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# Experimental Study on the Shear Strength of Different Interfaces of Fine-Grained-Tailing-Filled Geotextile Tubes

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**Abstract:** As damming material, fine-grained tailings present challenges such as low dam strength and poor stability. To address these issues, this study employs geotextile tube technology to mix water with fine-grained tailings, forming a tailing slurry with a concentration of 60%, which is filled into a geotextile bag to form a geotextile tube, so as to improve the stability of fine-grained tailings. The shear strength characteristics of each interface under different consolidation times and different filling degrees were studied via an indoor shear experiment, including the shear strength of tailing particles, that between tailings and geotextiles, and that within geotextile tubes themselves. The results show that the shear strength of each interface conforms to the Mohr–Coulomb strength criterion, and that the interface cohesion is greatly affected by the consolidation time, while the interface friction angle is mainly affected by the filling degree. Moreover, the shear strength comparison, based on the comprehensive friction angle concept, indicates a substantial increase in shear strength at the interfaces between geotextile tubes compared to both that of the tailings themselves and the interface between tailings and geotextiles, highlighting the reinforcing effect of the geotextile tube filling technology on tailings' shear strength.

**Keywords:** fine-grained tailings; geotextile tubes; interfacial shear; integrated friction angle

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## 1. Introduction

As the traditional method of upstream construction, fine tailing dams face problems such as the inadequate bearing capacity of the dam base, lagging drainage reinforcement, and insufficient flood protection [1,2]. Geotextile tube technology is currently used to solve the outstanding problems of fine tailings in dam construction and obtains good results [3,4]. Geotextile tubes are a type of large-area continuous bag-like material made of high-strength geowoven fabrics, which are filled with flowing cement, mortar, or concrete, and then consolidated to form stable wholes in order to improve the stability of dam construction by using the permeable and impermeable slurry characteristics of geotextile bags [5–8]. Because of the similar reinforced geotextile tubes formed by geotextile bags and tailings, they have high tensile and compressive strength and permeable as well as impermeable slurry [9]. Geotextile tubes are much stronger than sand, and so the use of geotextile technology can effectively solve a series of problems such as the poor permeability, high infiltration line, and low stability of fine-grained tailing dam construction [10,11].

As geotextiles gradually become good geotechnical reinforcement materials, there is no lack of domestic and foreign scholars desiring to study them [12]. Early on, Leshchinsky et al. [13] proposed geosynthetic tubes made of several geosynthetic sheets sewn together to form a shell capable of confining pressurized slurry, as well as presenting guidance for selecting suitable geosynthetics, including partial safety factors and filtration properties. Subsequently, Aiban and Ali [14] investigated the friction characteristics of sand–geotextile–sand and geotextile–geotextile–sand interfaces, considering different test parameters, and developed an experimental setup with which to perform pull-out experiments. Yin et al. [15]

used the fine-grained tailings of a nonferrous copper mine as a reinforced filler soil, and used pull-out tests to study the interfacial properties of geosynthetics with filler soils of different densities, moisture contents, and vertical loads, as well as the mechanism of reinforcing fine-grained tailings. After this, Yin et al. [16] examined the effect of reinforcing tailing pile dams with fine-grained tailing accumulation through a model test of fine-grained tailing pile dam reinforcement. Meanwhile, Chow [17] conducted a study on the fabrication of geotextile tubes, mainly including the seams and inlet structures as well as the type of polymer and geotextile to be used [8]. Plaut and Stephens found that interface friction between the filling and the tube may cause a significant increase in the maximum tension in the tube, and may induce failure via tearing. Carbone et al. [18] comprehensively analyzed the interfacial behavior of a nonwoven geotextile on a geomembrane over a tilting plane device under dry conditions using both a tilting plane and a shaking table, and proposed a new test procedure with defined friction-related parameters in order to correctly characterize the shear strength of the geosynthetic interface.

For the study of the strength characteristics of geotechnical materials, domestic and foreign scholars have also achieved some corresponding results. Carbone et al. [19] carried out 159 geosynthetic interface tests using a large straight shear machine to investigate the shear interaction mechanisms of three critical geosynthetic interfaces (geotextile/geomembrane; drainage geocomposite/geomembrane; and soil/geomembrane). Carbone et al. [20] investigated the effect of the geotextile layup method on interfacial shear strength, studying the interfacial shear strength of sand layers placed along inclined horizontal surfaces with different angles. In addition, Khachan and Bhatia [21] conducted a study on whether the use of synthetic fibers can improve the shear strength of sandy, silty, and clayey soils within geotextile tubes. Beliaev et al. [22] conducted an experimental study and computational estimation of interfacial shear by means of the interfacial friction of geotextile bags with different types of weaving under conditions of transverse pressure and determined the friction parameters of the fabric–fabric interface with different types of weaving. Fu et al. [23] studied the interfacial friction straight shear of geotextile tubes consolidated for a certain number of days, in addition to that of tailing sand and geotextiles with a certain degree of compaction. Dong and Zheng [24] discussed separate tests of the compressibility, straight shear strength, and triaxial strength of fine-grained tailing soils at different moisture contents. Yi et al. [25] investigated the effects of interface type and dry as well as wet states on interfacial shear properties and explored the influence mechanism, showing that the quasi-friction angle of an interface consists of sliding and occlusal friction angles. Due to the uncertainty and variability in the nature of tailings, the seismic performance of tailing dams in terms of horizontal acceleration and displacement under the action of horizontal peak ground acceleration was also investigated via shaking table modeling tests carried out by Li and Salam et al. [26,27].

However, most of the existing studies regard geo-bags as a separate reinforced material in the soil with which to study the stability of geo-bag dams [28–32]. The existing research on the mechanical properties of the bag body also pays more attention to the force of the bag body in the filling stage, and the research on the subsequent state of bag filling is not extensive. Subsequent geotextile tubes will be subjected to vertical pressure and horizontal force during damming and operation, such that they are in a state of compression and shear. The shear strength of a geotextile tube interface directly affects the stability of a dam. Especially for fine-grained tailings as filling materials, due to their poor water permeability and low strength, the consolidation process is relatively long, and the strength characteristics of geotextile tubes under different consolidation times need to be further studied. Due to their poor permeability, low strength, and other characteristics, their consolidation process is relatively long; different consolidation times under the strength characteristics of geotextile tubes also need to be studied in depth.

In this paper, the fine-grained tailings after cyclone classification of the Shilei tungsten mine tailing reservoir in Dayu County, Ganzhou City, Jiangxi Province, are used as test materials. Before conducting geotextile bag interface experiments, preconsolidation tests were performed on geotextile bags with tailing concentrations of 40%, 50%, and 60% under self-weight conditions. These tests determined that the consolidation rate of geotextile bags was relatively faster at a tailing concentration of 60%; therefore, the fine-grained tailings are added with water to a 60% concentration of tailing slurry, which is filled into geotextile bags, and the indoor test is carried out on the fine-grained-tailing-filled geotextile tubes that have entered the consolidation stage after filling. Through the test, the cohesion and friction angle of different interfaces of fine-grained tailing filling geotextile bags under different consolidation times and filling degrees are obtained. The effect of cohesion on the shear strength of different interfaces was equated with the effect of the friction angle on the shear strength of the interface, and the shear strength of different interfaces was compared by the integrated friction angle to analyze the law between the shear strength of the three interfaces. The study of shear tests at different interfaces of fine-grained-tailing-filled geotextile tubes is the basis for the stability analysis of geotextile tube dams and is of great significance for the design and construction applications of fine-grained tailing geotextile tubes.

## 2. Experimental Design

### *2.1. Test Content*

Fine-grained-tailing-filled geotextile tubes are composite bodies composed of geotechnical bag and tailings, which are mutually restrained in the process of force and deformation; therefore, this paper investigates the interfacial shear strength between the interface of geotextile tubes and the interior of geotextile tubes by means of indoor tests, which mainly include the following aspects:

(1) Straight shear test of tailing sand: A straight shear test was carried out on the tailing sand filled with geotextile tubes after consolidation to determine the internal friction angle and cohesion of the tailing sand as well as to analyze the effect of different filling levels and consolidation times on the shear strength of the tailing sand.

(2) Interfacial shear test of tailing sand and geotextiles: Through an interfacial shear test of tailing sand and geotextiles inside geotextile tubes, the change in the friction angle and cohesion of tailing sand and geotextile interfaces with the consolidation time of geotextile tubes is studied.

(3) Interface shear test between geotextile tubes: The interface shear test is carried out on two geotextile tubes to study the variation in the shear strength between geotextile tubes and the geotextile tube interface with filling degree and consolidation time.

### *2.2. Test Material*

The graded tailings from the site were transported to the laboratory, and the particle gradation analysis yielded an inhomogeneity coefficient $C_u$ of 3.8, a curvature coefficient $C_c$ of 1.1, and a particle size content of 69.04% for $d < 0.075$ mm; the particle size range with the highest tailing particle content was 0.03 mm~0.1 mm, with a content of approximately 60% of the total, and the tailing particle size distribution curve is shown in Figure 1. Tailings discharged to the tailing storage pile with less than 50% of the tailing particle size $d > 0.075$ mm are fine-grained tailings; therefore, these test tailings are fine-grained tailings [33].

According to the size of the existing instruments in the laboratory, the geo-bag is designed to be 300 mm long, 300 mm wide, and 80 mm high. The geo-bag is sewn around by electric sewing machines and made of a 180 g/m$^2$ split-film wire machine to weave geotextiles, which is consistent with the specifications of the geotextile bag commonly used in engineering. Its mechanical properties, such as tensile strength, tear strength, CBR bursting strength, and elongation, are shown in Table 1. The vertical permeability coefficient of the geotextile is more than 10 times the vertical permeability coefficient of the tailings used in the test, and the equivalent aperture of the geotextile $O_{95}$ is larger than the d85 of the tailings and smaller than $2D_{85}$, which is in line with the requirements of the technical code for applications of geosynthetics (GB/T50290-2014) [9,34].

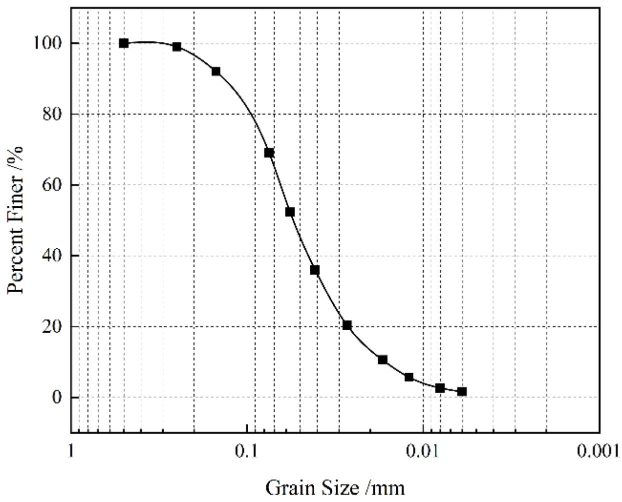



**Figure 1.** Tailing particle size distribution curve.

**Table 1.** Basic mechanical parameters of geotextiles.

| Indicator | Unit | Average | Reference Standard |
|---|---|---|---|
| Radial breaking strength | kN/m | ≥35 | GB/T17641-2017 [35] |
| Longitudinal elongation | % | ≤25 | GB/T17641-2017 [35] |
| Weft breaking strength | kN/m | ≥25 | GB/T17641-2017 [35] |
| Lateral elongation | % | ≤25 | GB/T17641-2017 [35] |
| Tear through power | N | ≥290 | GB/T17641-2017 [35] |
| CBR top breaks through power | N | ≥2600 | GB/T17641-2017 [35] |

## 3. Shear Tests at Different Interfaces

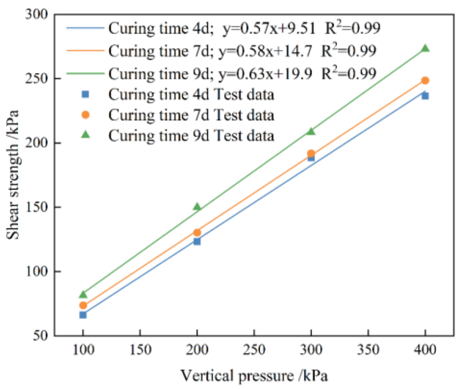
The graded tailings from the site were transported to the laboratory, and the particle gradation analysis yielded an inhomogeneity coefficient, $C_u$, of 3.8, a curvature coefficient, $C_c$, of 1.1, and a particle size content of 69.04% for $d$ < 0.075 mm; the particle size range with the highest tailing particle content was 0.03 mm~0.1 mm, with a content of approximately 60% of the total, and the tailing particle size distribution curve is shown in Figure 1. Prior to the shear test, the fine tailings filling the geotextile tubes were first filled and consolidated with a 60% tailing slurry configuration, filling geotextile bags with a size of 300 × 300 × 80 mm, and three filling levels were designed: low filling, 62.5%; medium filling, 75%; and high filling, 87.5%. To facilitate filling, the filling degree is converted into filling height according to the total volume of the geotextile tubes, which corresponds to the filling height of the tailing sand in the geotextile tubes: 50 mm, 60 mm, and 70 mm, respectively. The geotextile tubes are filled every hour until the height of the tailing sand in the geotextile tubes reaches the test setting height. The filling experiment of the geotextile bags involves multiple filling and drainage cycles. Initially, the tailing slurry is thoroughly mixed before grouting begins, and the start time of grouting is recorded. The filling process is stopped and the time is recorded when the geotextile bag reaches 100% filling capacity. Subsequently, the bag enters the drainage phase, during which the slurry suspends through the pores of the bag, and the drainage end time as well as the height of the geotextile bag are recorded, marking the completion of one filling cycle. This process is repeated every hour until the geotextile bag stabilizes at the target height required for the experiment, indicating the completion of the drainage consolidation process. After the filling was completed, the geotextile tubes were allowed to consolidate naturally in the chamber for 4 d, 7 d, and 9 d, as shown in Figure 2.

Three interfacial shear tests were carried out on fine-grained-tailing-filled geotextile tubes at different filling levels and different consolidation times to investigate the effect of different consolidation times and different filling levels on their interfacial friction characteristics.

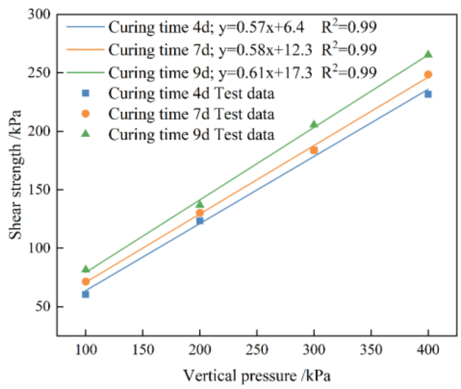

**Figure 2.** Consolidation of fine-grained-tailing-filled geotextile tubes.

### 3.1. Tail Sand Straight Shear

Geotextile tubes with different filling levels and different consolidation times were cut along the edge line and sampled with ring knives; four ring knife samples were taken from each geotextile tube for straight shear tests. The straight shear test was carried out using a strain-controlled electric straight shear with a fast shear method and a shear rate of 0.8 mm/min. The ring knife samples were placed in the shear box and subjected to pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa. A fitted curve of shear strength versus vertical pressure for tailing sand in geotextile tubes with different filling levels and different consolidation times was obtained and is shown in Figure 3. The solid line in the graph indicates the fitted curve and the discrete points indicate the actual measured data values.




(**a**)

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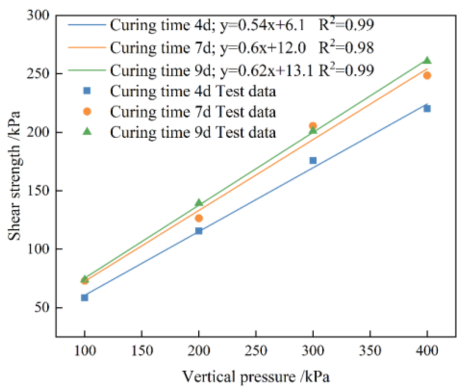


(**c**)

**Figure 3.** Vertical stress versus shear strength curve for tailing sand in geotextile bags. (**a**) Filling degree of 62.5%. (**b**) Filling degree of 75%. (**c**) Filling degree of 87.5%.

According to the tailing sand vertical pressure and shear strength curve, it can be seen that the two show a good linear relationship, and the correlation coefficient is greater than 0.98 according to the fitting results. Taking its intercept as the cohesion, the slope is the internal friction angle, and the results are shown in Table 2.

**Table 2.** Results for the shear strength of fine-grained tailing sand in geotextile tubes.

| Filling Level/% | Curing Time/d | Moisture Content/% | Cohesive Force/kPa | Angle of Internal Friction/° |
|---|---|---|---|---|
| 62.5 | 4 | 27.5 | 9.5 | 30.0 |
| | 7 | 22.7 | 14.7 | 30.4 |
| | 9 | 20.4 | 19.9 | 32.3 |
| 75 | 4 | 28.2 | 6.4 | 29.8 |
| | 7 | 23.7 | 12.3 | 30.3 |
| | 9 | 21.1 | 17.3 | 31.8 |
| 87.5 | 4 | 29.0 | 6.1 | 32.2 |
| | 7 | 24.6 | 12.0 | 32.6 |
| | 9 | 22.2 | 13.1 | 32.1 |

According to Table 2, the internal friction angle of the tailing sand in the geotextile tubes increases with an increase in the consolidation time, but the overall variation is not significant. The cohesive force also increases with an increase in the consolidation time, with greater variation compared to the internal friction angle, with the cohesive force at 9 days of consolidation being approximately 2 to 3 times that of 4 days of consolidation. In addition, the cohesion of the fine-grained tailings in the geotextile tubes decreases with an increase in the filling degree of the geotextile tubes; the cohesion of the tailings in the 62.5%-filling-degree geotextile tubes is about 20~55% larger than the cohesion of the tailings in the 87.5%-filling-degree geotextile tubes. The primary reason is that the greater the filling degree of the geotextile tube, the higher the initial water content within the tube. Consequently, the bound water film within the tailings is thicker, reducing the inter-particle cohesion among the tailings and thereby decreasing the overall cohesiveness. The effect of filling degree on the internal friction angle of the tailings in the geotextile tubes is relatively small, and the internal friction angle of the tailings in the geotextile tubes is basically similar in size for different filling degrees. It can be seen that both consolidation time and filling level have a strong influence on the cohesion of the tailing sand in the geotextile tubes.

### *3.2. Shear at the Interface of the Tailing Sand and Geotextile*

Regarding the study of the friction performance of the interface between geosynthetic materials and sandy soil, it can mainly be measured by a straight shear test and a pull-out test. When the relative displacement of sandy soil and geotextiles is small, the straight shear test is more in line with reality [36]. Due to the small size of the test bag in this paper, the relative displacement of the tailings and geotextile in the bag is small; therefore, this paper refers to the method of Yang's [37] geotechnical direct shear test with which to determine the interface shear characteristics of the tailings and geotextile.

We placed a wooden block of the same size as the box in the lower box of the strain-controlled electric straight shear and glued the geotechnical bag to the block with latex, as shown in Figure 4.

Before the test began, a 50 kPa weight plate was placed on the geotextile and maintained under the gravity of the plate for more than 12 h, the purpose being to make the geotechnical bag fully bonded with the wood block as well as eliminating the influence of geotextile bag folds on the friction properties. The shearing rate was 0.8 mm/min. The shear strength of the tailing sand was obtained for different filling levels and different consolidation times, as shown in Figure 5.


**Figure 4.** Shear at the interface of the tailing sand and geotextile.

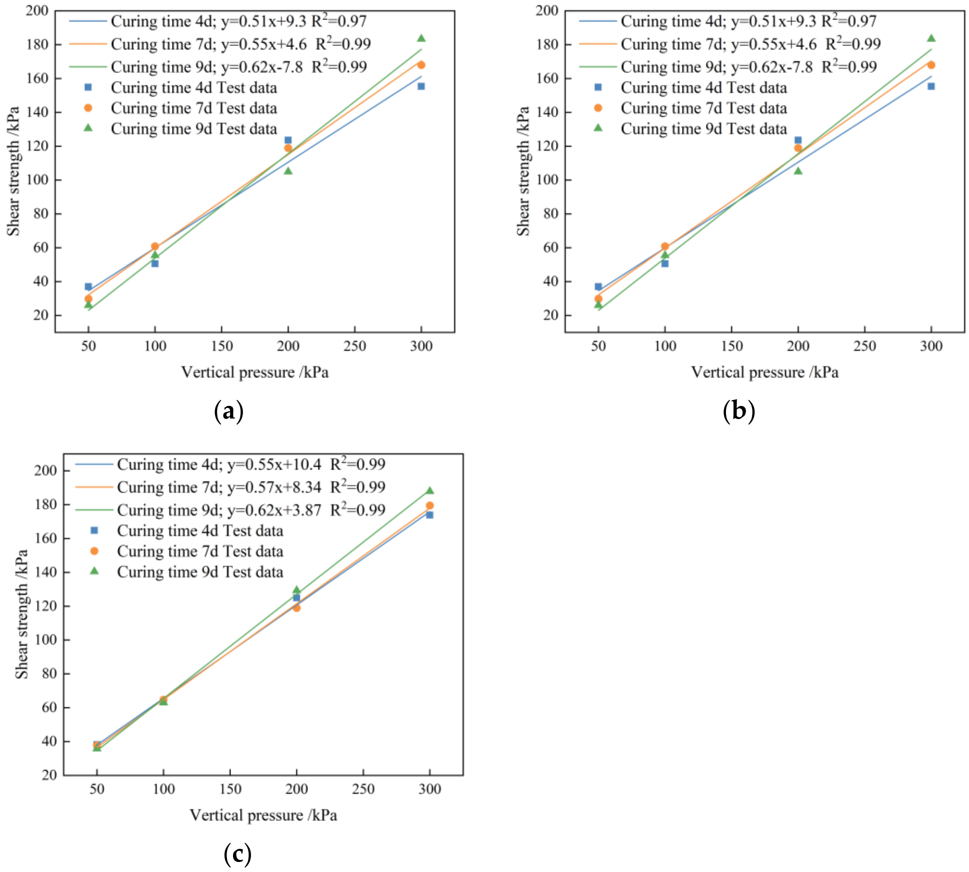


**Figure 5.** Vertical stress versus shear strength at the tailing sand–geotextile interface in the geotextile tubes. (**a**) Filling degree of 62.5%. (**b**) Filling degree of 75%. (**c**) Filling degree of 87.5%.

According to the tailing sand and geotextile interface shear strength and vertical pressure curve, it can be seen that the two have a very good linear relationship; its fitting correlation coefficient is above 0.97, according to the fitting results. Taking its intercept as the tailing sand–geotextile interface cohesion, the slope is the tailing sand–geotextile interface friction angle, and the results are shown in Table 3.

According to Table 3, with an increase in the consolidation time, the cohesive force of the interface between the tailing sand and geotextile in the geotextile tubes gradually decreases, while the interface friction angle increases accordingly, which is mainly because the water content is greater when the consolidation days are short, water increases the lubrication effect of the tailing sand and geotextile surface, and the friction force decreases, so the interface friction angle will be smaller for a short consolidation time. At 62.5% geotextile tube filling, the interfacial friction angle between the tailing sand and geotextile increased from 26.9° at 4 days of consolidation to 31.7° at 9 days of consolidation, an increase of 17.8%, while the cohesion decreased from 9.32 kPa at 4 days of consolidation to 0 kPa at 9 days of consolidation, a 100% reduction. At 87.5% filling, the interfacial friction angle increased by 9.4% and the interfacial cohesion decreased by 62.8%; therefore, the consolidation time of the geotextile tubes has a greater influence on the interfacial cohesion between the tailings and the geotextile.

**Table 3.** Shear strength results at the tailing sand–geotextile interface in the geotextile tubes.

| Filling Level/% | Curing Time/d | Interfacial Cohesion/kPa | Interface Friction Angle/° |
|---|---|---|---|
| | 4 | 9.3 | 26.9 |
| 62.5 | 7 | 4.6 | 28.9 |
| | 9 | 0 | 31.7 |
| | 4 | 9.3 | 28.3 |
| 75 | 7 | 7.9 | 29.6 |
| | 9 | 0 | 30.8 |
| | 4 | 10.4 | 28.9 |
| 87.5 | 7 | 8.3 | 29.5 |
| | 9 | 3.9 | 31.6 |

*3.3. Shear at the Interface between Geotextile Tubes*

In the actual project, the stacking of the geotextile tubes is carried out via the layered method. In addition to the vertical constraints of the upper and lower mold bags, single geotextile tubes are also constrained by the mutual constraints between the geotextile tubes in the horizontal direction; therefore, the test instrument is a large direct shear apparatus developed by Chengdu Donghua Excellence Technology Co., Ltd. (Chengdu, China), as shown in Figure 6. The upper and lower shear boxes of the direct shear apparatus are used to constrain the geotextile tubes, and the constraints of the geotextile tubes during the dam construction process are simulated.

**Figure 6.** Large straight shears.

After the consolidation of the geotextile tubes with different filling levels, they were placed in the shear box of the large straight shear, where one geotextile bag was placed in each of the upper and lower shear boxes. To eliminate the influence of the grouting opening on the interface friction, the grouting opening of the geotextile bags in the lower shear box was placed downwards and the grouting opening of the geotextile tubes in the upper shear box was placed upwards. After loading the geotextile tubes into the shear box, shear tests were carried out on the geotextile tubes with different filling levels and different consolidation times. Through the computer data acquisition and control system, vertical pressure was applied to the upper shear box first. When the predetermined load was reached, the upper shear box was subjected to steady pressure loading, the vertical load was kept stable, and the preloading was carried out for 10 min. The purpose is to stabilize the deformation of the geotextile tubes and make the surface of the mold bag smooth, so as to avoid wrinkling of the geotextile tubes.

Then, shearing began; to the lower shear box, horizontal thrust was applied, so that the geotextile tubes had 100 kPa, 200 kPa, 300 kPa, and 400 kPa of vertical pressure for the shear test, using strain control and a shear rate of 0.8 mm/min through the computer to collect horizontal shear displacement and shear stress data. To reduce the test error, two parallel tests were conducted for each group of shears.

A fitted curve of shear strength versus vertical pressure at the interface between geotextile tubes was derived from the tests at different filling levels and different consolidation times, as shown in Figure 7.

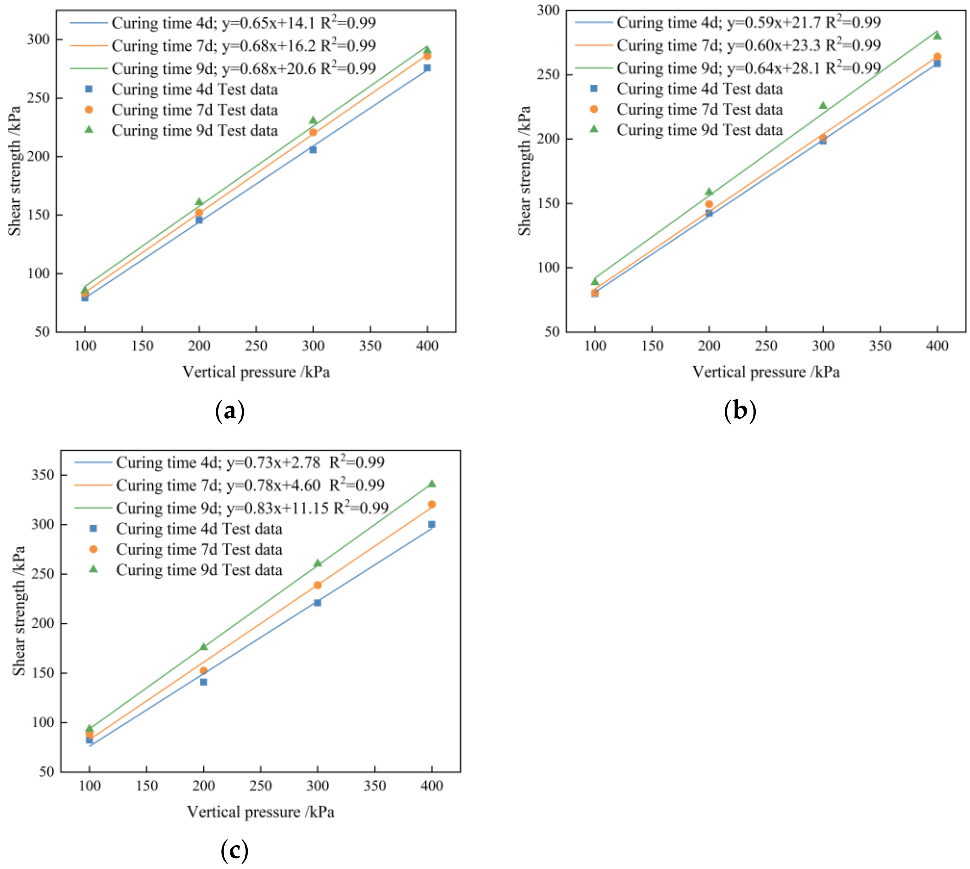


**Figure 7.** Vertical stress versus shear strength curve at the interface between the geotextile tubes. (**a**) Filling degree of 62.5%. (**b**) Filling degree of 75%. (**c**) Filling degree of 87.5%.

According to the fitting results in Figure 7, the interfacial cohesion and interfacial friction angle between the geotextile tubes can be derived for different filling levels and different consolidation times, and the results are shown in Table 4.

According to Table 4, with an increase in consolidation time, the interfacial friction angle and cohesion of the geotextile tubes show an increase. When the filling degree of the geotextile tubes is 62.5%, the interfacial friction angle of the geotextile tubes increases from 30.6° at 4 days of consolidation to 32.6° at 9 days of consolidation, an increase of 6.5%, while the cohesion increases from 21.7 kPa at 4 days of consolidation to 28.1 kPa at 9 days of consolidation, an increase of 29.5%. When the geotextile tubes are filled to 87.5%, the interfacial friction angle of the geotextile tubes increases by 5.3% and the interfacial cohesion increases by 312.9%; therefore, the effect of geotextile tube consolidation time on the interfacial cohesion of the geotextile tubes is greater.

**Table 4.** Shear strength results at the interface between geotextile tubes.

| Filling Level/% | Curing Time/d | Interfacial Cohesion/kPa | Interface Friction Angle/° |
|---|---|---|---|
| 62.5 | 4 | 21.7 | 30.6 |
| | 7 | 23.3 | 31.0 |
| | 9 | 28.1 | 32.6 |
| 75 | 4 | 14.1 | 33.0 |
| | 7 | 16.2 | 34.1 |
| | 9 | 20.6 | 34.4 |
| 87.5 | 4 | 2.7 | 37.5 |
| | 7 | 4.6 | 38.0 |
| | 9 | 11.2 | 39.5 |

The geotextile tube interface friction angle increases with an increase in the filling degree; the interface friction angle of geotextile tubes with a filling degree of 87.5% is about 1.2 times that of those with a filling degree of 62.5%. On the contrary, the cohesion decreases with an increase in the filling height. When the filling degree is 87.5%, the cohesion of the geotextile tube interface is about 0.2~0.4 times that of a 62.5% filling degree.

## 4. Comparison of Shear Stress and Shear Displacement at Different Interfaces

In order to study the shear failure characteristics of tailing direct shear, tailing–geotextile interface shear, and mold bag interface shear, the shear test results under different interfaces were compared. The curves of the shear stress and shear displacement of different interfaces under vertical pressures of 100 kPa, 200 kPa, and 300 kPa are plotted, as shown in Figures 8–10, respectively.

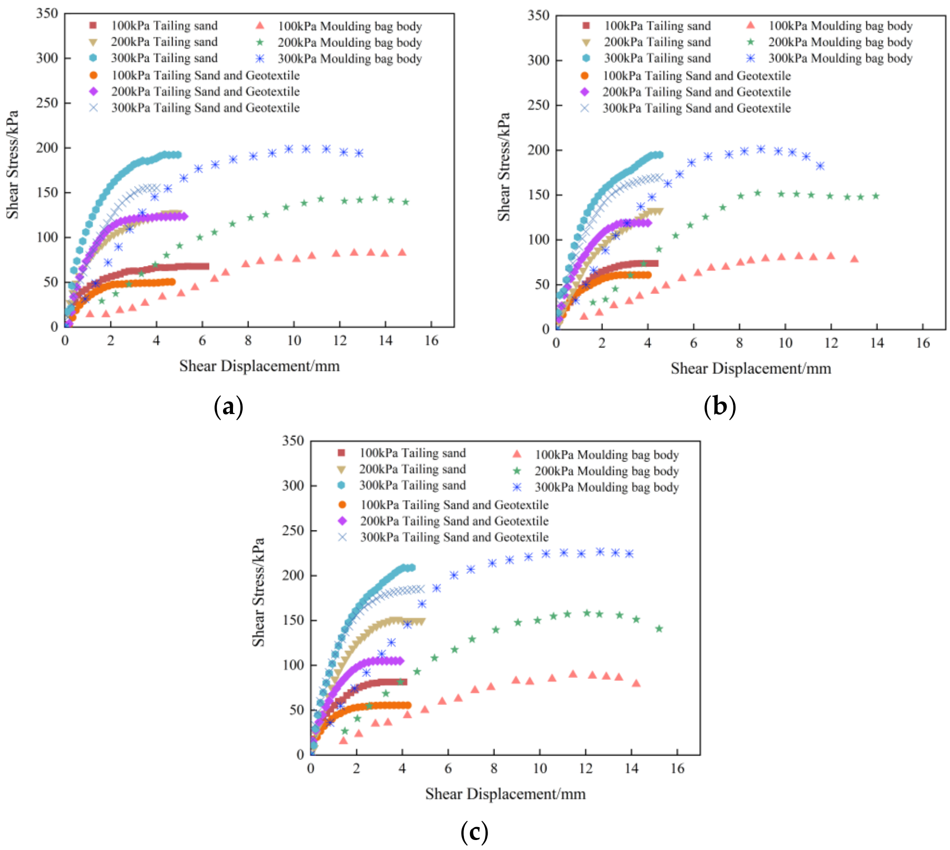


**Figure 8.** Shear stress–shear displacement curves at different interfaces for 62.5% filling of geotextile tubes. (**a**) Consolidation for 4 days. (**b**) Consolidation for 7 days. (**c**) Consolidation for 9 days.

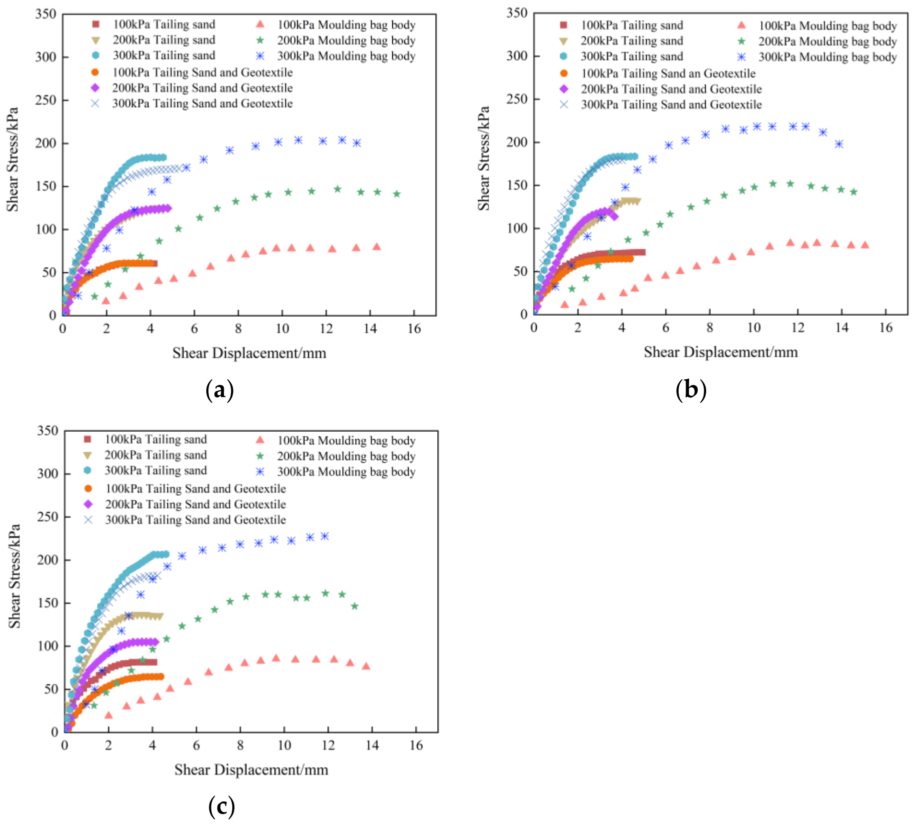


**Figure 9.** Shear stress–shear displacement curves for different interfaces for 75% filling of geotextile tubes. (**a**) Consolidation for 4 days. (**b**) Consolidation for 7 days. (**c**) Consolidation for 9 days.

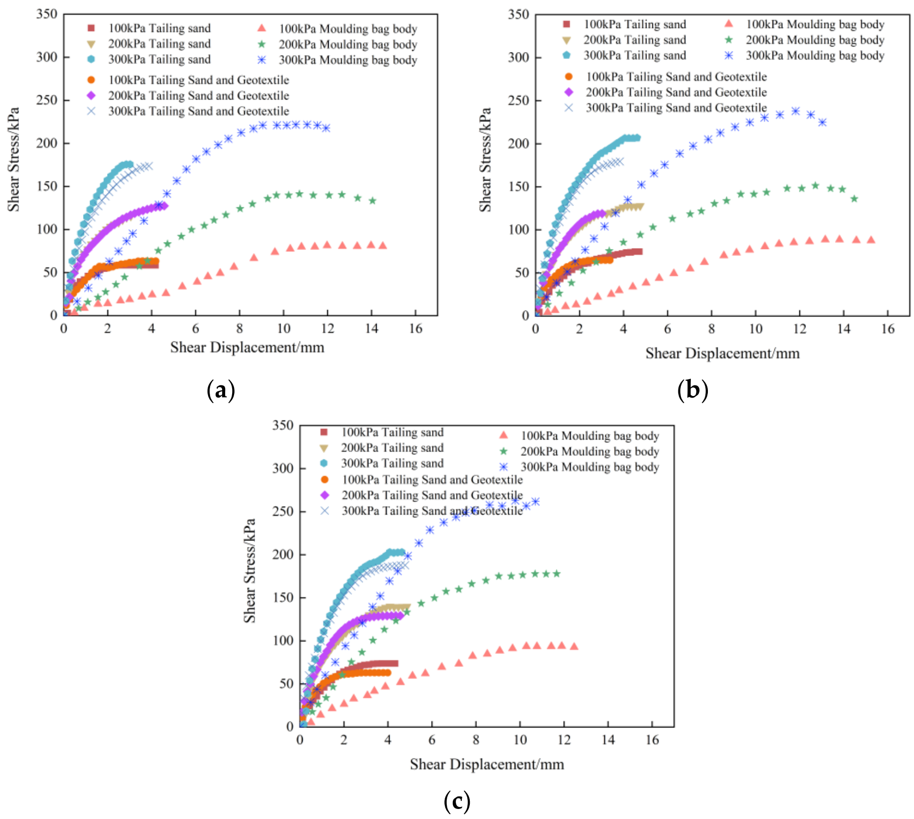


**Figure 10.** Shear stress–shear displacement curves for different interfaces for 87.5% filling of geotextile tubes. (**a**) Filling degree of 62.5%. (**b**) Filling degree of 75%. (**c**) Filling degree of 87.5%.

According to Figures 8–10, it can be seen that, under the action of normal pressure, the shear stress of the interface shear of geotextile tubes is the largest, and the shear stress of the interface shear of the tail sand and geotextile is the smallest. When the filling degree is 62.5%, the shear stress of the interface shear of the geotextile tubes is close to the shear stress of the straight shear of the tail sand, but with an increase in the vertical pressure, the difference between the shear stress of the interface shear of the geotextile tubes and the shear stress of the straight shear of the tail sand is greater. Additionally, with an increase in the filling degree of the geotextile tubes, the growth of the shear stress of the interface shear of geotextile tubes is also greater than the growth of the tailing sand straight shear as well as the tailing sand and geotechnical bag interface shear, and when the filling degree is 87.5%, the consolidation time is 9 days, and the shear stress of the interface shear of the geotextile tubes is much greater than the shear stress of the interface shear of the tailing sand straight shear, tailing sand, and geotechnical fabric. It can be seen that the geotextile tube technology can improve the overall shear strength of the fine-grained tailings.

Observation of the curves shows that an increase in shear stress is greater for the straight shear of tail sand and shear at the interface of the tail sand and geotextile, with a faster development of shear stress and a smaller increase in displacement, whereas the increase in displacement for shear at the interface of geotextile tubes is greater, with a slower development of shear stress compared to shear at other interfaces, and the shear displacement required when the shear stress reaches stability is much greater than that for the straight shear of tail sand and shear at the interface of the tail sand and geotextile.

## 5. Analysis of Shear Strength Parameters at Different Interfaces

Though the test results can be derived from the strength parameters of each shear interface, at the same time, in order to more clearly and intuitively express the enhancement effect of the interface shear strength of the geotextile tubes, this paper will take into consideration the friction angle and cohesion, the cohesion of the impact of shear strength equivalent to the friction angle of the impact of shear strength, and the introduction of the interface integrated friction angle, $\varphi_0'$, a concept to reflect the shear strength of all walks of life; its calculation, Equation (1), is as follows [38]:

$$\varphi_0' = tan^{-1}\left(tan\varphi + \frac{c}{\sigma}\right) \tag{1}$$

In Equation (1), $c$ is the interfacial cohesion, $\varphi$ is the interfacial friction angle, and $\sigma$ is the vertical pressure applied during shear, which is taken as 100 kPa in this paper.

The integrated friction angle of the tailing sand in direct shear, the integrated friction angle of the tailing sand in shear with the geotextile, and the integrated friction angle of the geotextile tubes in shear with the geotextile tube interface are calculated by Equation (1) and summarized as shown in Table 5.

According to Table 5, the shear strength index of the interface between the tailing sand and geotextile is slightly smaller than that of the tailing sand under the same consolidation time and filling height, and the friction angle of the interface between the tailing sand and geotextile is 0.85~0.99 times that of the internal friction angle of the tailing sand; the cohesive force of the interface between the tailing sand and geotextile is not much different from that of the tailing sand after 4 days of consolidation, and after 9 days of consolidation, the cohesive force of the interface between the tailing sand and geotextile is close to 0.

When the filling degree of the geotextile tubes is low, that is, when the filling degree is 62.5%, the friction angle of the interface between the geotextile tubes is close to the internal friction angle of the tailing sand, while the cohesive force is greater than the cohesive force of the tailing sand, about 1.4~2.3 times the cohesive force of the tailing sand; at this time, the shear strength of the interface between geotextile tubes is reflected in the increase in the cohesive force of the interface. When the filling degree is 75%, the friction angle and interfacial cohesion between the geotextile tubes and geotextile tube interface are greater than the internal friction angle and cohesion of the tailing sand, the cohesion is about

1.2~2.2 times that of the cohesion of tailing sand, the interfacial friction angle is about 1.1 times that of the internal friction angle of the tailing sand, and the shear strength of the geotextile tubes and geotextile tube interface is reflected in the increase in the interfacial cohesion and friction angle. When the filling degree of geotextile tubes is larger, that is, when the filling degree is 87.5%, the geotextile tube interface adhesion is close to or slightly less than the tail sand adhesion, but its interface friction angle is larger than the tail sand friction angle, about 1.2~1.3 times the tail sand friction angle; the shear strength of the geotextile tube interface is reflected in the increase in the interface friction angle.

**Table 5.** Shear strength parameters at each boundary.

| Filling Level/% | Curing Time/d | Cohesive Force/kPa | | | Friction Angle/° | | | Combined Friction Angle/° | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Tailings | Tailings and Geotextiles | Geotextile Tubes with Geotextile Tubes | Tailings | Tailings and Geotextiles | Geotextile Tubes with Geotextile Tubes | Tailings | Tailings and Geotextiles | Geotextile Tubes with Geotextile Tubes |
| 62.5 | 4 | 9.5 | 9.3 | 21.7 | 30.0 | 26.9 | 30.6 | 33.9 | 31.0 | 39.0 |
| | 7 | 14.7 | 4.6 | 23.3 | 30.4 | 28.9 | 31.0 | 36.3 | 30.9 | 39.8 |
| | 9 | 19.9 | 0 | 28.1 | 32.3 | 31.7 | 32.6 | 39.7 | 31.7 | 42.6 |
| 75 | 4 | 6.4 | 9.3 | 14.1 | 29.8 | 28.3 | 33.0 | 32.5 | 32.3 | 38.3 |
| | 7 | 12.3 | 7.9 | 16.2 | 30.3 | 29.6 | 34.1 | 35.3 | 32.9 | 40.0 |
| | 9 | 17.3 | 0 | 20.6 | 31.8 | 30.8 | 34.4 | 38.4 | 30.8 | 41.7 |
| 87.5 | 4 | 6.1 | 10.4 | 12.7 | 28.6 | 28.9 | 37.5 | 31.2 | 33.3 | 41.8 |
| | 7 | 12.0 | 8.3 | 4.6 | 31.2 | 29.5 | 38.0 | 36.0 | 33.0 | 39.6 |
| | 9 | 13.1 | 3.9 | 11.1 | 31.9 | 31.6 | 39.5 | 37.0 | 33.2 | 43.1 |

The reason for the above phenomenon is that when the filling degree is low, the binding force of the geotechnical bag on the tail sand is small, and the stretching effect of the geotechnical bag in the shearing process is not obvious, so the friction angle of the interface of the geotextile tubes is slightly greater than the internal friction angle of the tail sand, while in the geotextile tubes, in the shearing process, the shear displacement is relatively large. The friction of the tail sand and geotextile friction also play a certain role; the adhesive force of the interface of the geotextile tubes will be greater than the adhesive force of the tail sand. At this time, the shear strength of the interface of the geotextile tubes is increased by the cohesion and friction angle together, where the cohesion plays a greater role. When the filling degree of the geotextile tubes is larger, the binding force of the geotechnical bag on the tail sand increases; in the process of the tail sand and geotechnical bag slip, the geotextile bag stretching effect is obvious, making the denseness of the tail sand in the geotextile bags increase, thus increasing the friction angle of the geotextile tube interface. At this time, the increase in the shear strength of the geotextile tube interface is mainly due to the friction angle.

Through the comparison of the cohesion and friction angle of different interfaces, it is found that the friction angle of the interface of the geotextile tubes is larger than that of the tailing sand, but when the filling degree is larger, the cohesion of the interface of the geotextile tubes appears to be smaller than that of the tailing sand; therefore, in order to further study the enhancement effect of the shear strength of the interface of the geotextile tubes, this paper introduces a comprehensive friction angle of the interface to reflect the shear strength of all walks of life. As can be seen from Table 4, the trend in the integrated friction angle for different interfacial shears with consolidation time is basically the same, increasing with an increase in the consolidation time. When the filling degree is 62.5%, the integrated friction angle of the interface between the geotextile tubes is 1.07~1.15 times that of the integrated friction angle of the tailing sand and 1.26~1.34 times that of the integrated friction angle of the interface between the tailing sand and the geotextile. When the filling degree is 75%, the integrated friction angle of the interface between the geotextile tubes is 1.09~1.18 times that of the integrated friction angle of the tail sand and 1.19~1.35 times that of the integrated friction angle of the interface between the tail sand and the geotextile. When the filling degree is 87.5%, the integrated friction angle of the interface between geotextile tubes is 1.10~1.34 times that of the integrated friction angle of the tailing sand and

1.20~1.30 times that of the integrated friction angle of the interface between the tailing sand and the geotextile. It can be seen that the interface shear strength of the fine-grained-tailing-filled geotextile tubes is significantly greater than the shear strength of the fine-grained tailings and the shear strength of the tailings and geotextile interface, indicating that the use of geotextile tube technology can play a role in increasing shear strength, and the interface shear strength of the geotextile tubes is greater than the shear strength of the tailings and geotextile interface.

## 6. Conclusions

This study investigated the shear strength of tailing-filled geotextile bags under three different interfaces and presents the following conclusions:

(1) According to the results of the tailing sand direct shear test, the cohesion and internal friction angle of the tailing sand in the geotextile tubes are increased with an increase in the consolidation time of the geotextile tubes, the cohesion of the tailing sand in the geotextile tubes decreases with an increase in the filling degree of the geotextile tubes, and the internal friction angle is close to the size.

(2) The friction angle at the tailing–geotextile interface increases with consolidation time, with the variation in cohesion being significantly greater than that of the friction angle. Consolidation time has a substantial impact on the cohesion at the tailing–geotextile interface.

(3) Based on the shear test results of the geotextile bag interface, both the cohesion and friction angle at the interface increase with consolidation time. Cohesion increases by 29.5% to 312.5% from day 4 to day 9 of consolidation, while the friction angle increases by 4.2% to 6.5%. Consolidation time has a significant effect on cohesion at the geotextile bag interface. The friction angle at the geotextile bag interface increases with the filling degree, whereas the cohesion decreases as the filling degree increases. Additionally, when the filling degree is low, the shear strength at the geotextile bag interface is primarily due to the increase in cohesion. When the filling degree is high, the friction angle at the geotextile bag interface exceeds the internal friction angle of the tailings, and the shear strength at the interface is mainly due to the increase in the friction angle.

(4) Using the concept of the comprehensive friction angle, the shear strength of the three interfaces was compared. The comprehensive friction angle at the geotextile bag interface is 1.07 to 1.34 times that of the tailings' comprehensive friction angle and 1.19 to 1.35 times that of the tailing–geotextile interface's comprehensive friction angle.

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**Conflicts of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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