber into silt and studied the stress-strain characteristics of fiber-reinforced soil by unconsolidated and undrained shear test. The results show that PET fiber can greatly improve the ability of soil to resist deformation. The results of the previously mentioned studies and some other studies show that the strength of fiber-reinforced soil is related to many factors, such as fiber type, content, thickness, length, and so on [20–23].

The aforementioned fiber used in reinforcing soil is mainly artificial synthetic fiber. Although artificial synthetic fiber has the characteristics of high strength, acid and alkali resistance, it is costly and not green in manufacturing and transporting. At the same time, due to the increasingly severe global energy and environmental problems, more and more attention has been paid to the research of natural reinforced materials with the development of ecological civilization [24]. Endo [25] and Wu et al. [26] found that the horizontal and vertical roots of plants could improve the shear strength of soil by laboratory experiments. Ma'Ruf [27] conducted direct shear tests on soil containing plant roots to study the effects of roots of bamboo on the shear strength of soil. Bergado and Bukkanasuta [28] selected bamboo as reinforced material; its reinforcement effect was studied by direct shear tests and pull out tests in laboratory, and the results show that the reinforcement effect of bamboo net is slightly better than that of geogrid. Prabakar and Sridhar [9] used sisal fiber to reinforce silty clay; the effects of fiber content, length, and other factors on the strength parameters and compaction characteristics were investigated by triaxial test and compaction test, and the results showed that sisal fiber can effectively increase the maximum deviatoric stress of clay. Suits et al. [29] carried out triaxial unconsolidated undrained tests on coconut shell fiber-reinforced soft clay, and the tests results showed that 1% is the optimal fiber reinforcement ratio, and the reinforcement effect is more obvious under high confining pressure. Adili et al. [30] pointed out that the friction and cohesion of silt with sandy reached the maximum value when reinforcement ratio of papyrus reaches 10%. Mohamed et al. [31] studied the use of hay fiber to improve the properties of expansive clay. Zekkos et al. [32] tested the mixed soil consists of cardboard and plastic fiber, wood fiber, municipal solid waste, and other fiber, which proves that wood fiber is the best to improve the shear resistance of soil. Anggraini et al. [33] took coconut shell fiber as reinforced material, and considered that fiber content is the main factor affecting the strength of reinforced soil. The abovementioned studies show that natural fiber also performs good reinforcement effects. The acquisition and selection of natural fibers is mostly based on the ecological environment of the project, and there are many kinds of materials that can be selected locally [34]. These studies expand the sources and fields of reinforced material; however, there are relatively few research studies on the behavior of flax fiber-reinforced clay at present.

In this paper, the laboratory triaxial tests were carried out to investigate the mechanical properties and failure characteristics of flax fiber-reinforced clay, by controlling the reinforcement ratio and confining pressure. On the basis of triaxial tests, the relationship between the parameters (principal stress difference, shear strength, cohesion, and fraction) with reinforcement ratio and confining pressure of flax fiber-reinforced clay were investigated. Furthermore, the reinforcement mechanism of flax fiber was also discussed.

2. Materials and Methods

2.1. Materials. The clay used in the triaxial tests was taken from a 9 m deep foundation pit located at Han street in Wuhan, and its physical parameters are listed in Table 1. The fibers used in the test were flax fibers, which were taken from the flax trees on the campus of Hubei University of Technology. The tensile force and deformation curve of the fiber was obtained by a series of tensile tests, the mean values of which are shown in Figure 1, and the mean values of the parameters of the flax fiber are listed in Table 2.

2.2. Methods. TSZ-2 automatic triaxial apparatus (produced by Nanjing soil instrument factory Co., Ltd.) was adopted for the tests. As shown in Figure 2, the apparatus is composed of triaxial instrument and data acquisition system. The triaxial tests of flax fiber-reinforced clay under unconsolidated and undrained (UU) condition were carried out; the loading rate was controlled at 0.50 mm/min; the reinforcement effect of flax fiber on clay was investigated by controlling the fiber content and confining pressure of the sample.

According to the requirements of the Chinese Highway Geotechnical Test Code [35], the samples were prepared for triaxial tests. Flax fibers with the diameter about 0.2 mm~0.4 mm were gathered from natural state; then sheared in length of 20 mm; and the selected clay was dried, mashed, and sifted. The weighed dry clay was mixed with the flax fiber evenly, and the moisture content of the sample was controlled at 15% by adding water. Then the flax fiber-reinforced clay was cured for 24 hours to make its moisture content stable. The reinforced clay weighing 175 g is used for the preparation of each sample, which was compacted in 5 layers by a unified compaction hammer from the same height, and the compaction degree of the samples was controlled; the final size of the samples was 39.1 mm in diameter and 90 mm in height. In order to study the effect of the mass percentage of flax fiber on the strength of reinforced clay, the tests were carried out with 0.2% (0.35 g), 0.4% (0.7 g), 0.6% (1.05 g), 0.8% (1.4 g), and 1.0% (1.75 g) of

Table 1: Parameters of clay.

Natural density (g/cm^3)	Natural moisture content (%)	Liquid limit (%)	Plastic limit (%)
2.027	21.9	38.946	20.4314

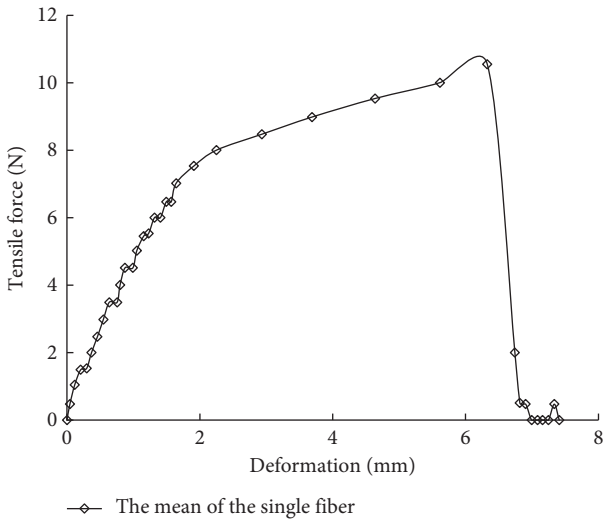

Figure 1: Tensile force versus deformation of flax fiber.

Table 2: Parameters of flax fiber.

Fiber length (mm)	Fiber diameter (mm)	Interface morphology	Ultimate tensile strength (MPa)	Modulus (GPa)
20	0.35	Sub-circular	127.54	0.51

flax fiber, respectively. In order to study the effect of confining pressure on the strength of reinforced clay, the tests were carried out for each group of samples at 100 kPa, 200 kPa, and 300 kPa, and there were 18 group tests in total in this study.

3. Results and Discussion

3.1. The Relationship between Principal Stress Difference ($\sigma_1-\sigma_3$) and Axial Strain (ε_1). The testing results show that the axial strains of the samples are less than 15%. Figure 3 shows the relationship between the principal stress difference ($\sigma_1-\sigma_3$) and the axial strain (ε_1) of pure clay and reinforced clay with fiber content of 0.2% at the confining pressure of 100 kPa, 200 kPa, and 300 kPa, respectively.

As it can be seen from Figure 3, (1) the difference of principal stress difference ($\sigma_1-\sigma_3$) between pure clay and flax fiber-reinforced clay is smaller, and the curves are closer when the axial strain is small ($\varepsilon_1 \leq 1\%$). With the increase of axial strain, the curves are gradually pulling away, and the principal stress difference of the flax fiber-reinforced clay is obviously larger than that of pure clay. (2) The principal stress difference of pure clay peaked at the axial strain less 15%, but that of the flax fiber-reinforced clay did not peak. The principal stress difference and axial strain curve of pure clay presents softening regulation; however, the curve

Figure 2: TSZ automatic triaxial test apparatus.

of principal stress difference and axial strain of flax fiber-reinforced clay presents hardening regulation, which indicates that the addition of flax fiber affects the strength and deformation resistance of clay.

Figure 4 shows the principal stress difference and axial strain relation curve of the flax fiber-reinforced clay under different confining pressures. As it can be seen from Figure 4, (1) the principal stress difference and axial strain curves of the flax fiber-reinforced clay are influenced by confining pressure, namely, the confining pressure affects the shear strength and deformation resistance of flax fiber-reinforced clay. (2) The curves of the flax fiber-reinforced clay are very close under different confining pressures when the axial strain is small ($\varepsilon_1 \leq 1\%$). But with the increasing of the axial strain, the distance of the curves of flax fiber-reinforced clay under different confining pressures is gradually drawn apart and increased, which indicates that the influence of confining pressure on the principal stress difference of flax fiber-reinforced clay is becoming more obvious when the axial strain increases.

Comparing Figure 3 with Figure 4, it can be seen that (1) the difference of principal stress of flax fiber-reinforced clay increases with the increasing of the content of flax fiber, which indicates that fiber content affects the strength and deformation resistance of reinforced clay. (2) When the axial strain is less than 15%, under the confining pressure of 100 kPa, the content of flax fiber increases from 0.2% to 0.8%, the corresponding increments of principal stress difference are 58.38 kPa, 36.14 kPa, and 23.6 kPa, respectively. Under the confining pressure of 200 kPa, the increments of principal stress difference are 83.32 kPa, 86.33 kPa, and 38.9 kPa, respectively. Under the confining pressure of 300 kPa, the increments of principal stress difference are 38.36 kPa, 111.14 kPa, and 120.74 kPa,

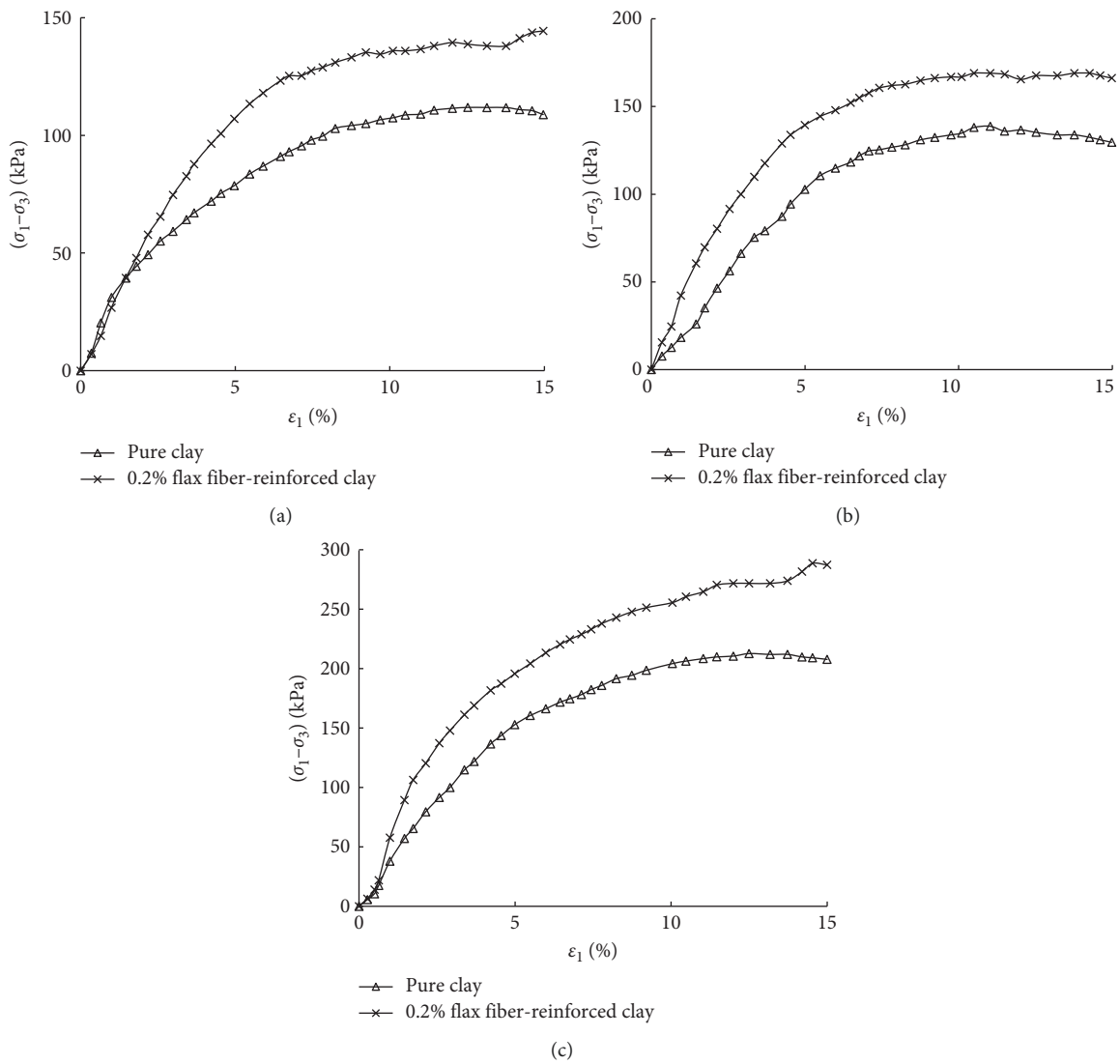

Figure 3: $(\sigma_1-\sigma_3)$ versus ε_1 of pure clay and reinforced clay. (a) 100 kPa confining pressure; (b) 200 kPa confining pressure; (c) 300 kPa confining pressure.

respectively. It shows that the effect of the reinforcement ratio on the strength of reinforced clay is different, and the principal stress difference of flax fiber-reinforced clay changes nonlinearly with the increase of fiber content.

Figure 5 shows the principal stress difference and axial strain relation curves of the tested samples with different flax fiber content at the confining pressure of 200 kPa.

As it can be seen from Figure 5, (1) when the axial strain is small ($\varepsilon_1 \leq 1\%$), the principal stress difference and axial strain relation curves of the pure clay and flax fiber-reinforced clay are closer, but with the increase of axial strain, the distance of the curves of the pure clay and flax fiber-reinforced clay was gradually drawn apart and increased. The results indicate that the reinforcing effect of flax fiber is becoming remarkable when the axial strain increases. (2) Compared with pure clay, the difference of principal stress of flax fiber-reinforced clay is higher, which indicates that flax fiber reinforcement can improve the shear strength of clay. (3) The principal stress difference and axial strain curves of pure clay present softening regulation, but the curves of flax fiber-reinforced clay present hardening regulation; it indicates that the strength and deformation resistance of clay are enhanced by adding flax fiber. (4) The effects of different content of flax fiber on the strength of reinforced clay are different; the difference of principal stress of flax fiber-reinforced clay increases first and then decreases with the increasing of fiber content, which indicates that the best content of flax fiber-reinforced clay exists. (5) When the content of flax fiber is 0.8%, the relative principal stress difference of flax fiber-reinforced clay reaches a peak value; hence, the optimum content of flax fiber-reinforced clay is 0.8%.

3.2. The Relationship between Principal Stress Difference ($\sigma_1-\sigma_3$) and Content of Flax Fiber. Figure 6 shows the relationship between the difference of principal stress and the content of flax fiber. It can be seen that there is a nonlinear

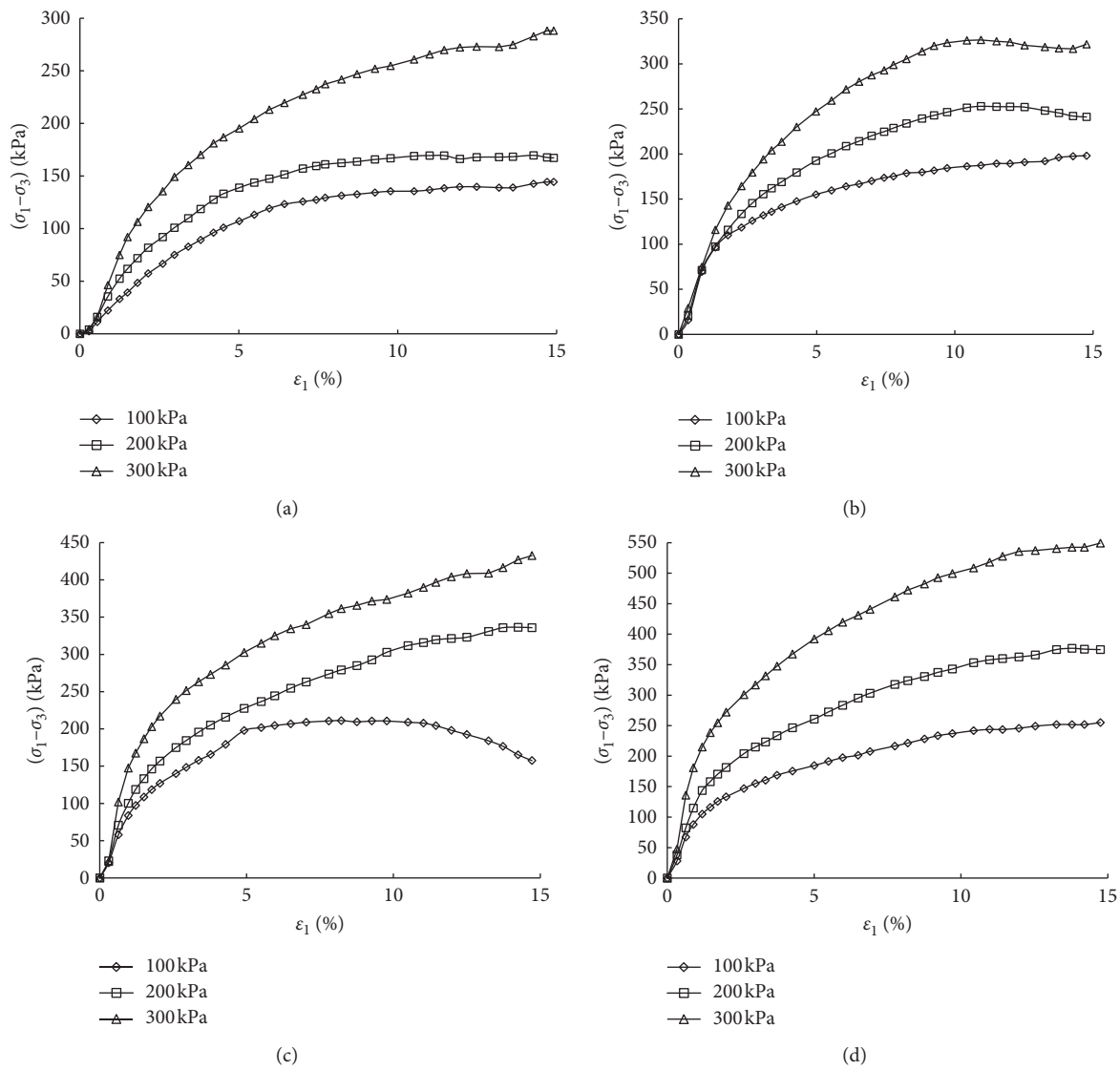

Figure 4: $(\sigma_1-\sigma_3)$ versus ε_1 of soil with various confining pressure. (a) 0.2% reinforcement, (b) 0.4% reinforcement, (c) 0.6% reinforcement, and (d) 0.8% reinforcement.

relationship between the principal stress difference and the content of flax fiber under the same confining pressure, with the increase of content of flax fiber; the principal stress difference of reinforced clay first increases and then decreases, and there exists a peak value, that is the optimum content of flax fiber, and the optimum content of flax fiber measured at this test is 0.8%. When the content of flax fiber in clay is less, the contact area between clay and fiber is smaller. However, with the increase of fiber content, the contact area between fiber and clay extends, the friction resistance between them increases, and the axial deformation decreases, the reinforcing effect of flax fiber is more obvious. The difference of principal stress in the same axial strain is higher than that of the pure clay, and this value increases with the increase of the content of flax fiber until the peak value is reached; when the content of flax fiber exceeds the peak, because of the excessive content of flax fiber, flax fiber accumulates in the clay, which makes the flax fiber not fully be in contact with clay to play the role of reinforcement and forms a kind of "barrier layer," which interrupts the integrity of clay; after reaching the peak value, the principal stress difference decreases with the increase of the content of flax fiber.

3.3. Shear Strength of Flax Fiber-Reinforced Clay. Under the confining pressure of 100 kPa, 200 kPa, and 300 kPa, according to the test results of multiple samples, the mean value was used to draw the Mohr stress circle envelope, and the shear strength indexes of reinforced clay with different flax fiber contents were obtained. Taking the reinforced clay with 0.8% flax fiber as an example, Figure 7 is the Mohr stress circle envelope of reinforced soil with 0.8% content of flax fiber.

The cohesion c and friction angle φ can be obtained by combining the whole test, as listed in Table 3. As it can be

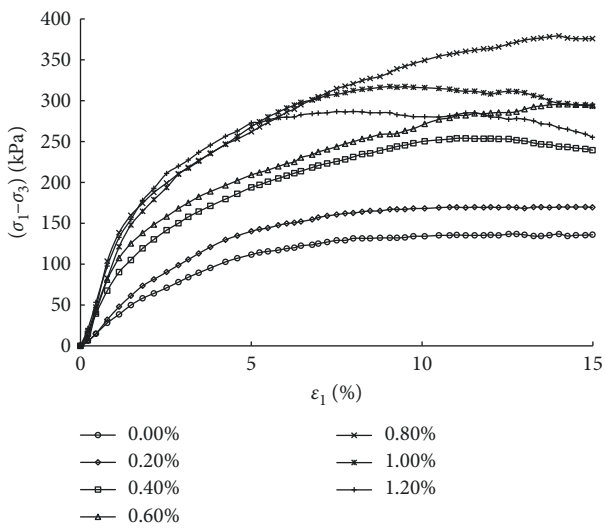

Figure 5: $(\sigma_1-\sigma_3)$ versus ε_1 of reinforced clay.

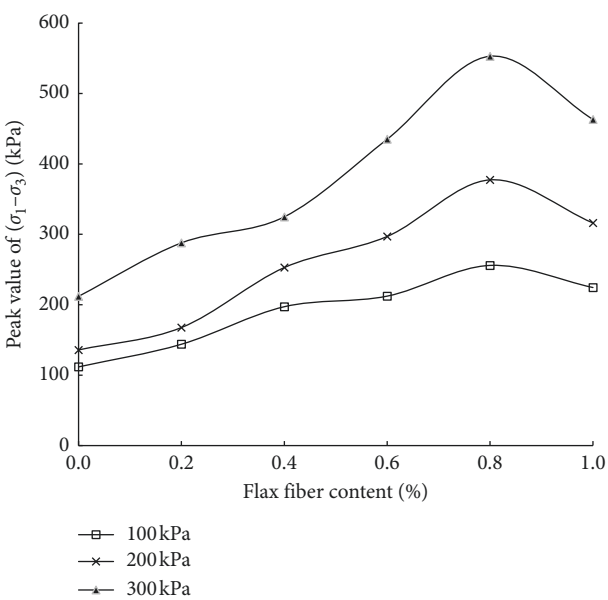

Figure 6: Peak value of $(\sigma_1-\sigma_3)$ versus flax fiber content.

seen in Table 3, the cohesion and friction angle of flax fiber-reinforced clay are improved compared with pure clay; the increase of cohesion is higher, but the increase of friction angle is smaller. When the content of flax fiber is 0.20%, the cohesion of reinforced clay is increased by 3.04%, and the friction angle is only increased by 1.57%. When the content of flax fiber is 0.40%, the cohesion of reinforced clay is increased by 18.22%, and the friction angle is only increased by 10.59%. When the content of flax fiber is 0.60%, the cohesion of reinforced clay is increased by 28.40%, and the friction angle is only increased by 17.65%. When the content of flax fiber is 0.80%, the cohesion of reinforced clay is increased by 39.68%, and the friction angle is only increased by 6.67%. When the content of flax fiber is 1.00%, the cohesion of reinforced clay is increased by 31.00%, and the friction angle is only increased by 3.92%. That is to say, when

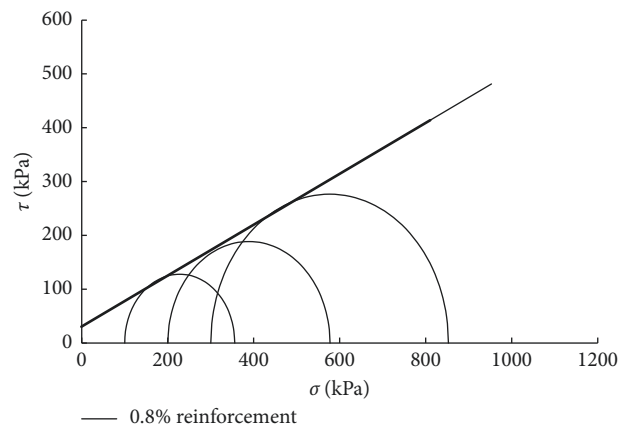

Figure 7: Mohr stress circle envelope of 0.8% reinforcement.

Table 3: Shear strength parameters.

Flax fiber content (%)	Shear strength index C (kPa)	φ (°)
0.0	34.9	25.5
0.2	35.96	25.9
0.4	41.26	28.2
0.6	44.81	30
0.8	48.75	27.2
1.0	45.72	26.5

the content of flax fiber is greater than 0.80%, the cohesion of reinforced clay is mostly increased, and the friction angle is slightly increased; it shows that the effect of flax fiber-reinforced clay is mainly reflected in the increase of cohesion.

3.4. Discussion on Reinforcement Mechanism of Flax Fiber-Reinforced Clay. By analyzing the results of triaxial tests, it can be seen that the mechanical properties of flax fiber-reinforced clay have been improved; its shear strength parameters have been enhanced, namely, the cohesion and friction angle of the clay have been increased by adding flax fiber. The increment of cohesion is higher and the increment of friction angle is smaller, which indicates that the reinforcement of flax fiber mainly affects the cohesion of reinforced clay.

The reinforcement mechanism of flax fiber-reinforced clay can be explained by analyzing the state of fiber in reinforced clay. Flax fiber is randomly distributed in clay in the state shown in Figure 8, and the clay particles in the tests are discrete under a certain degree of compaction, the pores among particles are compressed, and the particles are mainly in surface contact state. When flax fibers are mixed in clay, it connects with clay particles; hence, the bonding between particles is strengthened. Besides, the integrity of reinforced clay is enhanced, the deformation and displacement of clay particles are effectively constrained, and the cohesion of reinforced clay increases. Thus, the shear strength of reinforced clay is improved. When the content of flax fiber is not high, the main distribution state of flax fiber in clay is as shown in Figures 8(a) and 8(b), and the distribution of flax

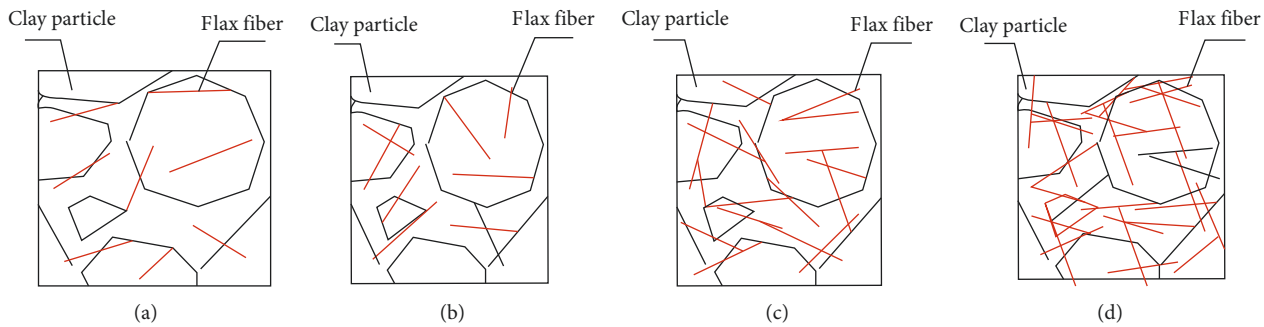

Figure 8: Distribution diagram of flax fiber. (a) Low content, (b) lower content, (c) optimum content, and (d) excessive content.

fiber in clay is more uniform, in a state of disjoint and partial or local intersecting; therefore, the tension of flax fiber strengthens the bond among clay particles, which enhances the shear strength of clay. When the content of flax fiber approaches the optimum content, the main distribution state of flax fiber in clay is as shown in Figure 8(c), the agglomeration of flax fiber in clay increases, and the interlacing among flax fiber is more obvious. Therefore, the flax fiber interlaces with each other and forms a network structure, and the local strengthening cell is formed; hence, the integrity of the clay sample increases, and the movements of the interlacing points caused by external force can be limited by the adjacent flax fiber when one of the fiber is stripped, so that the external forces can be transferd among the flax fibers. The flax fiber can withstand tension in all directions, realizing the decomposition of the force, promoting in the redistribution of internal forces in the sample. When the fiber content is more than the optimum content, the distribution of the fiber in the clay is obviously uneven, compared with the previous low content, as shown in Figure 8(d), part of the fibers is locally concentrated in clay, most of the fibers cannot contact with the clay particles, and thus they cannot fully play the role of reinforcement; these fibers separate the clay particles, and the integrity of clay is destroyed.

The flax fiber is randomly distributed in the clay, forming numerous interrelated local reinforcing cells in the clay; the reinforcing effect of this kind of local reinforcing cell mainly comes from the friction resistance between the fiber and clay and the spatial constraint of the fibrous network formed by the flax fiber.

4. Conclusions

The flax fiber reinforcement can both improve the properties of clay and reduce the engineering cost as it is a natural reinforcement material. From the laboratory triaxial test of flax fiber-reinforced clay, the following conclusions can be drawn.

(1) As a reinforcement material, flax fiber can improve the strength and resist deformation of clay; the reinforcement effect of flax fiber is more obvious when the axial strain is larger.

(2) The cohesion and friction angle of the reinforced clay are increased, but the increase of friction angle is smaller than that of the pure clay.

(3) There is a nonlinear relationship between principal stress difference, shear strength, and fiber content. With the increasing of fiber content, the difference of principal stress and shear strength increase first and then decrease, and there exists a peak value, which is corresponding to the optimum flax fiber content of reinforced clay, and the optimum content is 0.8% at the confining pressure of 200 kPa.

(4) The reinforcement mechanism of flax fiber is that the randomly distributed fiber in clay bend and interweave to form "local strengthening cell," and the reinforcing effect of this kind of "local strengthening cell" mainly comes from the friction resistance between the fiber and clay and the spatial constraint of the fibrous network formed by the flax fiber.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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