Study on shear performance of cotton straw fiber reinforced mud soil under freeze-thaw cycle

Mingrui Sun¹, Xiaojuan Yu²*, Minpu Xu¹
¹ School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, 232001, China
² College of Civil Engineering, Yancheng Institute of Technology, Yancheng, 224001, China
*Corresponding author’s yuxiaojuan@ycit.edu.cn

Abstract: To explore the shear properties in cotton straw fiber-reinforced mud soil under freeze-thaw(F-T) cycles, direct shear tests are carried out on soil samples after different F-T times to obtain the influence of fiber content and F-T times to the shear strength of cotton straw fiber-reinforced soil. Then combined with scanning electron microscopy(SEM) to observe the microstructure of fiber and reinforced soil. Results indicate that the shear strength and cohesion of mud soil can be significantly improved by the addition of cotton straw fibers compared with plain soil, and the shear strength and cohesion of reinforced soil are higher than the plain soil during the same F-T times. Among three fiber contents of 0%, 0.2% and 0.4%, the shear strength and cohesion of 0.2% fiber-reinforced soil are higher than those of plain soil and 0.4% reinforced soil. After F-T cycles, the cohesion of soil decreases, among which the decrease is larger for 1 and 3 F-T times, and then the decrease of cohesion will be slowed down gradually, and when the number of F-T times reaches 10, the cohesion becomes stable. The internal friction angle for reinforced soil is higher than the plain soil, and it decreases first, then rises and finally decreases under the effect of F-T cycles, but in general, the changes are not large. The SEM observation shows that the microscopic morphological changes of the fibers themselves are small under the influence of F-T cycles, but the reinforced soil structure is destroyed, the pores and cracks become more, by which the connection between the fibers and soil particles decreases, resulting in a decline in the soil's shear strength.

1. Introduction

Adding fibers into soil is a common method of soil reinforcement, which involves mixing fibers into the soil as reinforcing material for improving the characteristics to the soil. Due to the advantages of high strength and easy uniform dispersion of fibers in the soil [1], scholars in China and abroad have studied fiber reinforced soil [2]. Li et al. found that adding fibers to clay can enhance the shear strength and cohesion to the soil by conducting shear tests [3]. Tang et al. studied tensile tests on polypropylene (PP) fiber-reinforced soils to obtain the influence of fiber content, water content, as well as dry density on the tensile strength to the soil [4]. In addition, they revealed the reinforcement effect for fiber-reinforced soils depending on the interfacial shear strength by SEM and single fiber pulling tests [5]. Akbulut et al. studied the effect of PP fiber addition to the soil shear strength, and found that the fiber addition enhanced the shear strength index for the soil to some extent [6]. Yetimoglu et al. discovered that fiber addition can increase the residual shear strength of soil and obtained that the soil bearing capacity is proportional to the amount of fiber addition [7,8]. Liu et al. by analyzing the mode of effect among the fibers and soil particles, and found that the two are divided into three forms of interaction, namely contact, bending and interweaving, and these three functions provide interfacial shear force. It
is also believed the tensile stress in fibers restricts the movement of soil particles, thus making the shear strength to be increased in the soil[9]. Qu et al. added wheat straw fibers to clay and found that they could significantly increase the shear strength and friction angle to the soil, with the existence of an optimal fiber addition[10].

The above results are some experimental studies on fiber-reinforced soil at normal temperature, but it is not much research about the strength change characteristics of fiber-reinforced soil under F-T action. As for the application of cotton straw fiber as reinforcing material in mud soil, it is relatively rare. To address this situation, this paper uses a river mud soil in Yancheng, Jiangsu Province as the test soil and cotton straw fiber as the reinforcing material. Direct shear tests are conducted on the fiber-reinforced soil and the plain soil at different F-T times to explore the change law of shear strength for the fiber-reinforced soil under the influence of F-T cycles. Then, combined with SEM, the microstructure of fiber and reinforced soil is observed, which reveals the influence of cotton straw fiber content and F-T times to the shear strength of mud soil under F-T action from macroscopic and microscopic perspectives.

2. Materials and Methods

2.1. Fiber and Soil Sample Properties

The cotton straw used in the experiment is produced from the suburbs of Yancheng, and after the straw is retrieved, the straw bast is taken and made into fiber using a blender as in Figure 1(a). The fiber length of cotton straw is controlled at about 10 mm. After low temperature drying, the cotton straw is sealed and stored in the shade. The test mud soil is transported back from a river in Funing, Yancheng, Jiangsu Province. The returned soil sample is dark gray and had high moisture content. Before the experiment, put the soil sample in outdoor air-drying, as shown in Figure 1(b). After crushing and removing impurities, the soil sample is screened by 2 mm sieve. The basic physical properties can be seen in Table 1. The organic content are tested by muffle furnace combustion method. Store the sieved soil in sealed barrels so that it does not come into contact with moisture in the air, so as to ensure a basically unchanged moisture content for air-dried soil.

| Table 1. Basic physical indicators of mud soil |
|-----------------------------------------------|
| Liquid limit /%  | Plastic limit /% | Optimal moisture content /% | Maximum dry density/g cm⁻³ | Organic content /% |
| 57.75           | 22.9            | 23.04                      | 1.57                          | 4.93              |

![Figure 1. Test material morphology: (a) cotton straw fiber; (b) mud soil](image)

2.2. Soil Sample Preparation

The cotton straw fiber content is divided into three mass percentages of 0 %, 0.2 % and 0.4 %, and the soil sample is prepared with the optimal moisture content of 23.04 %. Since the fiber is easily agglomerated when mixed with water in the soil, it is necessary to consider how to uniformly add...
cotton straw fiber into the soil during the sample preparation. Through reviewing the previous experimental studies, it was found that Li et al. first configured the air-dried soil to a target water content, and then mixed a wet soil with fibers uniformly[3]. Since the mixing process of cotton straw fiber and soil sample takes a long time, if water is first mixed, the moisture content will change. Therefore, this paper uses the method of mixing fiber and air-dried soil first, and then mixing with water, which is basically similar to the method adopted by Tang [11]. Firstly, the amount of air-dried soil, cotton straw fiber and water is calculated. The air-dried soil and cotton straw fiber were mixed evenly. After the fiber and soil is stirred evenly, the spray kettle is sprayed, and the spray is stirred at the same time until the moisture content reaches the optimal moisture content. Finally, the air-dried soil is sealed in the plastic bag, and the stew is used after 48 hours. It should be noted that due to the large amount of soil used for direct shear, it is necessary to configure the moisture content of the soil sample in batches according to the proportion.

2.3. Experiment Method

2.3.1. F-T Experiment
To ensure that the moisture of the samples does not migrate in the process of freezing and thawing, the prepared specimens need to be wrapped and sealed with a plastic layer[12]. The F-T cycle process [13] is: firstly, the sample is stored in a freezer at -20°C for 12 hours, and then the sample is taken out and thawed in a constant temperature cabinet at 20°C for 12 hours. This is a complete F-T cycle process. Subsequently, the F-T cycles are repeated to achieve the required cycles, and then the test is carried out. The freeze-thaw cycles selected in this test are 0, 1, 3, 5, 10 and 20.

2.3.2. Direct Shear Experiment
The direct shear test instrument adopts the strain-controlled direct shear apparatus produced by Suzhou Topology Instrument Co., Ltd. According to the requirements of GB/T 50123-1999 “Standard for Soil Test Method” [14], the ring-knife sample preparation is carried out. The size of the modified ring-knife is 100 mm high and 50 mm high. The amount of soil required for the ring-knife is weighed, and four ring-knife samples are prepared by the static pressure method. In order to avoid excessive water loss in the sample during the freezing and thawing process, the test must be completely covered by the plastic layer after the sample preparation is completed. After the freezing and thawing cycle is completed, the shear is carried out under the vertical pressure of \( p_1, p_2, p_3 \) and \( p_4 \) (50, 100, 150 and 200 kPa), and the shear rate is 0.8 mm·min\(^{-1}\). The specific test scheme is shown in Table 2. According to the direct shear test results, the cohesion and internal friction angel of soil samples at different cotton straw fiber content are obtained after F-T cycles.

| Fiber content /‰ | Vertical pressure /kPa | Freeze-thaw cycles /N | Shear rate /mm·min\(^{-1}\) |
|-------------------|------------------------|-----------------------|-----------------------------|
| 0, 2, 4           | 50, 100, 150, 200      | 0, 1, 3, 5, 10, 20    | 0.8                         |

2.3.3. SEM Experiment
The FEI200 SEM is used to observe the microscopic changes of fibers and fiber reinforced soil samples after different numbers of freezing and thawing, so as to understand the microscopic changes of fibers and fiber reinforced soil. It should be noted that before the test, the specimen must first be frozen in liquid nitrogen and then put into a vacuum freeze dryer for drying to avoid the sample containing moisture to affect the test. After the removal of moisture from the sample, the sample is adhered to a specific sample test bench with conductive adhesive, and then the surface of the sample is
plated with gold. Finally, the sample is put into the test instrument. After the vacuum condition is reached, the appropriate magnification can be selected to scan the sample.

3. Results and Discussion

3.1. Influence of shear strength

To study the shear strength characteristics of plain soil and cotton straw reinforced soil after F-T cycles, plain soil and reinforced soil samples with different F-T times are prepared for direct shear tests. The three different contents of the sample test results are compared and analyzed, and the vertical pressure and shear strength curves of soil samples under different F-T times are plotted as shown in Figure 2, using the vertical pressure as the horizontal coordinate and the shear strength as the vertical coordinate.

Figure 2 shows the shear strength for fiber-reinforced soil is generally superior to plain soil. It indicates the inclusion of cotton straw fibers has improved the shear strength of the soil, but not the more fibers are added, the greater soil shear strength, which is similar to the conclusion obtained by other scholars[15,16]. Comparing Figure 2(b) with Figure 2(c), the shear strength of 0.2% reinforced soil is higher than that of 0.4% fiber reinforced soil. In addition, the shear strength of the soil decreases to different degrees with increasing F-T times. Whether it is the plain soil or the reinforced soil, the decrease of shear strength after one freezing and thawing is the largest. The largest decrease of 31.79% is observed in the plain soil sample in Figure 2(a). The decreases of shear strength are 19.55% and 20.02% for 0.2% fiber reinforced soil in Figure 2(b) and 0.4% fiber reinforced soil in Figure 2(c), respectively, after one time of freezing and thawing. After that, although the shear strength still decreases with the increase of F-T times, but the attenuation gradually tends to stabilize.

![Figure 2: Shear strength and vertical pressure curve under freezing and thawing](image)

Figure 2. Shear strength and vertical pressure curve under freezing and thawing: (a) plain soil; (b) 0.2% fiber reinforced soil; (c) 0.4% fiber reinforced soil.

3.2. Influence of Shear Strength Index

The two important factors of shear strength of soil are cohesion as well as internal friction angle respectively. According to the linear fitting curve in Figure 2, we can get the shear strength index of soil body. The specific test data of shear strength index are in Table 3. The change trend for shear strength indexes of plain soil and two kinds of reinforced soil obtained from the test at different F-T times is in Figure 3.

| F-T cycles /N | plain soil Cohesion | 0.2% fiber reinforced soil Cohesion | 0.4% fiber reinforced soil Cohesion |
|---------------|---------------------|------------------------------------|------------------------------------|
|               | Internal friction angle/° | Internal friction angle/° | Internal friction angle/° |

| 5 cycles | 1 cycle | 3 cycles | 5 cycles | 10 cycles | 15 cycles | 20 cycles |

Table 3. Shear strength index of soil sample

![Table 3](image)
Figure 3(a) shows that the cohesion of all the three soil types with different contents decreases gradually with increasing times of F-T, and the decrease of cohesion decreases gradually. The decrease of cohesion is the largest after 1 time of freeze-thawing, and finally it becomes smaller slowly, while the cohesion of plain soil and fiber soil basically tends to be stable after 10 times of freeze-thawing. Meanwhile, the cohesion of fiber soil is higher than the plain soil under equal number in F-T, indicating that the effect of cotton straw fiber enhances the cohesion of soil. In the absence of freeze-thaw, the cohesion of 0.2% reinforced soil increased by 52.2% compared to plain soil, while 0.4% reinforced soil increased by 30.7%, indicating that the effect is not better with more fibers, and the cohesion of the soil with 0.2% fibers is higher than that of the soil with 0.4% fibers from other equal freeze-thaw cycles. Figure 3(b) shows that the angle of internal friction of both plain and fiber soil decreases at 1 time of freezing and thawing, followed by a rise and then a fall, however, the changes are not large. The variation of the internal friction angle of the plain soil ranged from 16.83° to 18.18°, and the variation of the internal friction angle of the 0.2% reinforced soil and 0.4% reinforced soil ranged from 20.43° to 22.53° and 16.92° to 21.86°, respectively. Overall, two kinds of fiber soils generally have higher internal friction angles than plain soils, while the soil with 0.2% fiber content is clearly higher than the plain soil and the soil with 0.4% fiber reinforcement.

![Figure 3](image_url)

**Figure 3.** Comparison of shear strength index of different fiber mixing content under freezing and melting: (a) cohesion; (b) internal friction angle.

### 3.3. Microstructure Change and Mechanism Analysis

The morphology of fibers and soil samples before and after freezing and thawing are observed by SEM to understand the changes of fiber surface morphology and microstructure of soil samples as well as the interconnection effect among soil particles and fibers, the high magnification mode is selected to adjust the clarity of soil sample morphology during the SEM test, and then the low

|     | /kPa | /kPa | /kPa |
|-----|------|------|------|
| 0   | 72.09| 18.175| 109.72| 21.559| 94.225| 17.963|
| 1   | 49.175| 17.635| 88.265| 20.942| 75.36| 16.915|
| 3   | 46.97| 16.694| 68.995| 22.529| 65.07| 18.572|
| 5   | 42.445| 17.307| 58.555| 21.291| 55.205| 20.35|
| 10  | 32.86| 17.802| 52.525| 21.801| 35.76| 21.861|
| 20  | 29.761| 16.831| 47.97| 20.43| 32.12| 19.453|
magnification mode is used to take photos for preservation. The micro-test diagrams of cotton straw fiber, plain soil and reinforced soil before and after F-T cycles are figure 4 (a), (b) and (c), respectively. Among them, 1, 2 and 3 are freezing and thawing for 0, 10 and 20 times, respectively.

Figure 4 (a-1) taken by SEM is the morphology of the fiber before the freeze-thaw cycle. According to the subsequent photographs of figure 4 (a-2) freeze-thaw 10 times and figure 4 (a-3) freeze-thaw 20 times, it can be seen that the surface morphology of the fiber does not change basically during the F-T cycle, indicating that the fiber itself does not degrade during the F-T cycle. Consequently, fiber degradation during 0 to 20 F-T cycles can be considered as a relatively small impact on the mechanical characteristics of the soil.

Figure 4(b) shows that before the F-T cycle, the plain soil body has a compact structure (Figure 4(b-1)) and there are basically no voids and cracks on the surface. However, after F-T cycles the number of pores and cracks in the soil appears (Figure 4(b-2)) and increases according to the number of times of F-T (Figure 4(b-3)). During the F-T process, soil structure is damaged, rearranging soil particles and changing soil particle structure, which makes the connection between soil particles decrease, which will certainly also affect the shear strength of soil greatly. Therefore, the cohesion of the plain soil decreases under the effect of F-T cycles. However, the overall change is not significant for the internal friction angle.

The cohesion of reinforced soil gradually decreases in the presence of freezing and thawing, but still increases compared to plain soil. Before the F-T cycle, the fiber surface is wrapped with a huge amount of soil particles (Figure 4(c-1)), and when the fiber moves in the soil, it needs to overcome not only the bonding force among the fiber and the soil particles, but also the frictional force between both. Therefore, the soil shear strength is improved after adding fibers. Upon undergoing F-T cycles, the contact area is reduced among the fibers and soil particles, furthermore, pores and cracks appear around the soil (Figure 4(c-2)) as well as more complex interweaving phenomena than before F-T (Figure 4(c-3)), which leads to a reduction in the bond between the soil and fibers and a decrease in the fiber-soil interface strength.

4. Conclusion

Through the direct shear test of cotton straw fiber reinforced soil and its plain soil under freeze-thaw action and the microstructure observation of fiber and fiber reinforced soil, the following conclusions are obtained.

(1) Compared with the plain soil, cotton straw fiber reinforced soil has different degrees of shear strength and cohesion, and the shear strength and cohesion of the fiber soil are higher than the plain soil at the same freeze-thaw cycles, and among the three soils selected in this test, the reinforcement effect of the 0.2% fiber content is the best.

(2) The soil shear strength and cohesion decreases according to the increase of the number of freeze-thawing, and after the first freeze-thawing, the shear strength and cohesion of the soil decreases the most, and then the decreasing trend gradually slows down, and when the cohesion of the soil basically tends to level off after 10 freeze-thawing. In general, the internal friction angle of the fibrous soil is higher than the plain soil, and with the increase of the number of freezing and thawing, all of them appear to decrease and then increase and then decrease, but overall, the change of the internal friction angle is not significant.

(3) Microscopic observation by SEM shows that the change in microscopic characteristics of fibers under F-T is not obvious, indicating that the fiber degradation affects little change in soil strength. Soil structure changes following F-T cycles, the number of pores in the soil becomes more numerous, and the bonding effect between soil particles decreases. Fibers and soil particles decrease the contact area between them, and fiber-soil interface strength is reduced.
Figure 4. Variation in the microstructure of samples with F-T cycles: (a) cotton straw fiber and (b) unreinforced samples and (c) reinforced samples

Acknowledgment
This study is supported by National Natural Science Foundation of China (Grant No.51778556, 51978597, 51808481)

References
[1] I.M.C.F.G. Falorca, M.I.M. Pinto. Effect of short, randomly distributed polypropylene microfibres on shear strength behaviour of soils [J]. Geosynthetics International, 2011,18(1).
[2] Liu, B.; Tang, C.; Li, J.; Wang, D.; Zhu, K.; Tang, W. Advances in engineering properties of fiber reinforced soil. J. Eng. Geol. 2013, 21, 540–547.
[3] LI G X, CHEN L, ZHENG J Q, et al. Experimental study on fiber-reinforced cohesive soil [J]. Journal of Hydraulic Engineering, 1995(6): 31-36. (in Chinese)
[4] Tang C S, Wang D Y, Cui Y J, et al. Tensile Strength of fiber-reinforced soil [J]. Journal of Materials in Civil Engineering, 2016, 28(7): 1-13.
[5] TANG C S, SHI B, GAO W et al. Single fiber pull-out test and the determination of critical fiber reinforcement length for fiber reinforced soil [J]. Rock and Soil Mechanics, 2009, 30(8): 2225-2230. (in Chinese).
[6] Akbulut S, Arasan S, Kalkan E. Modification of clayey soils using scrap tire rubber and synthetic fibers [J]. Applied Clay Science, 2007, 38(1–2): 23–32.
[7] YETIMOGLU T, SALBA O. A study on shear strength of sands reinforced with randomly distributed discrete fibers [J]. Geotextiles and Geomembranes, 2003, 21(2):
103-110.

[8] YETIMOGLU T, INANIR M, INANIR O E. A study on bearing capacity of randomly distributed fiber-reinforced sand fills overlying soft clay [J]. Geotextiles and Geomembranes, 2005, 23(2): 174-183.

[9] Liu J L, Hou T S, Luo Y S, Cui Y X. Experimental Study on Unconsolidated Undrained Shear Strength Characteristics of Synthetic Cotton Fiber Reinforced Soil [J]. Geotechnical and Geological Engineering: An International Journal, 2020, 38(10).

[10] Qu J L, Sun Z M. Strength Behavior of Shanghai Clayey Soil Reinforced with Wheat Straw Fibers [J]. Geotechnical and Geological Engineering, 2016, 34(2).

[11] Tang H, Li H H, Duan Z et al. Direct Shear Creep Characteristics and Microstructure of Fiber-Reinforced Soil [J]. Advances in Civil Engineering, 2021, 2021.

[12] Roustaei, M., Eslami, A., Ghazavi, M., 2015. Effects of freeze-thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters. Cold Reg. Sci. Technol. 120, 127-137.

[13] Zheng F, Shao S J, Wang S H. Effect of freeze-thaw cycles on the strength behaviour of recompacted loess in true triaxial tests [J]. Cold Regions Science and Technology, 2021, 181:

[14] GB/T 50123-1999. Standard for Soil Test Method. Ministry of Construction, Beijing, PR China.

[15] WELKER A L, JOSTEN N. Interface friction of a geomembrane with a fiber reinforced soil[C] // Geo-Frontiers Congress, ASCE, Austin, Texas, United States, 2005: 1–7.

[16] MOHAMED A E M K. Improvement of swelling clay properties using hay fibers [J]. Construction and Building Materials, 2013, 38: 242–247.