Experimental Study on the Mechanical Properties of Cotton Straw Fiber-Reinforced Soil Interface under Dry–Wet Cycles

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Abstract. Fiber-reinforced soil technology has been employed in engineering. However, reinforced soil often undergoes dry–wet (D–W) changes because of high temperatures and rain in summer; consequently, its strength deteriorates. Its mechanical properties are mainly affected by the force between a fiber interface and a soil matrix. In this study, the effect of D–W cycles on the interfacial mechanical properties of cotton straw fiber-reinforced soil was investigated. Fiber-reinforced soil with different normal stresses was subjected to single fiber pullout tests on the 0th, 1st, 3rd, 6th, and 9th D–W cycles. Results showed that the trend of the changes in the pullout force–displacement curve was consistent; in particular, the trend initially showed a linear increase. Then, it peaked, decreased, and finally stabilized. The pullout force had a linear relationship with normal stress and increased linearly as normal stress increased. The relationship between interfacial shear strength and the number of D–W cycles exponentially decreased, and the most significant decrease occurred in the first to three D–W cycles.

1. Introduction
Fiber-reinforced soil technology has been applied to various engineering projects, such as retaining walls [1,2], slope protection [3], abutments [4,5], and embankments [5–7]. The stability of these reinforced soil engineering projects is significantly influenced by changes in dry–wet (D–W) cycles caused by high temperature and rain in summer; furthermore, their structures become damaged, and their strength reduces.

The characteristics of reinforced soil under D–W cycles have been studied through unconfined compression tests [8], triaxial tests [9], tensile tests [10], and direct shear tests [11,12]. Although the incorporation of fibers can improve the strength of soil, the properties of fiber-reinforced soil still deteriorate to varying degrees when it is subjected to D–W cycles.

Some studies have shown that the mechanical properties of reinforced soil are largely influenced by various factors between a reinforcing material and a soil matrix. Tang et al. [13] performed a single fiber pullout test (SFPT) and found that reducing water content, increasing dry density, or adding cement to soil can effectively improve the interfacial strength of fibers and soil. Zhu et al. [14] and Zhang et al. [15] studied the interface properties of fiber and sand and proposed a tri-linear model to describe the pullout force–displacement relationship. Tang et al. [16] compared the pullout test of wave-shaped fibers and ordinary straight fibers and observed that fiber shape is an important factor
that affects pullout force, in addition to moisture content and dry density. Wu et al. [17] explored the interfacial bond properties based on fiber shape and matrix composition.

However, many studies have focused on the effect of various factors, such as soil type, water content, dry density, fiber length buried in soil, fiber shape, surface roughness, and pullout speed, on the fiber–soil interfacial strength. Few studies have explored the mechanical properties of fiber–reinforced soil interface subject to D–W cycles.

This study investigates the effect of D–W cycles on the mechanical strength of the fiber–soil interface by using cotton straw fiber as a reinforcement object and provides an experimental basis for engineering design.

2. Test program

2.1. Test materials

Silty clay as the test soil was collected from a construction site in Dongtai City, Jiangsu Province, with a natural water content of 24.6%. The retrieved soil was air dried under natural conditions, crushed, passed through a 2 mm sieve, and packed into barrels for later use. The basic physical parameters of the soil are listed in Table 1.

In this study, cotton straw fiber, which was provided by the manufacturer (Guangxi Longzhou Qiangli Hemp Industry Co., Ltd), was selected as the test material. The parameters of cotton straw fiber are presented in Table 2.

Table 1. Parameters of the tested soil.

| parameter | value |
|-----------|-------|
| Liquid limit | 30.2% |
| Plastic limit | 17.2% |
| Plasticity index | 13.0 |
| Maximum dry density | 1.73 g/cm³ |
| Optimum water content | 18.0% |
| Particle size distribution | 21.66% 76.54% 1.80% |

Table 2. Physical and mechanical parameters of cotton straw fiber.

| parameter | value |
|-----------|-------|
| Length | ≥10 mm |
| Average diameter | 0.360±0.02 mm |
| Density | 1.55 g/cm³ |
| Tensile strength | 290 MPa |
| Elastic modulus | 5500 MPa |
| Elongation at break | 7.0-8.0% |

2.2. Specimen preparation

Zhang et al. [15] indicated that a longer fiber–soil interface enhances the repeatability of pullout test data; as such, the mold used in the SFPT in our study was stainless steel standard cutting rings with a diameter Φ of 61.8 mm and a height H of 20 mm. Before the specimens were prepared, a relative hole with a diameter of 1 mm was drilled in the middle of the wall of the cutting ring, and the fiber could pass through the two holes. In the first step, the pre-prepared soil was sprayed with water and humidified until the optimum water content was obtained. The mixed soil was then placed into black plastic bags and sealed for more than 24 h to ensure the uniformity of water in soil. In the second step, half of the soil with a precalculated dry density of 1.7 g/cm³ was placed into the cutting ring and compacted to the middle height of the cutting ring. In the third step, a fiber was slowly passed through the two holes in the cutting ring. In the fourth step, the same mass of soil was weighed again as in the second step and placed in the cutting ring. Next, the two ends of the fiber were pulled slightly to ensure that the fiber was straight in the specimen. Afterward, the soil was compacted to the height of the cutting ring. Lastly, the prepared specimen was wrapped with plastic film to prevent the variations in the water content of the specimens.

2.3. Test device and test method

2.3.1. SFPT device
A set of test devices for SFPT was designed (Figure 1) in accordance with the methods of Zhu et al. [14]. The fiber pullout device consisted of a force gauge (measuring range: 30 N, accuracy: 0.01 N), a dial indicator (measuring range: 50 mm, accuracy: 0.01 mm), an improved portable low-voltage consolidation apparatus, and a sliding table module controlled by a stepper motor. The force gauge was fixed on the sliding table of the sliding table module. The portable low-pressure consolidation instrument was modified to apply normal pressure to the specimens. The specimen was placed on the platform of the consolidometer and connected to the force gauge through a homemade-connecting clamp. The force on the fiber was applied by a motor to control the sliding table to move, and the movement speed was 1 mm/min. The dial indicator probe was pointed to the sliding table to measure the pullout displacement of the fiber. In this test, normal pressures of 0, 50, 100, and 150 kPa were applied.

![Figure 1. Photograph of the SFPT device](image)

**Figure 1. Photograph of the SFPT device**

2.3.2. **D–W cycle test**

The moisture content of the specimens in this test was controlled within 5%–25% during D–W cycles to simulate the D–W effects of reinforced soil under the conditions of high temperature and rain in summer. In dehumidification, an electric drying oven was used for drying, and the drying temperature was set to +40 °C. Humidification was achieved by adding water to the specimens by using a burette. The moisture content during drying and wetting was determined by the weighing method. After each D–W cycle, the specimens were sealed with plastic wrap and placed in an environment at constant room temperature for more than 24 h so that the uniform distribution of the water content in specimens was maintained. Then, the next D–W cycle was conducted. After the preset D–W cycles (i.e., 0, 1, 3, 6, and 9), the specimens were further subjected to SFPT.

3. **Test results and analyses**

3.1. **Force-displacement curves**

The curves of pullout force versus displacement can be plotted by recording the force and displacement during tests. Figure 2 shows the force–displacement curves of five parallel specimens at 0 kPa and 0 D–W cycle. The results of the five parallel specimens are similar, indicating that the pullout test in this study has good repeatability. Therefore, in the following sections, for the convenience of description, the data for only one of the parallel specimens are selected as a typical pullout curve.

![Figure 2. Force vs. displacement curves of five parallel specimens at a normal pressure of 0 kPa and 0th D–W cycle](image)

Figure 3 shows the force–displacement curves of different normal pressures subjected to D–W cycles. The variation in the force–displacement curve in Figure 3 can be divided into three parts. First, before the peak pullout force is reached, the force linearly increases rapidly with displacement. At this
time, relative sliding between the fiber and soil has not yet occurred. When the force peaks, a gradual debonding occurs between the fiber and soil, and the fiber slides in the soil. Correspondingly, the force decreases. When the force decreases to a certain extent, it tends to gradually stabilize. At this time, the force between the fiber–soil interface is mainly sliding friction. Although the trend of the changes in the curves under each normal pressure is consistent, they increase almost linearly at first and then decline after they peak. Afterward, they tend to be stable. However, at the second stage, the force of decline is different. When the applied normal pressure (50 and 100 kPa) is small, the slope of the force drops at the second stage after the 3rd D–W cycle. Its value is significantly smaller than that of the 0th D–W cycle, as shown in Figures 3(a) and 3(b). When the applied normal pressure gradually increases, as shown in Figures 3(c) and 3(d), this phenomenon is no longer obvious, and the shapes of the curves are similar.

At the same time, the pullout forces corresponding to the normal stresses of 0, 50, 100, and 150 kPa are 5.28, 5.89, 6.39, and 7.86 N, respectively, when the D–W cycles are not performed. The relationship between the force and the normal stress increases linearly. Similarly, for the 1st, 3rd, 6th, and 9th D–W cycles, the force increases linearly as the normal stress increases. As the pressure applied to the specimen increases, the fiber–soil contact area expands, and the interlocking effect enhances. Thus, the friction in the fiber–soil interface increases and causes an increase in the pullout force.

![Figure 3. Force–displacement curves of different normal pressures subjected to D–W cycles](image)

3.2. Effect of D–W cycles on the interfacial shear strength

$\tau_f$ and $\tau_r$ were used to represent the fiber–soil interfacial peak shear strength (IPSS) and interfacial residual shear strength (IRSS), respectively [13,18]:

$$\tau_f = \frac{F_{\text{max}}}{\pi d l},$$  

(1)
\[
\tau_f = \frac{F_r}{\pi dl},
\]

where \(F_{\text{max}}\) is the maximum pullout force during the entire pullout test; \(F_r\) is the force applied to the fiber when the force gauge reading becomes stable before the end of the test; \(d\) is the average diameter of the fiber actually measured through scanning electron microscopy; and \(l\) is the length of fiber embedded in the soil. In this test, the fiber-embedded length of all specimens was 61.8 mm.

Figure 4 shows the fiber–soil IPSS and IRSS subjected to D–W cycles. IPSS and IRSS decrease exponentially as the number of D–W cycles increases. The reduction range in IPSS and IRSS decreases as the number of D–W cycles increases. In Figure 4(a), the corresponding average fiber–soil IPSS and IRSS are 76.1 and 38.9 kPa in the 0th D–W cycle, respectively, when the normal stress is 0 kPa. The fiber–soil IPSS and IRSS decrease by 42.3% and 47.8% in the 3rd D–W cycle, respectively. After nine D–W cycles, the IPSS and IRSS decrease by 50.5% and 58.4%, respectively. The decrease in interfacial shear strength is mostly centered during the first three D–W cycles. In the 3rd to 9th D–W cycles, the degree of reduction in the strength is gradually weakened by the effect of the D–W cycle. In addition, Figures 4(b), (c), and (d) show that the decrease in interfacial shear strength has the same trend as the increase in the number of D–W cycles.

**Figure 4.** Peak shear strength and residual shear strength of the fiber–soil interface during different D–W cycles

### 3.3 Analysis of strength deterioration mechanism

D–W cycles cause the destruction of the cementation between soil particles; consequently, the distance between soil particles increases, and micropores evolve into medium and large pores [19-21]. When the interaction force between soil particles decreases, strength decreases, and the same finding occurs in the fiber–soil interface. The results demonstrate that the fiber is in close contact with the surrounding soil before the D–W cycles, fewer pores form, and the force between the fiber and soil interface is large; therefore, the interfacial shear strength increases. However, when the specimens...
undergo D–W cycles, the size and number of pores between the fiber and soil increase, the contact between them no longer becomes tight. Consequently, the interfacial interaction force weakens, and the interfacial shear strength decreases.

4. Conclusions
In this study, SFPTs were conducted to investigate the effect of D–W cycles on the mechanical properties of the fiber–soil interface at different normal pressures. The main conclusions based on the experimental results were as follows:

1) The trends of the pullout force–displacement curves of the specimens with different normal stresses applied are consistent under the D–W cycles. The curve is divided into three processes. As the pullout displacement increases, the pullout force initially shows a linear increase. Then, it peaks, decreases, and stabilizes.

2) The pullout force increases linearly as the normal stress increases. This increase is independent of the number of D–W cycles because increasing the normal pressure expands the fiber–soil interface contact area, the interaction force at the fiber–soil interface increases, and the force required for fiber pullout increases accordingly.

3) The relationship of interfacial shear strength, including peak and residual strength, with the number of D–W cycles exponentially decreases. The fiber–soil interaction force is weakened by D–W cycles, resulting in a decrease in the interfacial shear strength. Strength most significantly decreases in the first three D–W cycles. The strength decay rate slows down from the 3rd to 9th D–W cycles, indicating that the effect of D–W cycles on the fiber–soil interface weakens.

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