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Research Article

Effect of Freeze-Thaw Cycles on Shear Strength Properties of Loess Reinforced with Lignin Fiber

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Freeze-thaw cycles caused by climate change can change the structure and strength of the soil. In seasonally frozen soil areas, the use of improved loess as a filling material must consider the effects of freeze-thaw cycles. With the increasingly severe global environmental problems, the search for suitable new environmental protection improvement materials has become one of the hotspots in soil performance improvement research. The purpose of this paper is to use lignin fiber to improve the engineering performance and freeze-thaw resistance of loess and to reduce the negative impact of engineering construction on the environment of the loess area. Based on a series of triaxial shear tests, the effects of freeze-thaw cycles on the stress-strain relationship, shear strength, and Mohr-Coulomb's strength parameters of loess reinforced with lignin fiber were analyzed. Combined with the volume change and microstructure characteristics of fiber-reinforced loess before and after the freeze-thaw cycles, the reasons for the effects of the freeze-thaw cycles on the shear strength characteristics of fiber-reinforced loess are discussed. The research results showed that after 15 freeze-thaw cycles, the shear strength of loess reinforced with 1% fiber increased by 0.15%, 2.05%, and 1.35% at 80, 140, and 200 kPa, respectively. The shear strength of the reinforced loess with other fiber contents decreases to different degrees, and the maximum reduction ratio can reach 9.54%. Freeze-thaw cycles changed the variation of shear strength and strength parameters with fiber content. When the fiber content is less than 1%, the shear strength, cohesion, and friction angle of fiber-reinforced loess increase the fastest after freeze-thaw cycles. When the fiber content is 1%, the overall destruction effect of freeze-thaw cycles on fiber-reinforced loess is inhibited, and the soil has the best freeze-thaw resistance.

1. Introduction

Loess is a kind of Quaternary loose deposit with loose structure, high porosity, weak cementation, and mainly silt [1, 2]. Typical loess has obvious grid-like overhead pores and vertical joints and often exhibits strong water and dynamic load sensitivity [3–5]. In loess-covered areas, engineers usually treat the loess before using it as a filling material to make its performance meet the engineering requirements [6, 7]. However, since most of the loess distribution area belongs to the seasonal frozen soil area, the effect of the freeze-thaw cycle caused by climate change on the treated loess is inevitable. The ice lens formed when the soil is frozen will cause the separation of soil aggregates and the weakening of the connection between soil particles. This will lead to the weakening of the soil structure and deterioration of the mechanical properties of the soil and eventually even affect the safe operation of the infrastructure system [8–11]. Thus, when using treated loess as fill material in seasonally frozen soil areas, the effects of freeze-thaw cycles must be considered [12, 13].

Improvement treatment is a common method to improve the mechanical properties of loess. In recent years, many studies on the effects of freeze-thaw cycles on the mechanical properties of improved soils have been reported one after another. However, due to different focuses, the types of materials used by researchers are also different. Some researchers still use traditional chemical additives such as cement, lime, and fly ash as soil performance improvement materials, such as Tebaldi et al. [14] and Zhang et al. [15] who studied the effect of freeze-thaw cycles on the shear strength of lime-improved clay and loess. Liu et al. [16] studied the inhibitory effect of cement on the negative effects of soil shear strength caused by freeze-thaw cycles. Solanki et al. [17] studied the effect of fly ash addition in reducing the effect of freeze-thaw effect on the strength of silt and clay. However, these research results show that traditional chemical additives can improve the ability of soil to resist the effects of freeze-thaw cycles based on enhancing the strength of the soil. But, with the increasingly severe global environmental problems, a large number of carbon emissions and the consumption of renewable mineral resources caused by the production of traditional chemical additives and environmental pollution have become unignorable [18–20]. Numerous studies on the mechanical properties of soil under freeze-thaw cycles using new additives as improved materials have begun to emerge. In these studies, fiber materials have been widely used for their advantages in enhancing the mechanical properties of soil through physical action and showed a good effect of soil performance improvement. Orakoglu and Liu [21] found that adding basalt fiber can reduce the attenuation ratio of shear strength and cohesion of clay under the action of freeze-thaw cycles. Kravchenko et al. [22] and Eskisa and Altun [23] found that the weakening effect of freeze-thaw cycles on the shear strength and compressive strength of polypropylene fiber reinforced soil was less than that of unreinforced soil. Liu et al. [24] found that the effect of freeze-thaw cycles on the unconfined compressive strength of the clay becomes smaller after adding cotton fiber. Güllü et al. [25] found that jute fiber can effectively prevent the postpeak strength of the soil reduce after the freeze-thaw cycles and can control the tensile cracking of the soil. Ahmadi et al. [26] found that adding glass fiber to the clay can prevent the shear strength of the soil from decreasing during the freeze-thaw cycles. A wide variety of fibrous materials play a very active role in reducing the effects of freeze-thaw cycles on soil strength. This greatly enhances the researchers' confidence in using suitable environmentally friendly fiber materials to replace traditional chemical additives to improve the freeze-thaw resistance of the soil.

Lignin fiber is an environmentally friendly fiber material with a huge storage capacity in nature. It has the advantages of strong reproducibility, low production cost, and hardly any effect on the environment [27]. At present, many studies on using lignin substances as soil performance improvement materials have been reported one after another. Alazigha et al. [28] studied the mechanism of lignosulfonate to improve expansive soil. Yang et al. [29] studied the compressive strength, durability, and microstructure characteristics of different types of soil stabilized with biofuel by-products (BCP) containing lignin. Zhang et al. [30–32] used lignin stabilized silt as the research object and studied the basic engineering properties and microstructure characteristics of stabilized soil, the non-destructive prediction method of stabilized soil strength considering the shear wave velocity, and the method of estimating the strength of stabilized soil based on the falling cone test method. Kong et al. [33] studied the effect of lignin content on the compaction performance, compressive performance, and water stability of silt. Zheng et al. [34] studied the possibility of alkali lignin as a soil stabilizer based on the unconfined compressive strength test. Liu et al. [35] studied the geotechnical application technology of sulfur-free lignin as a soil stabilizer from the aspects of engineering properties, microstructure characteristics, mineral composition, and functional groups. Fernandez et al. [36] studied the compressive strength of calcium lignosulfonate stabilized high-swelling clay soil and the mechanism of calcium lignosulfonate inhibiting soil swelling. Wang et al. [37, 38] studied the dynamic elastic modulus and damping ratio of lignin-modified loess and analyzed the mechanism of lignin to modify loess in combination with the microstructure and mineral composition of the modified loess. Gao et al. [39] studied the preparation method of lignin fiber in improved soil samples. Although these studies have achieved rich results, there are still few studies on improving the mechanical properties of soil under freeze-thaw cycles. In particular, the research on the effect of freeze-thaw cycles on the shear strength of loess reinforced with lignin fiber has not been reported yet and needs to be carried out urgently.

To clarify the effects of freeze-thaw cycles and fiber content on the mechanical properties of loess reinforced with lignin fiber, this study uses shear strength and Mohr-Coulomb's strength parameters as the analysis indicators. Through a series of experiments, this paper analyzes the change rule of the strength of loess reinforced with lignin fiber under different conditions. The reasons for the differences in the change rule of the shear strength characteristics of loess reinforced with different fiber content during freeze-thaw cycles were also discussed. The research results have positive significance for the use of lignin fiber to enhance the mechanical properties and freeze-thaw resistance of loess in seasonally frozen soil areas, carry out related engineering design, and reduce the negative impact of engineering construction on the environment of the loess area.

2. Materials and Methods

2.1. Materials. The loess used in this study was taken from Pangwan Village, Xiji County, Ningxia Hui Autonomous Region, China. The typical loess is light yellow with uniform texture and no obvious large particles (Figure 1). Its physical properties and particle size distribution are measured following the Standard for geotechnical testing method: GB/T50123-2019 and listed in Table 1 [40]. The lignin fiber used in the study comes from Hebei Province of China, which is white, has no peculiar smell, and contains some detritus particles. The fiber length is about 1 mm, the average diameter is about 40 μm, the bulk density is about 370 g/L, water content is less than 5%, ash content is 18%, the heat-resisting ability is 230°C, and pH is 7.0.

Figure 1: Loess and lignin fiber used in the study.

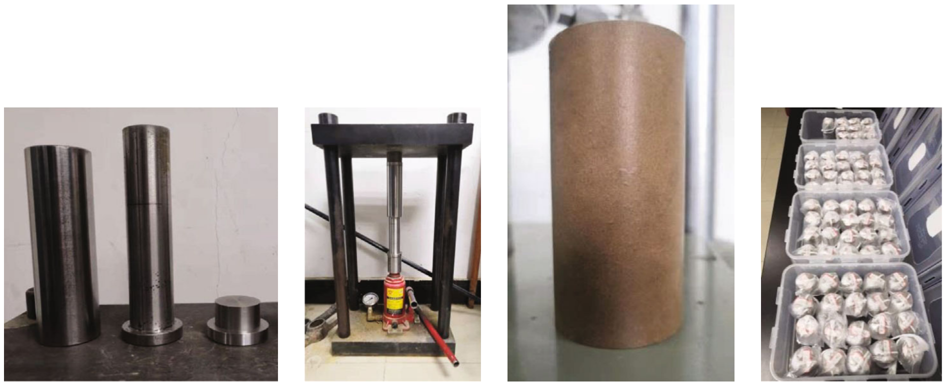
Table 1: Physical properties and particle size distribution of loess.

Property	Value
Specific gravity, G_s	2.72
Grain composition (%)	
Clay ($d \leq 0.005$ mm)	6.1
Silt ($0.005 < d \leq 0.075$ mm)	79.9
Sand ($0.075 < d \leq 2$ mm)	14.0
Liquid limit, w_L (%)	24.0
Plastic limit, w_P (%)	14.5
Maximum dry density, ρ_{dmax} (g/cm^3)	1.79
Optimum water content, w_{opt} (%)	14.5
Cohesion (kPa)	35.4
Frictional angle (°)	30.3

2.2. Sample Preparation. Before sample preparation, the natural loess needs to be crushed and put into a large basin to be naturally air-dried until dry. During the air-drying period, the loess is stirred every day to ensure that the loess is evenly air-dried. After the loess is air-dried, test the water content of air-dried loess, and complete the preparation calculation. Preparation calculations are based on the maximum dry density and optimal moisture content of loess, the water content of air-dried loess, the compaction degree and size of the sample, and the fiber content, that is, to calculate the weight of materials required to prepare mixed soils with different fiber contents, including the weight of dry loess, the weight of fibers, and the weight of pure water, as well as the weight of mixed soils required to prepare a single sample. Fiber content is the ratio of fiber weight to dry loess weight [38]. The fiber content of the mixed soil material is $m = 0$ %, 1%, 1.5%, 2%, and 3%, the compaction degree is set to 0.94, and the sample size is 80 mm in height and 39.1 mm in diameter [40, 41]. After the preparation calculation is completed, the sample preparation is carried out according to the following steps: in the first step, a 2-mm sieve is used to remove large particles and impurities in the air-dried loess. In the second step, according to the dry loess weight and fiber weight obtained by preparation and calculation, the dry loess and fibers required for mixing soil materials with different fiber contents are mixed. During the mixing process, fibers are added to the dry loess multiple times for mixing. For each fiber addition, first sprinkle a small amount of fiber evenly on the surface of the dry loess and then stir in one direction for at least 2 minutes until the fiber and loess are evenly mixed. After the fiber and the loess are evenly mixed, repeat the adding and mixing process until all the required fiber is mixed with the dry loess. In the third step, according to the weight of pure water obtained from the calculation results, slowly add pure water to the dry mixed soil material and stir synchronously. In the third step, according to the weight of pure water obtained from the calculation results, slowly add pure water to the dry mixed soil material and stir synchronously. Stop stirring after the pure water and dry mixed soil are evenly mixed. The well-stirred mixed soil materials with different fiber content are sealed in polyethylene bags for 24 hours to ensure that the water in the mixed soil materials has sufficient time to spread evenly. In the fourth step, load the mixed soil material into a cylindrical sample preparation mold with an inner diameter of 39.1 mm according to the weight of mixed soil material required to prepare a single sample obtained from the preparation calculation results (Figure 2(a)). And use a jack to apply pressure from both ends to the mold in turn by double-end static pressure method until the sample reaches the set height (Figures 2(b) and 2(c)). In the fifth step, take out the compacted sample from the mold and measure the diameter and height. After the measurement is completed, the sample is wrapped and sealed with three layers of polyethylene film, and then the sample is placed in a plastic box to wait for the freeze-thaw cycle (Figure 2(d)). The sample is wrapped with multilayer polyethylene film to prevent water loss in the sample during the freeze-thaw cycle. When taking out the sample and wrapping the sample, it is necessary to operate slowly to avoid damage to the sample.

2.3. Test Methods

2.3.1. Freeze-Thaw Procedure. The sealed samples were subjected to freeze-thaw cycles in a closed system. The freeze-thaw cycle was completed using the LK-120G high- and low-temperature test chamber (Figure 3). The test chamber can automatically complete all freeze-thaw cycles according to the set temperature, time, and the number of times. The freezing and thawing temperatures are set to -20°C and 20°C, respectively. This is determined based on comprehensive consideration of the historical meteorological data of the sampling location and the winter limit temperature, as well as the freezing and thawing temperatures of adjacent areas used in the previous research literature [42]. Both the freezing time and the thawing time are set to 12 hours according to the research results of Zhang et al. Their research results show that 12 hours can already ensure that the internal



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

Figure 2: Procedure of sample compaction: (a) sample preparation mold; (b) sample compaction tool; (c) compacted lignin fiber-reinforced loess sample; (d) wrapped samples in the plastic boxes.

(a) (b)

Figure 3: Procedure of sample freeze-thaw cycle: (a) high- and low-temperature test chamber; (b) samples placed in the high- and low-temperature test chamber.

temperature change of the sample meets the requirements [15]. In addition, the number of freeze-thaw cycles used in this study was determined by an early unconfined compressive strength test [43]. The change of unconfined compressive strength of lignin fiber-reinforced loess with freeze-thaw cycles is shown in Figure 4. The compressive strength of reinforced loess changes relatively greatly after 1 and 5 freeze-thaw cycles and has entered a stable state after 15 freeze-thaw cycles. Therefore, the number of freeze-thaw cycles in this study is set to $n = 0$, 1, 5, and 15 times. The freeze-thaw cycle scheme of the samples is shown in Table 2.

2.3.2. Triaxial Shear Test Procedure. After the sample has passed the set number of freeze-thaw cycles, first remove the polyethylene film that wraps the sample and measure the height and diameter of the sample. The samples were then subjected to the consolidation-undrained triaxial shear test.

The instrument used in the triaxial shear test is the triaxial shear equipment produced by Nanjing Water Conservancy and Electric Power Instrument Factory (Figure 5). The triaxial shear equipment has a 25-speed mechanical transmission, and the test results are stable. In the triaxial test, isotropic consolidations are used. The consolidated confining pressures are 80, 140, and 200 kPa, respectively. After the consolidation is completed, the confining pressure remains unchanged, and the sample is sheared by applying axial pressure at 0.24 mm/min. The test is terminated when the axial strain of the sample reaches 20%. The selection of consolidation pressure and axial pressure loading speed and the test operation process are completed in accordance with the requirements of the Standard for geotechnical testing method: GB/T50123-2019 [40].

The height and diameter of the sample are measured using a vernier caliper in accordance with the requirements of the Standard for geotechnical testing method: GB/T50123-2019 [40]. Measure the height three times at different locations of the sample. Take the average of three measurements as the sample height. The diameter of the sample is measured at the upper, middle, and lower parts of the sample, respectively. Add the value of the upper diameter, twice the value of the middle diameter, and the value of the lower diameter. Take a quarter of the sum as the sample diameter.

2.3.3. Scanning Electron Microscope (SEM) Test Procedure. The microstructure of soil is closely related to the macroscopic mechanical properties it exhibits. To analyze the reasons for the change of macroscopic mechanical properties of loess reinforced with lignin fiber under the action of freeze-thaw cycles, the samples were freeze-dried, sanded, pasted, and gold sprayed. Then use KYKY-2800B scanning electron

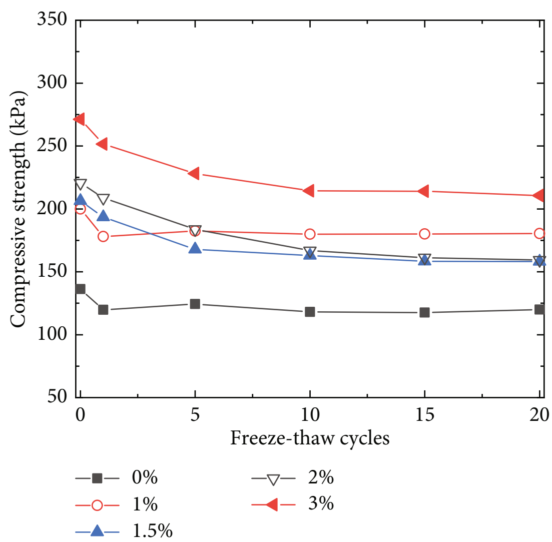


Figure 4: Variation in the unconfined compressive strength with freeze-thaw cycles.

Table 2: Freeze-thaw cycle scheme of sample.

Fiber content (%)	Temperature (°C) Thaw	Temperature (°C) Freeze	Time (hours) Freeze	Time (hours) Thaw	Number of freeze-thaw cycles
0					
1					
1.5	-20	20	12	12	0, 1, 5,15
2					
3					

microscope to obtain the microstructure picture of enhanced loess under 500 times magnification.

3. Results

Based on the above test methods, the test results of loess reinforced with lignin fiber are summarized, including stress-strain relationship, shear strength, Mohr-Coulomb's strength parameters (cohesion and friction angle), volumetric changes, and microstructure characteristics.

3.1. Stress-Strain Relationships. The stress-strain relationship of loess reinforced with lignin fiber can reflect the effect of freeze-thaw cycles on the behavior of loess reinforced with different fiber contents. Figures 6–8 are the stress-strain curves of fiber-reinforced loess after different freeze-thaw cycles when the confining pressure is 80, 140, and 200 kPa.

From Figures 6–8, both fiber-reinforced loess before and after freeze-thaw cycles exhibit strain-softening behavior. And the strain-softening behavior of fiber-reinforced loess is weakened under the action of freeze-thaw cycles. The change of stress-strain relationship of fiber-reinforced loess can reflect the change of soil structure. This change indicates the effect of freeze-thaw cycles on the structure and arrangement of soil particles in fiber-reinforced loess. Under different confining pressures, the softening degree of fiber-reinforced loess under the same conditions is different. At the confining pressure of 80 kPa, the strain-softening behavior of fiber-reinforced loess is the strongest. As the confining pressure increases, the strain-softening behavior of fiber-reinforced loess begins to weaken. At the confining pressure of 140 kPa, the strain-softening behavior of fiber-reinforced loess after different freeze-thaw cycles is weakened. This is consistent with the transformative effect of freeze-thaw cycles and increasing confining pressure on the stress-strain relationship of loess and silt soil found by Zhang et al. and Liu et al. [15, 44].

In addition, the effect of freeze-thaw cycles on the stress-strain relationship of fiber-reinforced loess weakened when the confining pressure increased. At the confining pressure of 80 kPa, except for loess reinforced with 0% and 1% fiber, the effects of freeze-thaw cycles on the stress-strain relationship of reinforced loess are all obvious. The maximum reduction ratios of the deviatoric stress peak of loess reinforced with 1.5%, 2%, and 3% fiber were 5.9%, 3.9%, and 9.4%, respectively. The maximum increase ratios of failure strain of reinforced loess with three fiber contents are 18.2%, 15.7%, and 21.5%, respectively. At the confining pressure of 140 kPa, the effect of freeze-thaw cycles on the stress-strain relationship of loess reinforced with 0% and 1% fiber is also less obvious. And the effect of freeze-thaw cycles on the stress-strain relationship of loess reinforced with 1.5%, 2%, and 3% fiber began to decrease. When the confining pressure reaches 200 kPa, the maximum reduction ratios of the deviatoric stress peak of loess reinforced with 1.5%, 2%, and 3% fiber decrease to 2.1%, 1.0%, and 2.9%, respectively. The maximum increase ratios of the failure strain of the reinforced loess with three fiber contents decreased to 3.5%, 5.2%, and 15.3%, respectively. The stress-strain relationship of only 3% fiber-reinforced loess is relatively significantly affected by freeze-thaw cycles. This indicates that the confining pressure will cause the soil particles to rearrange, close the pores and cracks formed during the freeze-thaw cycle of the reinforced loess, and inhibit the effect of the freeze-thaw cycle on the structural changes of the fiber-reinforced loess. However, the higher the fiber content in the reinforced loess, the greater the confining pressure required to restrain the effects of freeze-thaw cycles.

3.2. Shear Strength. The change rule of shear strength can explain the effect of freeze-thaw cycles on the ability of soil to resist shear failure. The strength at the peak point of the stress-strain curve of fiber-reinforced loess is taken as the shear strength according to the Standard for geotechnical testing method: GB/T50123-2019. That is, the shear strength of fiber-reinforced loess is the difference between the axial stress (σ_1) and the radial stress (σ_3) when the specimen fails in shear. The shear strength of reinforced loess with different fiber contents varies with freeze-thaw cycles, as shown in Figure 9.

As shown in Figure 9, the effects of freeze-thaw cycles on reinforced loess with different fiber contents were different. After 1 freeze-thaw cycle, the shear strength of fiber-reinforced loess decreased overall. After 5 freeze-thaw cycles,

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

Figure 5: Procedure of triaxial shear test: (a) triaxial shear apparatus; (b) installed sample; (c) sample during shearing; (d)) sample after the test.

the shear strength of fiber-reinforced loess was dynamically adjusted, and the shear strength slightly rebounded. This phenomenon of dynamic adjustment of soil shear strength during freeze-thaw cycles is the same as the results of Wang et al. [45]. After 15 freeze-thaw cycles, the fiber-reinforced loess reached a new dynamic equilibrium state during the freeze-thaw cycles. Compared with before freeze-thaw cycles, the shear strength of loess reinforced with 1% fiber at this time increased by 0.15%, 2.05%, and 1.35% under the three confining pressures, respectively. The shear strength of loess reinforced with other fiber content decreased in different proportions, and the maximum decrease proportion was 9.54%. After loess reinforced with 1% fiber reaches a stable state under the action of freeze-thaw cycles, its shear strength is enhanced.

Figure 10 shows the variation of the shear strength of lignin fiber-reinforced loess with fiber content after different freeze-thaw cycles. The shear strength of fiber-reinforced loess before and after freeze-thaw cycles both increased with the increase of fiber content, but the growth laws were different. For fiber-reinforced loess before freeze-thaw cycles, when the fiber content increases from 0% to 1.5%, the shear strength increases linearly. When the fiber content increased from 1.5% to 3%, although the shear strength still generally increased with the fiber content, the increase became slower. Among them, when the fiber content increases from 1.5% to 2%, the increase of shear strength becomes extremely slow. Especially, at the confining pressure of 80 kPa, the shear strength remains almost unchanged. For the fiber-reinforced loess after freeze-thaw cycles, the increased rate of shear strength showed a trend of rapid increase at first and then gradually slowed down with the increase of fiber content. When the fiber content increased from 0% to 1%, the shear strength increased linearly and rapidly. When the fiber content increased from 1% to 3%, the increase of shear strength began to gradually become slower.

3.3. Cohesion and Friction Angle. According to the triaxial shear test results of the samples under different conditions, the failure principal stress line of the sample is drawn with $(\sigma_1 - \sigma_3)/2$ as the ordinate and $(\sigma_1 + \sigma_3)/2$ as the abscissa under different confining pressures, where σ_1 is the failure axial stress and σ_3 is the corresponding failure radial stress. The general behavior of failure principal stress line can be expressed as [45]:

$$\frac{\sigma_1\text{-}\sigma_3}{2} = a + \frac{\sigma_1 + \sigma_3}{2} \times \tan\alpha, \tag{1}$$

where a is the longitudinal intercept of the failure principal stress line and α is the slope. According to the Mohr-Coulomb failure criterion, the formulas for calculating cohesion (c) and friction angle (φ) of soil are as follows [40, 45]:

$$\varphi = \sin^{-1}(\tan\alpha), \qquad c = \frac{a}{\cos\varphi}. \tag{2}$$

The change rule of Mohr-Coulomb's strength parameters of reinforced loess with different fiber contents with freeze-thaw cycles is shown in Figure 11. From the figure, freeze-thaw cycles reduce the cohesion of fiber-reinforced loess. After 1 freeze-thaw cycle, the cohesion of fiber-reinforced loess decreases the most. The cohesion of loess reinforced with 0%, 1%, 1.5%, 2%, and 3% fiber decreased by 4.6%, 11.8%, 19.3%, 11.1%, and 19.9%, respectively. After 5 freeze-thaw cycles, the cohesion of loess reinforced with 0%, 1%, 1.5%, and 2% fiber showed an overall small increase. The cohesion of loess reinforced with 3% fiber continued to decrease. After 15 freeze-thaw cycles, the cohesion of reinforced loess with different fiber contents all decreased again. From 5 freeze-thaw cycles to 15 freeze-thaw cycles, the cohesion of loess reinforced with 0%, 1%, 1.5%, 2%, and 3% fiber, respectively, decreased by 9.5%, 2.8%, 4.1%, 6.5%, and 1.3%. The cohesion of loess added with lignin fiber changes very small.

The effects of freeze-thaw cycles on the friction angle of reinforced loess with different fiber contents were different. After 1 freeze-thaw cycle, the friction angle of unreinforced loess ($m = 0\%$) decreased by 2.1%. On the contrary, the friction angle of loess reinforced with 1%, 1.5%, 2%, and 3% fiber increased by 2.5%, 4.9%, 3.3%, and 3.9%, respectively. After 5 freeze-thaw cycles, the friction angle of loess reinforced with 0% and 3% fiber still decreased and increased, respectively. The friction angles of loess reinforced with other fiber contents fluctuated slightly. From 5 freeze-thaw

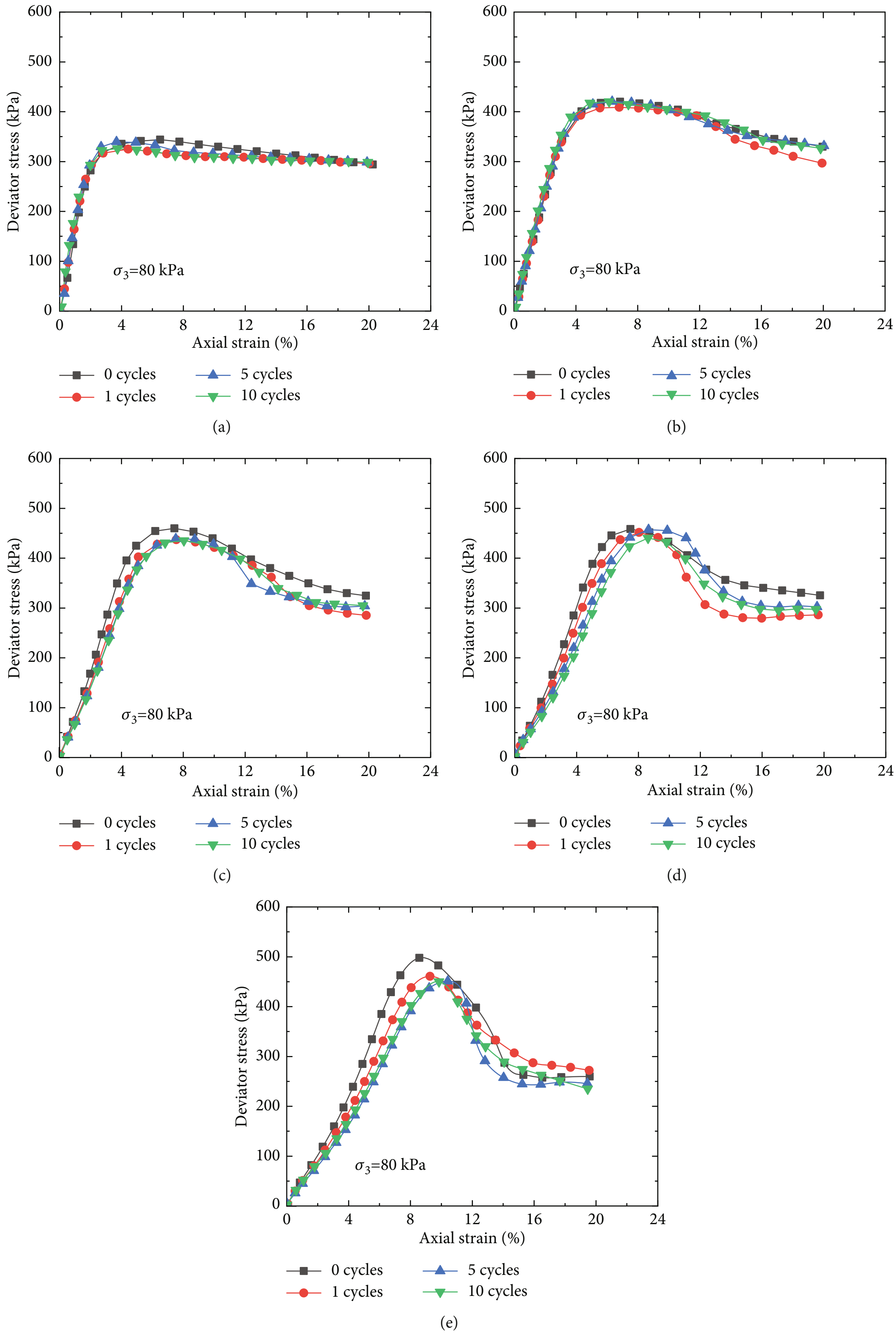


Figure 6: Stress-strain curve (σ_3 = 80 kPa) of lignin fiber-reinforced loess with different fiber content: (a) 0%, (b) 1%, (c) 1.5%, (d) 2%, and (e) 3%.

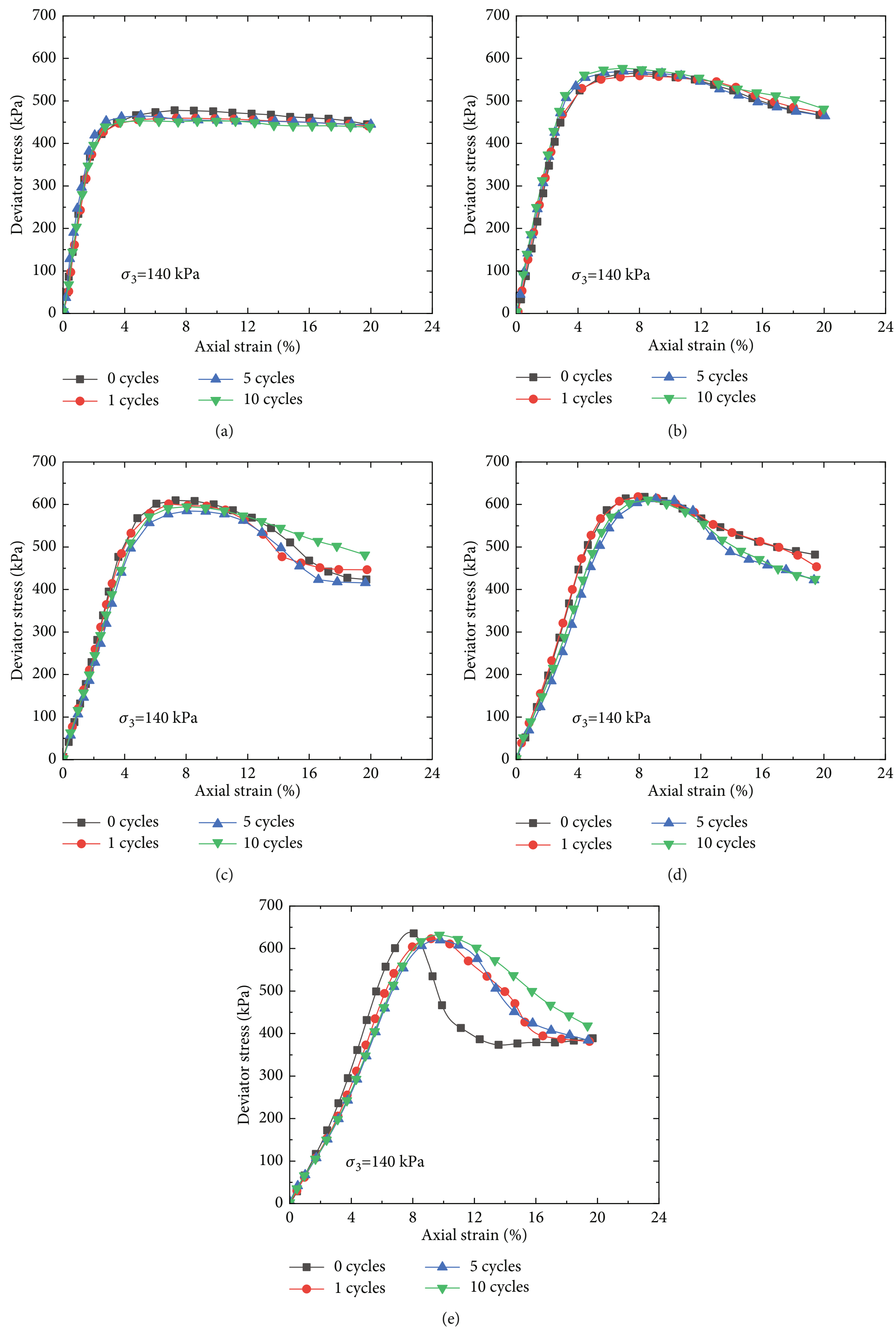


Figure 7: Stress-strain curve (σ_3 = 140 kPa) of lignin fiber-reinforced loess with different fiber content: (a) 0%, (b) 1%, (c) 1.5%, (d) 2%, and (e) 3%.

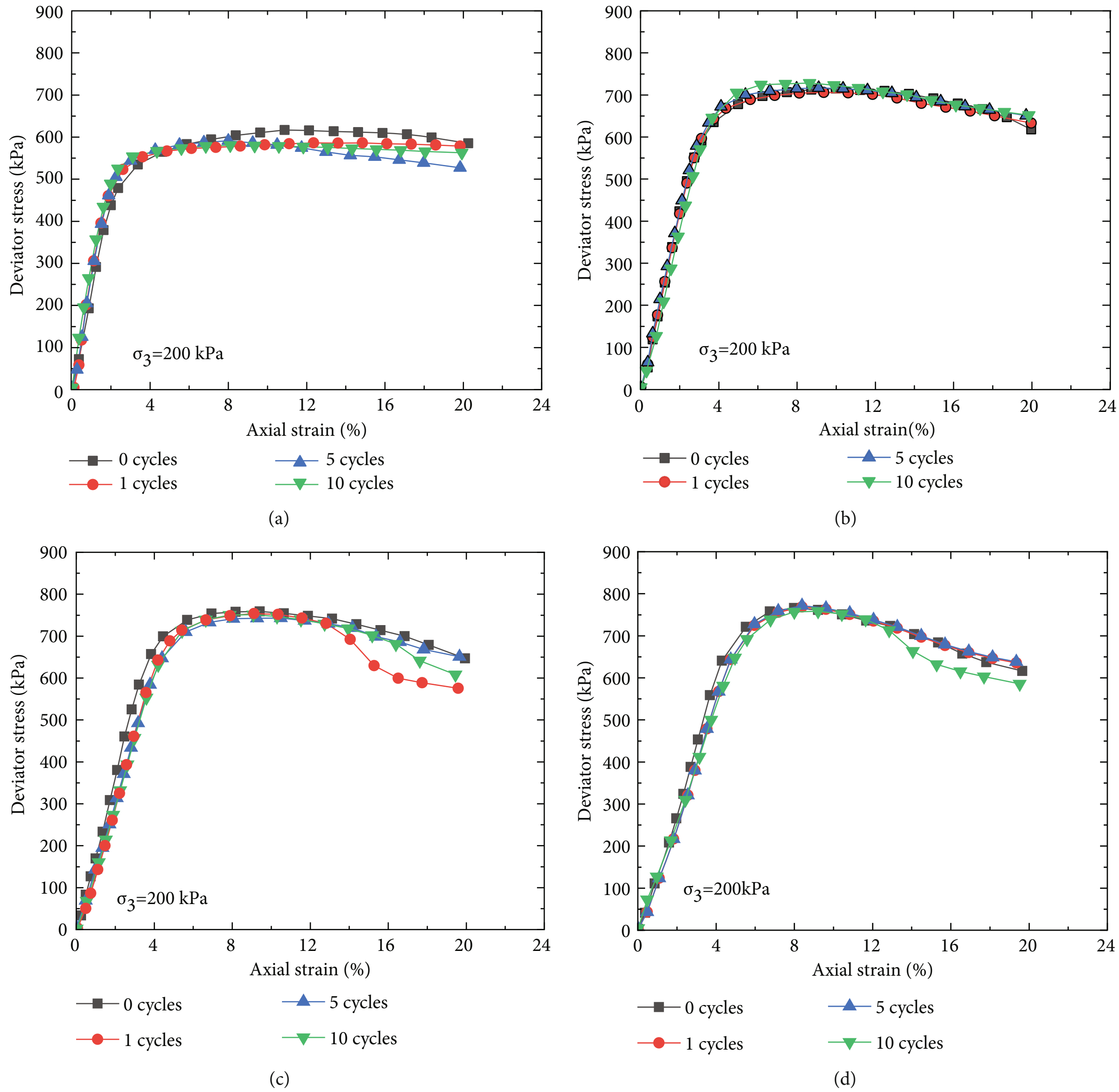
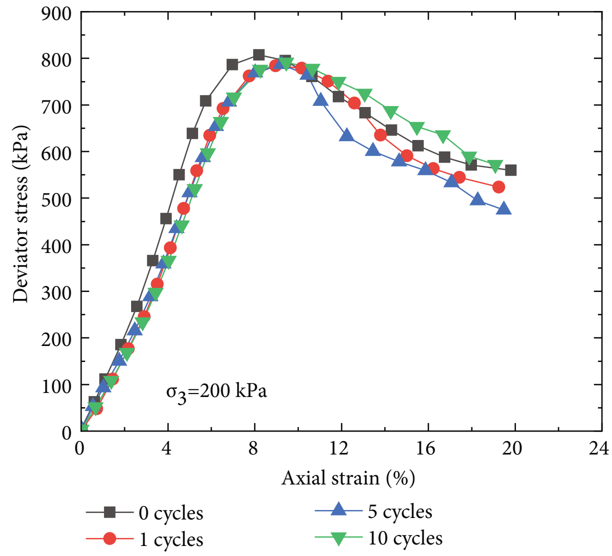


Figure 8: Continued.



(e)

FIGURE 8: Stress-strain curve ($\sigma_3 = 200$ kPa) of lignin fiber-reinforced loess with different fiber content: (a) 0%, (b) 1%, (c) 1.5%, (d) 2%, and (e) 3%.

cycles to 15 freeze-thaw cycles, the change rates of friction angle of loess reinforced with 0%, 1%, 1.5%, 2%, and 3% fiber were 0.7%, 1.3%, 1.6%, 0.6%, and 0.8%, respectively. The changes are very small and remain stable. In general, the friction angle of unenhanced loess ($m = 0\%$) showed a trend of decreasing at first and then tending to be stable under the action of freeze-thaw cycles. The friction angle of loess reinforced with 1%, 1.5%, 2%, and 3% fiber showed a trend of increasing first and then tending to be stable under the action of freeze-thaw cycles. After adding lignin fibers to loess, the effect of freeze-thaw cycles on the friction angle of loess changed from weakening to strengthening. Lignin fiber changed the effect of freeze-thaw cycles on the friction angle of loess.

The effect of freeze-thaw cycles on the reduction of the cohesion of loess reinforced with lignin fiber is consistent with the research results of Kravchenko et al. and Ahmadi et al., but the effect on the friction angled is different from their research results [22, 26]. Kravchenko et al. found that the cohesion of clay reinforced with polypropylene fiber and clay reinforced with basalt fiber decreased under the action of freeze-thaw cycles. But the friction angle of fiber-reinforced clay after 15 freeze-thaw cycles had little change compared with those before freeze-thaw cycles. Ahmadi et al. found that after adding glass fiber, the cohesion and friction angle of fiber-reinforced clay decreased under the action of freeze-thaw cycles. This change in friction angle reduction is consistent with the change in the unreinforced loess ($m = 0\%$) in this paper but is opposite to the change in the loess with added lignin fiber.

Figure 12 shows the variation of Mohr-Coulomb's strength parameters of fiber-reinforced loess with fiber content after different freeze-thaw cycles. For fiber-reinforced loess before freeze-thaw cycles, when the fiber content increased from 0% to 1.5%, the cohesion increased linearly. When the fiber content increased from 1.5% to 2%, the cohesion increased slightly negatively. When the fiber content increased from 2% to 3%, the cohesion started to increase again. When the fiber content is less than 1.5%, the cohesion of fiber-reinforced loess before freeze-thaw cycles increases the fastest. After freeze-thaw cycles, the change rule of cohesion of fiber-reinforced loess with fiber content was changed. After 1 freeze-thaw cycle, the cohesion increased first and then stabilized with the increase of fiber content. After 5 freeze-thaw cycles, the cohesion increased first and then decreased with the increase of fiber content. The changing trend of cohesion of fiber-reinforced loess after 15 freeze-thaw cycles is the same as that of 5 freeze-thaw cycles. The cohesion of reinforced loess with fiber content less than 1% increased the fastest with the increase of fiber content under freeze-thaw cycle conditions.

The friction angle of fiber-reinforced loess before and after freeze-thaw cycles both increased with the increase of fiber content, but the increasing trend and speed were different. Before freeze-thaw cycles, the friction angle of fiber-reinforced loess showed an approximately linear increase trend, but the increase rate was small. When the fiber content increased from 0% to 3%, the friction angle only increased by 1.62 degrees. After freeze-thaw cycles, the friction angle showed an increasing trend of increasing rapidly at first and then increased slowly. After 1, 5, and 15 freeze-thaw cycles, when the fiber content increased from 0% to 1%, the friction angle increased by 2.19, 2.77, and 3.02 degrees, respectively. When the fiber content increased from 1% to 3%, the friction angle increased by 1.44, 2.12, and 1.97 degrees, respectively. When the fiber content is less than 1%, the friction angle of the fiber-reinforced loess under freeze-thaw cycles increases the fastest.

3.4. Volumetric Changes. The phase change of water in the sample during freeze-thaw cycles can cause the volume of the sample to change. The difference in a volume change

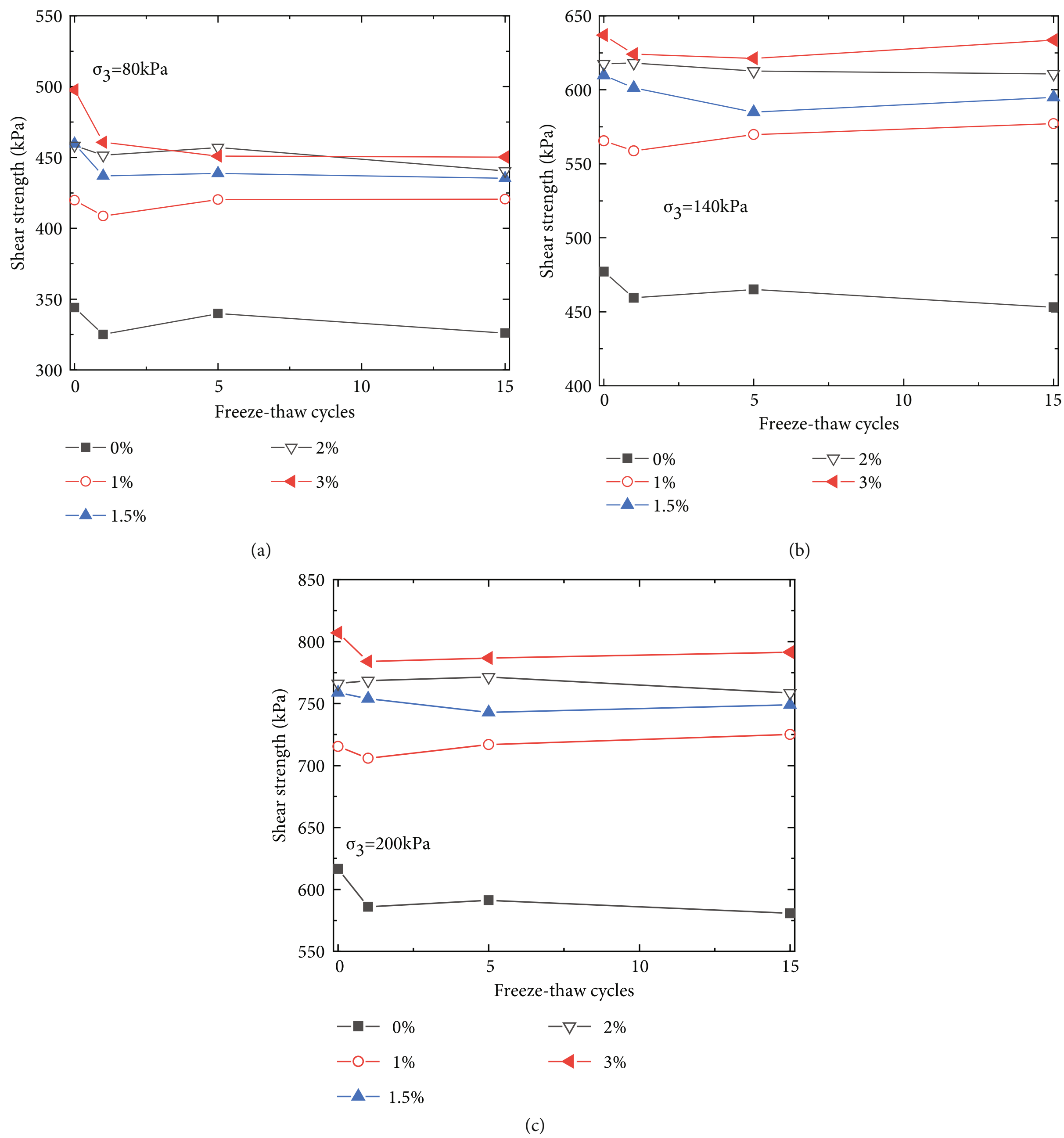


FIGURE 9: Variation of shear strength of lignin fiber-reinforced loess with freeze-thaw cycles: (a) $\sigma_3 = 80$ kPa, (b) $\sigma_3 = 140$ kPa, and (c) $\sigma_3 = 200$ kPa.

of loess reinforced with different fiber contents can reflect the effect of fiber content during freeze-thaw cycles. Therefore, the volume change ratio ($\Delta V_n/V_0$) of fiber-reinforced loess during the freeze-thaw cycle was calculated according to the height and diameter of the sample measured after the sample preparation and after the freeze-thaw cycle. The calculation formula is as follows [15]:

$$\frac{\Delta V_n}{V_0} = \frac{V_n - V_0}{V_0} \times 100\%, \tag{3}$$

where V_0 is the sample volume measured after the sample preparation is completed. V_n is the sample volume measured after n freeze-thaw cycles. The volume changes of loess reinforced with different fiber contents for different freeze-thaw cycles are shown in Figure 13.

As shown in Figure 13, the effects of freeze-thaw cycles on the volume change of loess reinforced with different fiber contents are different. The volume of loess reinforced with 0% and 1% fiber changed little under freeze-thaw cycles. The maximum value of the volume change ratio of the two is 0.26% and 0.33%, respectively. The volume change ratio of loess

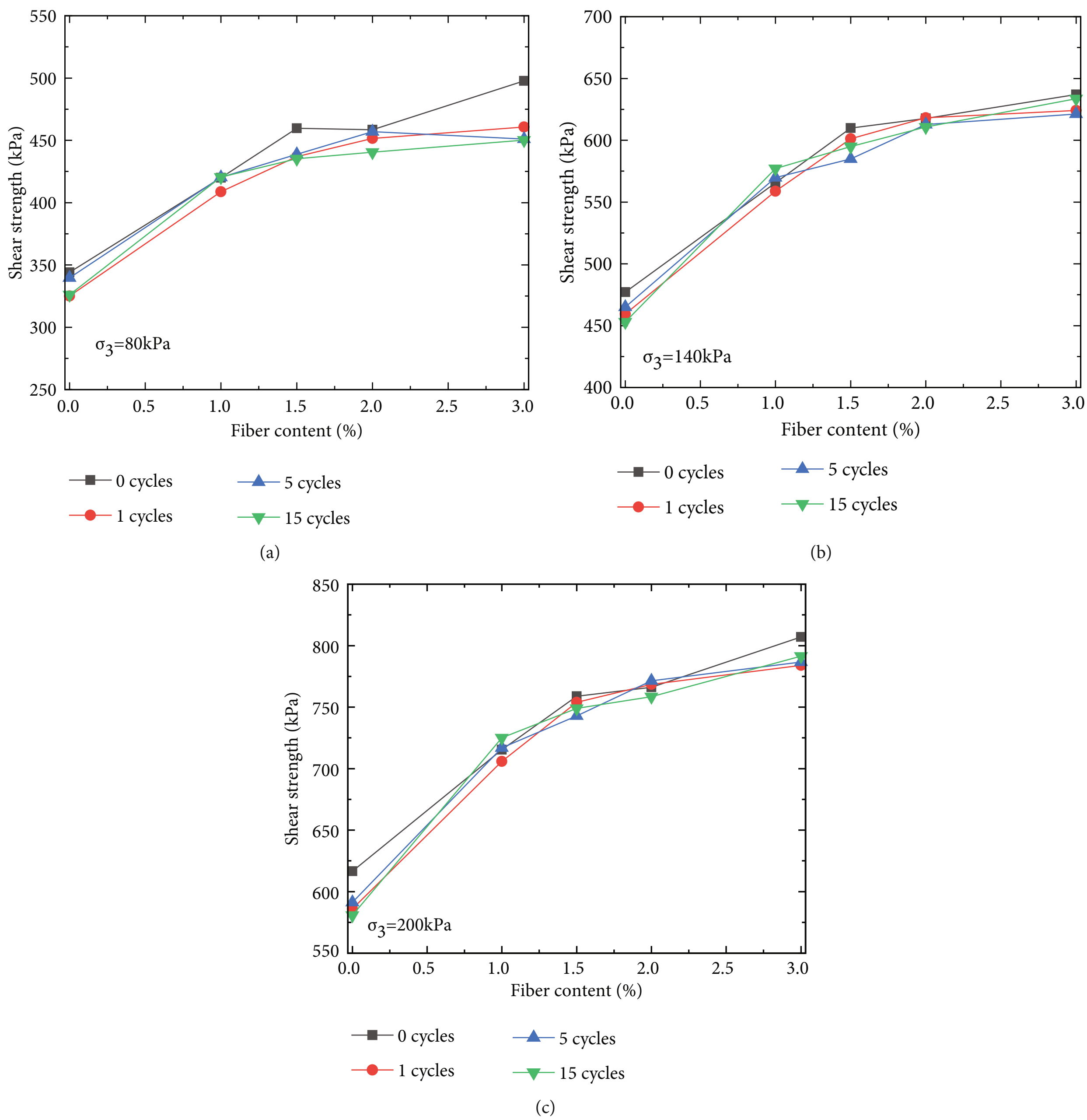


Figure 10: Variation of shear strength of lignin fiber-reinforced loess with fiber content: (a) $\sigma_3 = 80$ kPa, (b) $\sigma_3 = 140$ kPa, and (c) $\sigma_3 = 200$ kPa.

reinforced with 1.5%, 2%, and 3% fiber increased with the increase of the number of freeze-thaw cycles. The average value of the volume change ratio of loess reinforced with 1.5% fiber after 1, 5, and 15 freeze-thaw cycles was 0.65%, 0.97%, and 1.28%, respectively. The average value of the volume change ratio of loess reinforced with 2% fiber after 1, 5, and 15 freeze-thaw cycles was 0.80%, 1.31%, and 1.91%, respectively. The average value of the volume change ratio of loess reinforced with 3% fiber after 1, 5, and 15 freeze-thaw cycles was 0.92%, 1.59%, and 1.95%, respectively. This indicates that when the fiber content in the loess reaches 1.5%, the fiber will aggravate the effect of freeze-thaw cycles on the volume change of the reinforced loess. This is not conducive to the stability of fiber-reinforced loess during freeze-thaw cycles. However, this aggravation has limits. When the fiber content exceeds 2%, the volume change ratio of reinforced loess during freeze-thaw cycles will begin to stabilize.

3.5. Microstructure Characteristics. To analyze the effect of freeze-thaw cycles on the microstructure characteristics of loess reinforced with lignin fiber, some representative microstructure pictures of fiber-reinforced loess were selected for comparative analysis. The analysis result is shown in Figure 14.

For lignin fiber-reinforced loess before the freeze-thaw cycle, the microstructure of unreinforced loess ($m = 0\%$) is dominated by point contacts between soil particles and large

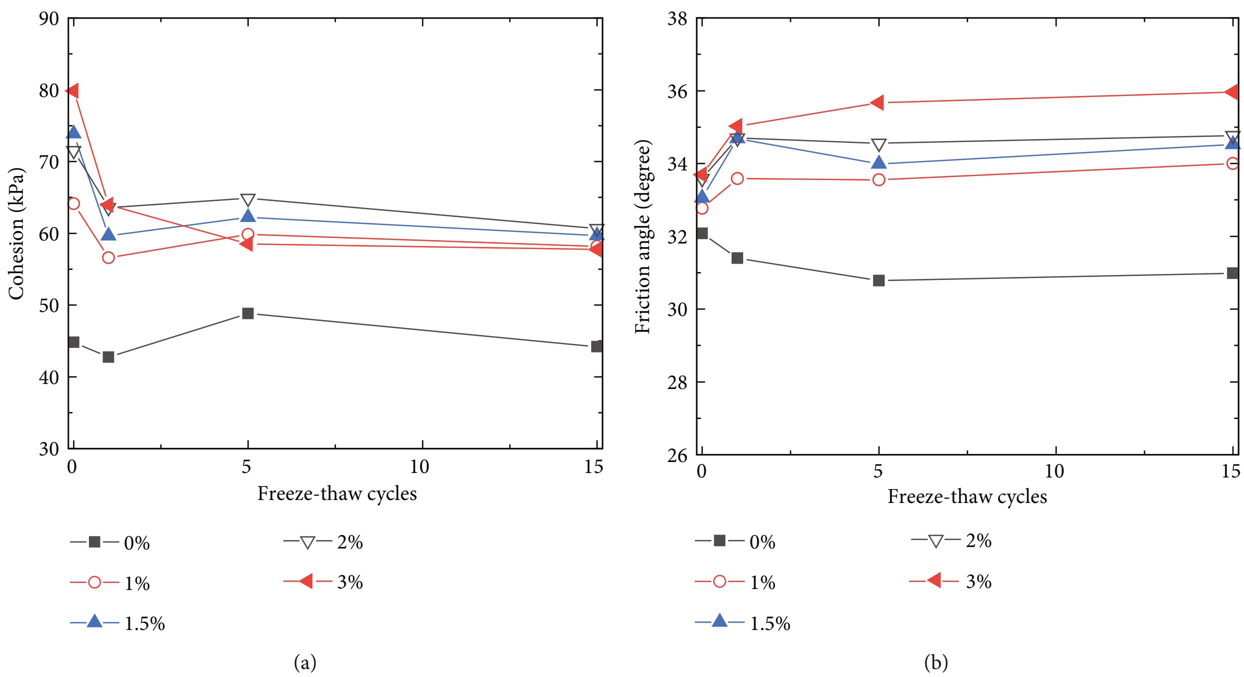


FIGURE 11: Variation of Mohr-Coulomb's strength parameters of lignin fiber-reinforced loess with freeze-thaw cycles: (a) cohesion and (b) friction angle.

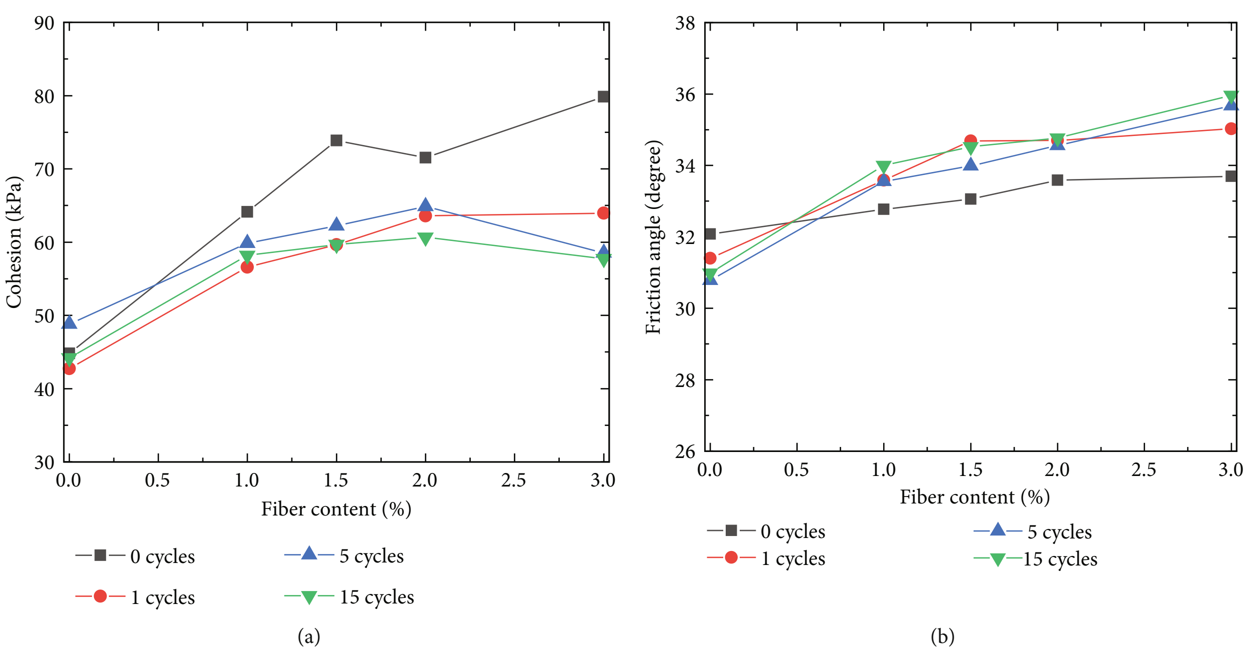


FIGURE 12: Variation of Mohr-Coulomb's strength parameters of lignin fiber-reinforced loess with fiber content: (a) cohesion and (b) friction angle.

overhead pores. There are fewer attachments on the surface of the particles and fewer fillers in the pores. The microstructure of loess reinforced with 1.5% fiber compared with that of loess reinforced with 0% fiber has reduced large pores, increased small pores, increased surface attachments of soil particles, and better pore filling. The microstructure of loess reinforced with 3% fiber is similar to that of loess reinforced with 1.5% fiber, and it can be found that the fiber and soil particles are tightly bonded, with only a small amount of pores distributed on the surface of the fiber. Before the freeze-thaw cycle, the interface interaction between the fiber and soil in the reinforced loess is strong, and the filling of the pores of the loess by the debris in the fiber makes the fiber-reinforced loess denser [46].

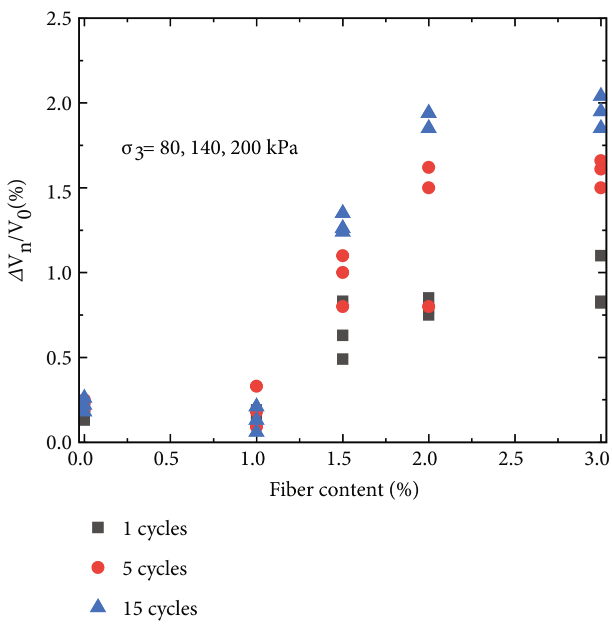


Figure 13: Change ratios of volume of fiber-reinforced loess with fiber content.

After the freeze-thaw cycle, the pore connectivity in the unenhanced loess ($m = 0\%$) becomes better. The pores in the loess reinforced with 1.5% fiber also showed similar changes. Some narrow and long pores with a relatively larger area appeared in the small pores evenly distributed. The change of loess reinforced with 3% fiber is the same, and these large pores are mainly distributed along the fiber surface. The formation of such large pores is caused by the formation and melting of ice and the corresponding displacement of soil particles during the freeze-thaw cycle [11]. It will not only destroy the soil structure but also weaken the interaction between the fiber and the soil interface [47].

4. Discussion

The research results of the shear strength and Mohr-Coulomb's strength parameters of loess reinforced with lignin fiber show that the freeze-thaw cycles will change the change rule of shear strength and strength parameters with fiber content. To explain the reasons for this change, the reinforcing efficiency of per unit content fiber is used as an analysis index for discussion. The reinforcing efficiency of per unit content fiber refers to the reinforcing efficiency of 1% fiber content in the loess with different fiber contents. The calculation formula is as follows:

$$S_{1\%} = \frac{S_m - S_0}{S_0 \times m},$$
$$c_{1\%} = \frac{c_m - c_0}{c_0 \times m}, \quad (4)$$
$$\varphi_{1\%} = \frac{\varphi_m - \varphi_0}{\varphi_0 \times m},$$

where $S_{1\%}$, $c_{1\%}$, and $\varphi_{1\%}$ are the reinforcing efficiency of per unit content fiber to shear strength, cohesion, and friction angle, respectively. S_m, c_m, and φ_m are the shear strength, cohesion, and friction angle of the reinforced loess with a fiber content of m, respectively. m is fiber content. S_0, c_0, and φ_0 are the shear strength, cohesion, and friction angle of unreinforced loess ($m = 0\%$), respectively. The change rule of reinforcing efficiency of per unit content fiber to the shear strength and Mohr-Coulomb's strength parameters with fiber content is shown in Figure 15.

From Figure 15, before the freeze-thaw cycle, the reinforcing efficiency of per unit content fiber to shear strength and Mohr-Coulomb's strength parameters is significantly different. The changing trend of the reinforcing efficiency of the cohesion is the same as that of the shear strength, but the reinforcing efficiency of the cohesion is significantly greater than the shear strength. The reinforcing efficiency of the friction angle is much smaller than that of the shear strength, and it is very small. This indicates that the change of the shear strength of fiber-reinforced loess before freeze-thaw cycles is mainly affected by cohesion and very weakly affected by friction angle. After the freeze-thaw cycles were stabilized, the reinforcing efficiency of per unit content fiber to shear strength and the Mohr-Coulomb's strength parameters changed significantly. The reinforcing efficiency of the shear strength and that of the friction angle increase synchronously. And the changing trend of the reinforcing efficiency of the friction angle and that of the reinforcing efficiency of the shear strength become similar. Although the changing trend of the reinforcing efficiency of the cohesion is still the same as that of the reinforcing efficiency of the shear strength, the reinforcing efficiency of the cohesion has dropped to the same level as that of the shear strength. This indicates that when the state of fiber-reinforced loess reaches a stable state under freeze-thaw cycles, the changes of shear strength are decreased by the influence of cohesion and significantly increased by the influence of friction angle.

Before freeze-thaw cycles and after freeze-thaw cycles were stabilized, the change trends of the reinforcing efficiency of per unit content fiber to shear strength and Mohr-Coulomb's strength parameters were also different. Before the freeze-thaw cycle, the changing trend of the enhancement efficiency of cohesion and shear strength with the increase of fiber content can be divided into three stages: maintaining stability, sudden decreasing, and tending to be stable. The reinforcing efficiency of the friction angle is unchanged with the increase of fiber content. After the freeze-thaw cycles were stable, the change trends of the reinforcing efficiency of shear strength, cohesion, and friction angle all changed to gradually decrease first and then stabilize with the increase of fiber content.

The volume change of water is the main reason for the freeze-thaw effect. The reason for the change rule of reinforcing efficiency should be closely related to the water in the soil. From Figure 14, the microstructural characteristics of loess reinforced with lignin fiber indicate that long and narrow pores are formed on the fiber surface during the freeze-thaw cycle. This indicates that when the fiber-

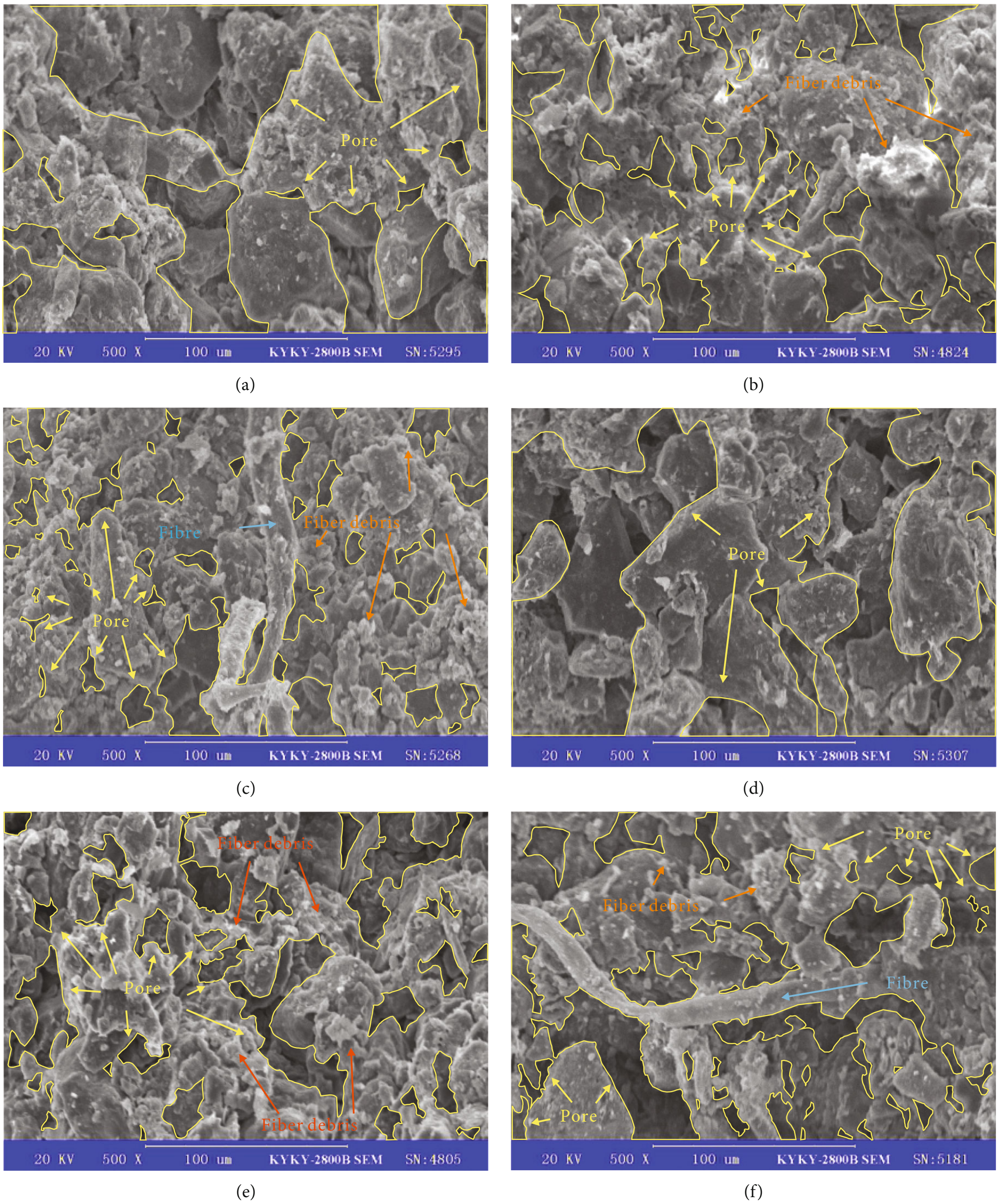


Figure 14: Microstructure picture of lignin fiber-reinforced loess: (a) $m = 0\%$, 0 cycles; (b) $m = 1.5\%$, 0 cycles; (c) $m = 3\%$, 0 cycles; (d) $m = 0\%$, 15 cycles; (e) $m = 1.5\%$, 15 cycles; (f) $m = 3\%$, 15 cycles.

reinforced loess freezes, some ice lenses form along the fiber surface. The formation of these ice lenses can also indicate that some water in the loess accumulated on the fiber surface before the freeze-thaw cycle. Lignin fiber is a natural fiber. This phenomenon that part of the water in the reinforced loess accumulates on the surface of the fibers may be caused by the adsorption of water by the hydrophilic groups in the fibers [43]. The research result of Wang et al. showed that higher water content reduces the reinforcing effect of fibers by acting as a lubricant in the interface between fibers and soil particles [48]. Before the freeze-thaw cycle, the adsorption of water by the fibers made the water in the reinforced loess accumulate on the surface of the fibers, thereby forming a lubricating effect and weakening the reinforcing effect of the fibers. When the fiber content is less than 1.5%, the lubricating effect is limited, the macroscopic effect on the strength of the loess can be ignored, and the reinforcing effect of the fiber on the loess is stable. When the fiber

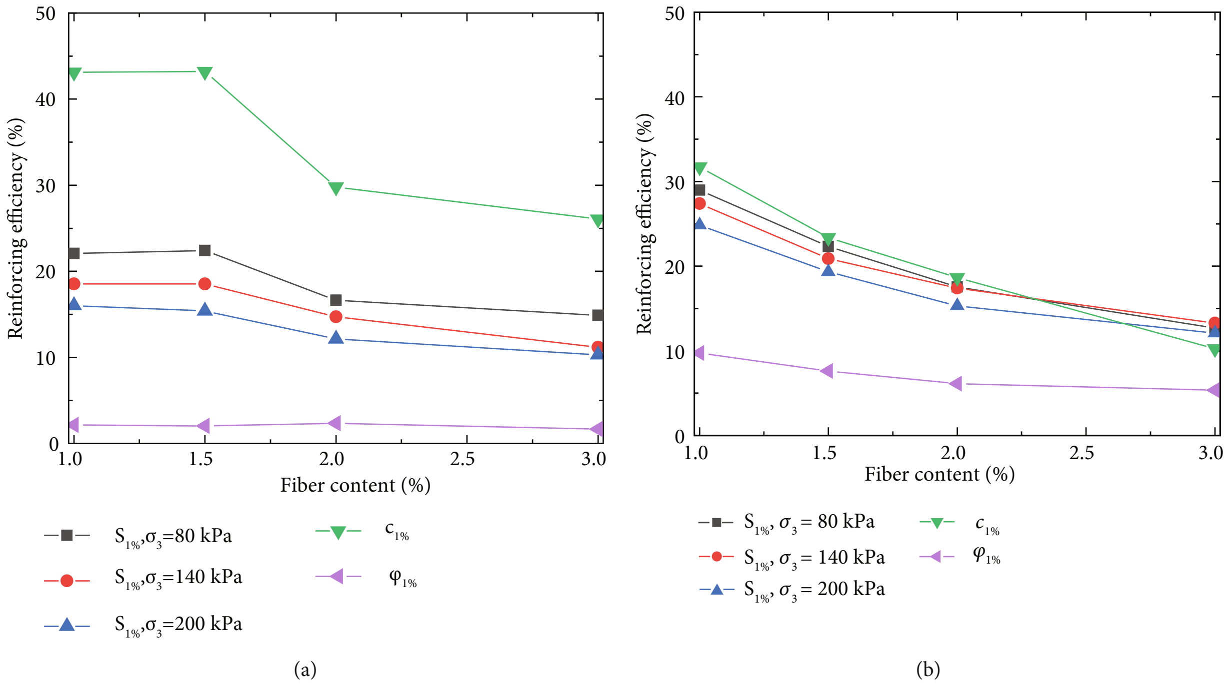


Figure 15: Variation of reinforcing efficiency of per unit content fiber with fiber content: (a) 0 cycles; (b) 15 cycles.

content exceeds 1.5%, the lubricating effect breaks through the limit. It starts to have an effect on the macroscopic strength of loess, which makes the reinforcing efficiency of cohesion and shear strength suddenly decrease greatly. When the fiber content exceeds 2%, since the total amount of water is constant, the interaction between the adsorption force of the fiber and the suction force of the loess matrix makes the adsorption of water by the fiber no longer unlimited increase with the increase of the fiber content. The lubricating effect reaches a certain limit so that the reinforcing efficiency of cohesion and shear strength begins to stabilize. After freeze-thaw cycles, the shear strength, cohesion, and friction angle reinforcing efficiency of fiber-reinforced loess all changed to a gradual change trend that first gradually decreased and then tended to be stable. This shift in trend may be related to the formation of ice lenses during soil freezing. The study of Steiner et al. showed that there are two factors for the formation of ice lenses. One is the volume expansion of water as it turns into ice. Another is the migration of pore water in unfrozen soils towards the freezing front. This migration leads to an overall change in the distribution of water in the soil [49]. During freeze-thaw cycles, not only the phase change of water accumulated on the fiber surface will weaken the interfacial interaction between the fiber and loess [24, 47]. The formation of ice lenses on the fiber surface may also cause the migration of pore water from nearby unfrozen regions to the fiber surface. This may lead to an increase in the water content of the area on the fiber surface, enhancing the lubricant effect of water in the fiber-loess particle interface. The combined effect of the two may be the reason why the trend of reinforcing efficiency turned into a gradual one.

In addition, from Figures 9 and 11, the effects of freeze-thaw cycles on the shear strength properties of reinforced loess with different fiber contents were different. This may also be related to the adsorption of water by the fibers. As shown in Figure 13, the volume change of loess reinforced with 1% fiber after freeze-thaw cycles is the same as that of unreinforced loess ($m = 0\%$). The volume change of the unreinforced loess ($m = 0\%$) during the freeze-thaw cycle is entirely borne by the water in the pores of the loess. After adding fibers to the loess, the volume change of the reinforced loess is jointly borne by the water in the pores of the loess and the water accumulated on the surface of the fibers. The adsorption of water by fibers reduces the volume change caused by water in the pores of loess. After adding 1% fiber, the damage to the overall structure of loess by freeze-thaw cycles was suppressed to a certain extent. This may be the reason why the shear strength of loess reinforced with 1% fiber is enhanced under the action of freeze-thaw cycles. Meanwhile, excessive addition of fibers will promote the destruction of the reinforced loess structure by freeze-thaw cycles, which is not conducive to soil stability. The change ratios of shear strength and Mohr-Coulomb's strength parameters of loess reinforced with different fiber contents after freeze-thaw cycle stabilization are shown in Figure 16. Comparing Figures 13 and 16, it can be seen that the volume increase ratio of loess reinforced with 1% fiber is relatively small, and the cohesion reduction ratio is also relatively small. The volume increase ratio of loess reinforced with 1.5%, 2%, and 3% fiber becomes larger, and the decreased ratio of cohesion also becomes larger. Therefore, based on comprehensive consideration of fiber reinforcing effect and reinforcing efficiency, fiber-reinforced loess volume change, and enhancement of loess freeze-thaw resistance, it is recommended to use 1% as the fiber content of improved loess in seasonally frozen soil areas.

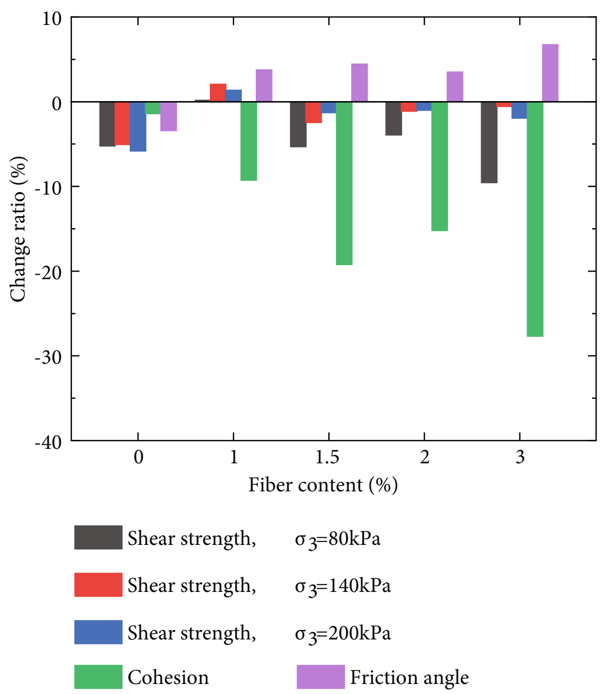


FIGURE 16: Change ratios of shear strength and Mohr-Coulomb's strength parameters after freeze-thaw cycle stabilization.

5. Conclusions

This paper studies the shear strength characteristics of the loess reinforced with lignin fiber under freeze-thaw cycles. And combined with the effects of the freeze-thaw cycles on the volume changes and microstructure characteristics of fiber-reinforced loess, the effects of the freeze-thaw cycles on the shear strength characteristics of fiber-reinforced loess are analyzed. Based on the results of this research, the following conclusions are drawn:

(1) Both freeze-thaw cycles and the increase of confining pressure can weaken the strain-softening behavior of loess reinforced with lignin fiber. Confining pressure can inhibit the effect of freeze-thaw cycles on the structural changes of fiber-reinforced loess. The higher the fiber content in the reinforced loess, the greater the confining pressure required to suppress the effects of freeze-thaw cycles

(2) After 15 freeze-thaw cycles, the shear strength of loess reinforced with 1% fiber was enhanced, and the maximum enhancement ratio was 2.05%. The shear strength of reinforced loess with other fiber contents decreases, and the maximum decrease ratio can reach 9.54%. Freeze-thaw cycles can decrease and increase the cohesion and friction angle of the fiber-added loess, respectively. Before the freeze-thaw cycle, the shear strength and cohesion increased the fastest when the fiber content increased from 0% to 1.5%. After freeze-thaw cycles, when the fiber content increased from 0% to 1%, the increases in shear strength, cohesion, and friction angle were the fastest

(3) The change rules of shear strength properties of fiber-reinforced loess before and after freeze-thaw cycles are different. Before freeze-thaw cycles, the change rule of shear strength of fiber-reinforced loess is mainly affected by cohesion. After the freeze-thaw cycles are stable, the influence of cohesion on the change rule of shear strength of fiber-reinforced loess decreases, and the influence of friction angle increases. The adsorption of water by fibers and the migration of water in the loess caused by freeze-thaw cycles are the reason for the change in the change rule of shear strength properties

(4) Appropriate fiber content ($m = 1\%$) can inhibit the damage to the overall structure of fiber-reinforced loess by freeze-thaw cycles and enhance the freeze-thaw resistance of loess. Excessive addition of fibers will aggravate the structural damage and volume increase of reinforced loess during freeze-thaw cycles, which is not conducive to soil stability

(5) Based on considering freeze-thaw resistance, strength enhancement effect, environmental protection, and economy, it is recommended to use 1% lignin fiber for loess improvement and engineering design in seasonally frozen soil areas. This study only considers the effect of freeze-thaw cycles on loess reinforced with lignin fiber in a closed system. Subsequent research needs to further study the fiber-reinforced loess subjected to freeze-thaw cycles in an open rehydration system

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Acknowledgments

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