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Research Article

Influences of Drying and Wetting Cycles and Compaction Degree on Strength of Yudong Silt for Subgrade and Its Prediction

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In order to investigate the influences of drying and wetting cycles, initial degree of compaction, and water content on shear strength of the Yudong subgrade silt, a series of direct shear tests were performed at saturated and unsaturated states. The test results show that effects of the drying and wetting cycles, water content, and compaction degree on cohesion are more evident than those on the internal friction angle. According to the test data, a formula for the cohesion was proposed, which accounts for the drying and wetting cycles, water content, and degree of compaction. Because Bishop's strength formula for unsaturated soils could not be applied to Yudong silt, a formula is given based on Fredlund's formula for predicting the shear strength of unsaturated Yudong silt from the soil-water characteristic curve.

1. Introduction

The silt distributes widely on the Yellow River alluvial plain in the eastern Henan province (referred to as Yudong) and thus is often used as a road subgrade or fill material. Yudong silt has a high content of silt-size particles, and the silt-size particles do not bond very well in drying state and are easily crushed. However, it is sensitive to water and easily becomes liquefaction alike, which means that it has poor engineering stability as a road building material. The soils in nature are subjected to climate change and undergo periodical drying and wetting cycles. The drying and wetting cycles can significantly alter the hydromechanical behavior of soil and damage earth structures [1]. In the natural environment, there are changes in groundwater level and seasonal drying and wetting by evaporation and infiltration of precipitation, respectively, and thus, subgrade soils are subjected to multiple drying and wetting cycles, resulting in deformation and uneven settlement of the subgrade layer, surface crack, and other failures. Because of their importance in engineering applications, the effect of drying and wetting cycles and water content on the shear strength of silt needs to be considered.

In recent years, there have been many studies on the effect of drying and wetting cycles on soil strength. A literature review on hydraulic cycles shows that several drying-wetting cycles [2–4] produce an equilibrium state after which the soil exhibits elastic behavior. Moreover, the irreversible volumetric deformation during the drying and wetting cycles was found to be the function of compaction conditions and the subsequent variation of stress/hydration paths [5, 6]. Goh et al. [7] showed that the shear strength characteristics of soils under the drying and wetting cycles are different. Zhang et al. [8] and Sun et al. [9] showed that even if the same path of net stress and suction was followed during triaxial shearing, the stress-strain and strength behavior are different between specimens experiencing different suction histories. After experiencing a larger suction, the void ratio decreases significantly, and thus, the specimen exhibits the deformation characteristics similar to the overconsolidated clay during shearing [10]. The effect of

Table 1: Basic physical properties of Yudong silt.

Specific gravity (G_s)	Liquid limit, w_L (%)	Plastic limit, w_p (%)	Plasticity index, I_p	Maximum dry density, ρ_d (g/cm^3)	Optimum water content, w_{opt} (%)
2.72	24.5	17.3	7.2	1.72	12.7

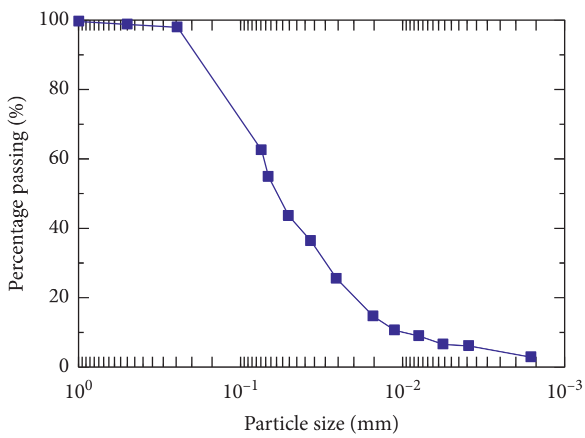

Figure 1: Grading curve of Yudong silt.

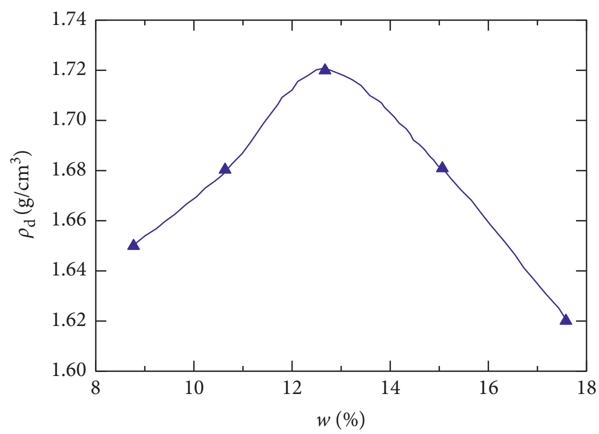

Figure 2: Compaction curve of Yudong silt.

hydraulic hysteresis on shear strength of unsaturated clay was studied by Chiu et al. [11]. Nowamooz et al. [12] developed an effective stress parameter to assess the cyclic behavior of swelling soils in drying and wetting cycles. Several studies have been conducted to assess the effect of drying and wetting cycles on hydraulic conductivity, and the swelling capacity of clay barriers by using different methods [13–18]. In summary, the influence of drying and wetting cycles on mechanical properties of soils is obvious, and the study on silty soil is less compared with expansive soils.

The soil-water characteristic curve (SWCC) plays a key role in unsaturated soil mechanics. Measurement of the SWCC is expensive and time consuming and requires special technique or equipment in laboratory. Sun et al. [19–22] studied the affecting factors of the SWCC by results of the pressure plate tests and concluded that the direct affecting factor is the void ratio rather than the stress or stress history. Gallage and Uchimura [23] studied the effects of dry density and grain size distribution on the SWCC of sandy soils. Gao and Sun [24] studied the soil-water retention behavior of compacted soil with different densities over a wide suction range. Zhou and Sheng [25] proposed an advanced hydromechanical constitutive model for unsaturated soils with different initial densities considering the changes of the SWCC. Ho et al. and Kong et al. [26, 27] studied the SWCCs of granite residual soils experiencing multiple drying and wetting cycles. Zhou [28] proposed a contact angle-dependent model in incremental form to reproduce the soil-water hysteresis behavior. From the above discussion, it can be seen that the effects of the void ratio and drying and wetting cycles on the SWCC are significant, and the quantitative relationship between them can help us to predict the strength of unsaturated soils with the SWCC.

The effects of drying and wetting cycles and water content on the soil strength have been well documented, but to date, few scholars have reported how drying and wetting cycles affect the strength of Yudong silt, which are not fully understood. Besides, the silt is formed by alluvial deposits of the Yellow River, and it has a special geological condition and mainly contains silt-size particles. The silt is used widely as a road subgrade or fill material. Therefore, it is very necessary to study the effect of drying and wetting cycles on the strength of Yudong silt. By performing a series of direct shear tests, the effects of water content, drying and wetting cycles, and degree of compaction on the shear strength of Yudong silt were investigated. And a formula for predicting the shear strength of unsaturated Yudong silt from the SWCC is established, and it can be applied to the design of a highway subgrade by using Yudong silt as a road subgrade or fill material.

2. Experimental Materials

Testing silt was collected from eastern Henan province, China. Because the eastern part of Henan province is referred to as Yudong, the soil is called Yudong silt in this study. The soil, from a depth of 6 m, is grayish yellow in color, slightly wet, and slightly dense. The soil was air-dried, crushed, and passed through 2 mm sieve and then was oven-dried for 24 h before analysis. The physical properties of the soils are presented in Table 1.

Figure 1 shows the grading curve of Yudong silt obtained according to the test methods of soils for highway engineering (JTG/E40-2007) [29]. The curvature coefficient (C_c) of 1.3 and the uniformity coefficient (C_u) of 7.2 met the requirements of the highway roadbed design specifications (JTG/D30-2004) [30]. From above, the soil is classified as sandy silt with low liquid limit.

Figure 2 shows the compaction curves for Yudong silt with 25 blow per layer (3 layers in total) and the compaction work of 2684.9 kJ/m^3 according to test methods of soils for highway engineering (JTG/E40-2007) [29]. The water content of specimens is on the dry or wet side of the optimum or just on the optimum.

3. Experimental Methods

3.1. Soil-Water Characteristic Curve. The GCTS unsaturated soil consolidation apparatus [31] was used to test the soil-water characteristic curve of the silt that had not experienced wetting or drying cycle under a net stress of 0, a degree of compaction of 96%. Matric suction imposed on the specimens was applied by using the axis translation technology [32].

The specific suction path is shown in Table 2. The suction equilibrium was determined from the amount of water drainage, by measuring the amount of water pumped in and out through the burette. The variation in the water content was based on the difference between the suction equilibrium points measured for the specimens. During the test process, the bottom pipes below the ceramic plate were flushed out at regular intervals so that there was more free drainage, thereby shortening the time to achieve equilibrium. The suction equilibrium of each level was achieved in between 2 and 3 days during the test conditions. The tests for measuring the soil-water characteristic curves in drying and wetting cycles were carried out over a period of about 1.5 months.

3.2. Effect of Water Content on Strength of Unsaturated Yudong Silt. After passing through a 2 mm sieve, soil samples were placed in an oven and were dried at 110°C for 24 h. They were then cooled in a dryer and divided into 9 portions with 8 different water contents and one with the optimum water content. The amount of water was calculated according to the targeted water content and the quality of the dry soil, and then, the water was added to the dry soil to reach the targeted water content. The soils were mixed with the water, and the mixtures were then placed into double-layer storage bags and were allowed them to be sealed for 24 hours. The actual initial water content of the soil samples was measured from part of the soil samples oven-dried.

To study the effect of water content on the strength of Yudong silt, a series of direct shear tests were performed on 24 unsaturated specimens of Yudong silt. The test specimens with the same initial degree of compaction of 96% have the initial water contents of 6.9%, 10.4%, 12.3%, 15.8%, 18.2%, 20.5%, 22.1%, and 23.9%. The specimens were subjected to vertical stresses of 100, 200, and 400 kPa, respectively. To ensure that the pore water pressure is completely dissipated during shearing, the shear method was adopted slowly, and the shear rate is 0.02 mm/min. The specific details of the tests are listed in Table 3.

3.3. Effects of Drying and Wetting Cycle and Degree of Compaction on Shear Strength of Saturated Yudong Silt. To obtain better and more realistic simulations of the true environmental conditions in eastern Henan, the testing conditions reported in this study were based on the regional annual average precipitation. The maximum and minimum water contents during drying and wetting cycles were estimated from the amount of evaporation from samples, that is, $w_{max} = w_s$ and $w_{min} = 10\%$ [27]. The laboratory temperature was controlled between 17°C and 18°C. Specific details of the test conditions are as follows:

Table 2: Suction paths.

Path type	Suction path
Drying	1 kPa → 10 kPa → 20 kPa → 40 kPa → 80 kPa → 160 kPa → 320 kPa → 480 kPa
Wetting	480 kPa → 320 kPa → 160 kPa → 80 kPa → 40 kPa → 20 kPa → 10 kPa → 1 kPa

Table 3: Direct shear test program for unsaturated Yudong silt.

Compaction degree, d (%)	Initial water content, w_0 (%)	Normal stress, σ_v (kPa)
96	6.9 10.4 12.3 15.8 18.2 20.5 22.1 23.9	100, 200, 400

Note. w_s is saturated water content in % and $w_s = 23.9\%$.

Table 4: Testing conditions for direct shear tests on saturated Yudong silt.

Compaction degree, d (%)	Number of drying and wetting cycles, n (times)	Normal stress, σ_v (kPa)
94, 96, 98	0 1 3 5	100, 200, 300, 400

(1) During the drying process, the prepared saturated specimens were wind-dried indoor. The specimens were weighed, and the water content was calculated every 2 hours until it reached the minimum water content w_{min}. The drying process was stopped, and the specimens were allowed to stand for 24 hours.

(2) During the wetting process, the air-dried specimens were saturated with a vacuum pump to achieve a water content of w_s. The vacuum pump was stopped, and the specimens were allowed to stand for 24 hours.

(3) Steps 1 and 2 were repeated to replicate multiple drying and wetting cycles.

The initial degrees of compaction of the specimens were controlled at 94%, 96%, and 98%. The specimens were subjected to 0, 1, 3, and 5 drying and wetting cycles, and vertical stresses of 100, 200, 300, and 400 kPa were applied. The 48 direct shear tests were performed, using the slow-velocity shear method at the shear rate of 0.02 mm/min. Details of the test setup are provided in Table 4.

4. Results and Discussion

4.1. Soil-Water Characteristic Curve. The soil-water characteristic curves for the saturated Yudong silt specimen experiencing drying and wetting cycles with a compaction degree of 96% and under a net stress of 0 kPa are shown in Figure 3. The results show that the water content and saturation degree

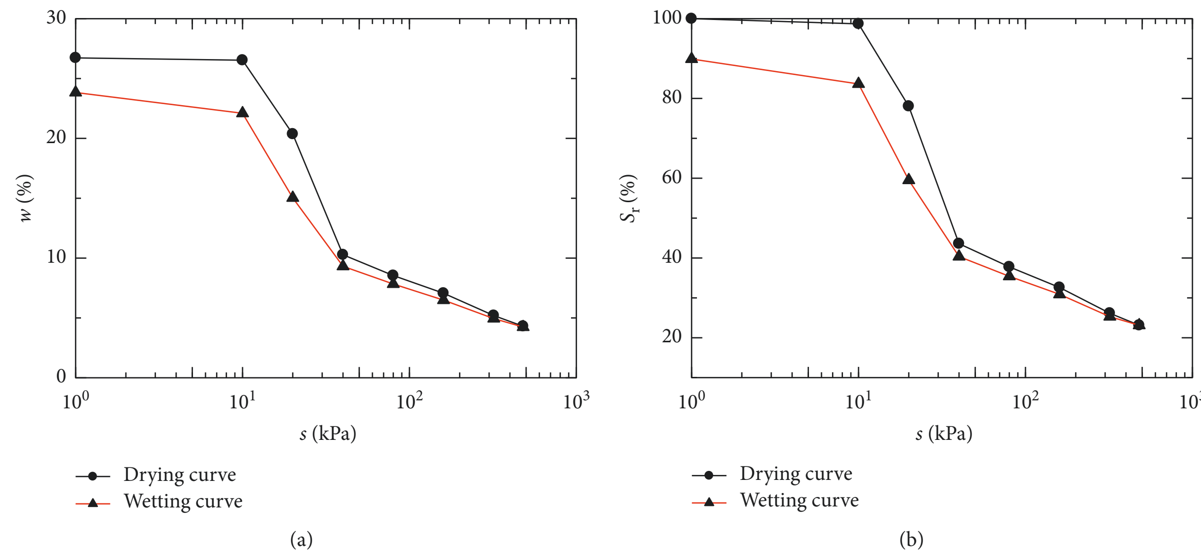

FIGURE 3: SWCCs of Yudong silt: (a)w-s curve; (b) s-s_r curve.

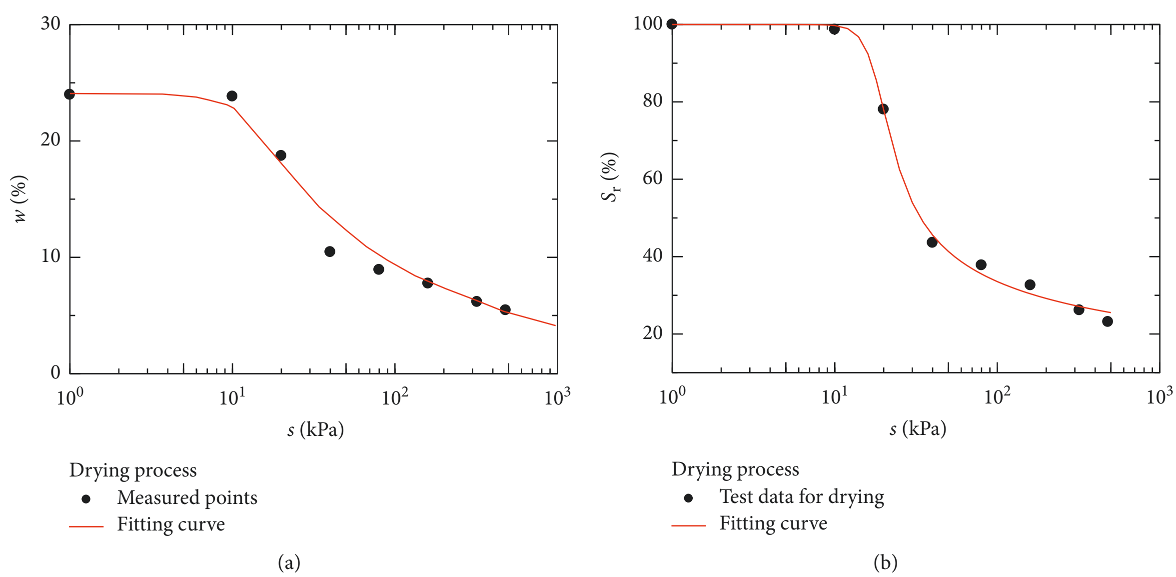

FIGURE 4: Fitting of the drying curve: (a)w-s curve; (b) s-s_r curve.

of the specimen decrease as the suction increases and increase as the suction decreases. Because of the bottle ink effect, there was hysteresis in the drying and wetting curves and consistent with the results from other studies [9, 33]; that is, the drying curve was always higher than the wetting curve. When the suction was less than 100 kPa, there was significant hysteresis in the drying and wetting soil-water characteristic curves, but there was no hysteresis when the suction was greater than 100 kPa.

The measured drying curve can be fitted using the Van Genuchten model [34] as follows:

$$w = \frac{w_s}{\left[1 + (\psi/a)^n\right]^m}, \tag{1}$$

where ψ denotes the suction; w denotes the water content corresponding to the suction; w_s is the saturated water content; and a, n, and m are the fitting parameters. $w_s = 23.9$, $a = 8.95$, $n = 40.02$, and $m = 0.01$ were used for fitting the SWCC in Figure 4(a).

The renowned mathematical equation developed by Fredlund and Xing [35] was adopted to fit the drying SWCC measured by the pressure plate method, as shown in Figure 4(b). The SWCC equation proposed by Fredlund and Xing [35] can be expressed as

$$S_r = \frac{C(s)}{\{\ln[2.71828 + (s/a)^n]\}^m},$$

where (2)

$$C(s) = 1 - \frac{\ln\left(1 + \left(s/s_{re}\right)\right)}{\ln\left(1 + \left(10^6/s_{re}\right)\right)},$$

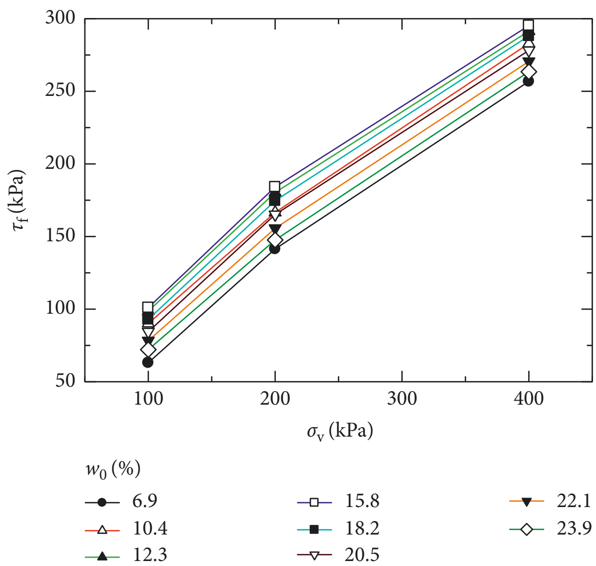

Figure 5: Relationship between shear strength and normal stress at different water contents.

where s_{re} is the residual suction and a, n, and m are three fitting parameters. The fitting parameters of the SWCC in Figure 4(b) are as follows: $s_{re} = 100000$ kPa, $a = 17.02$, $n = 7.60$, and $m = 0.42$.

4.2. Effect of Water Content on Strength of Unsaturated Yudong Silt. The relationships between the shear strength and normal stress for unsaturated silt specimens with different initial water contents are shown in Figure 5. The shear strength line of Yudong silt increases first and then decreases as the initial water content increases.

The strength indexes were determined by fitting the test data using the least squares method under different test conditions, as shown in Table 5. The cohesion increases first and then decreases as the initial water content increases, as shown in Figure 6. However, the initial water content has little influence on the internal friction angle, which changes only between 29° and 31°, as shown in Figure 7; the result is consistent with the results of Vanapalli et al. [36].

The pore water in an unsaturated soil can be divided into two categories: capillary water and adsorbed water. Only the capillary water contributes to the shear strength [37, 38]. The water content is an important influential factor on the cohesion except for the soil strength caused by the friction. The changes in cohesion mentioned above are related to the mode of connection between soil particles. For example, when the soil is dry, the bound water decreases, the weakly-bound water in the diffusion layer becomes thinner, and the concentrations of the dissolved liquid electrolyte increase, resulting in dry coagulation. The clay content of silt is low, so the cohesion is very weak during drying, and the particles are mainly connected with the capillary water. When the water content is low, silt is held together very loosely and can be broken easily. When the water content is very high, the connection force of soil particles from the capillary water becomes weak, resulting in reduced cohesion. Therefore, the cohesion of silt first increases and then decreases as the initial water content increases.

As silt particles are generally within a relatively narrow range of particle size, the effect of water on the lubrication between the particles is limited, and thus, the impact on the frictional strength is limited. Therefore, the internal friction angle changes little during the change of water content.

Table 5: Initial state and strength parameters of unsaturated Yudong silt.

w_0 (%)	c (kPa)	φ (°)
6.9	33.53	30.00
10.4	57.02	29.91
12.3	67.56	29.78
15.8	69.53	29.91
18.2	61.52	30.09
20.5	53.57	29.96
22.1	47.05	29.87
23.9	41.44	30.34

Note. w_0 is initial water content in %; w_s is saturated water content in %; $w_s = 23.9\%$.

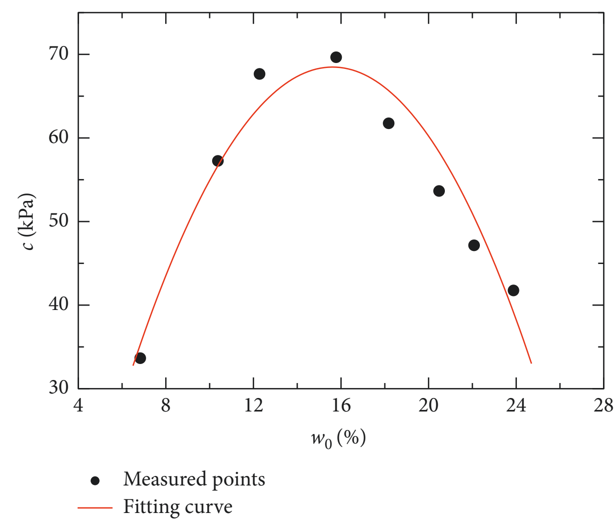

Figure 6: Relationship between initial water content and cohesion.

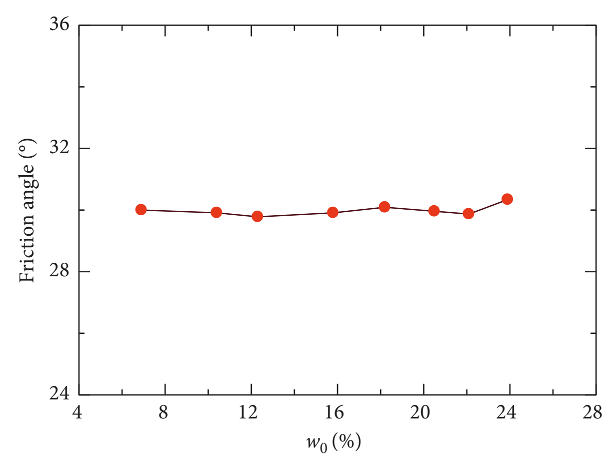

Figure 7: Relationship between initial water content and friction angle.

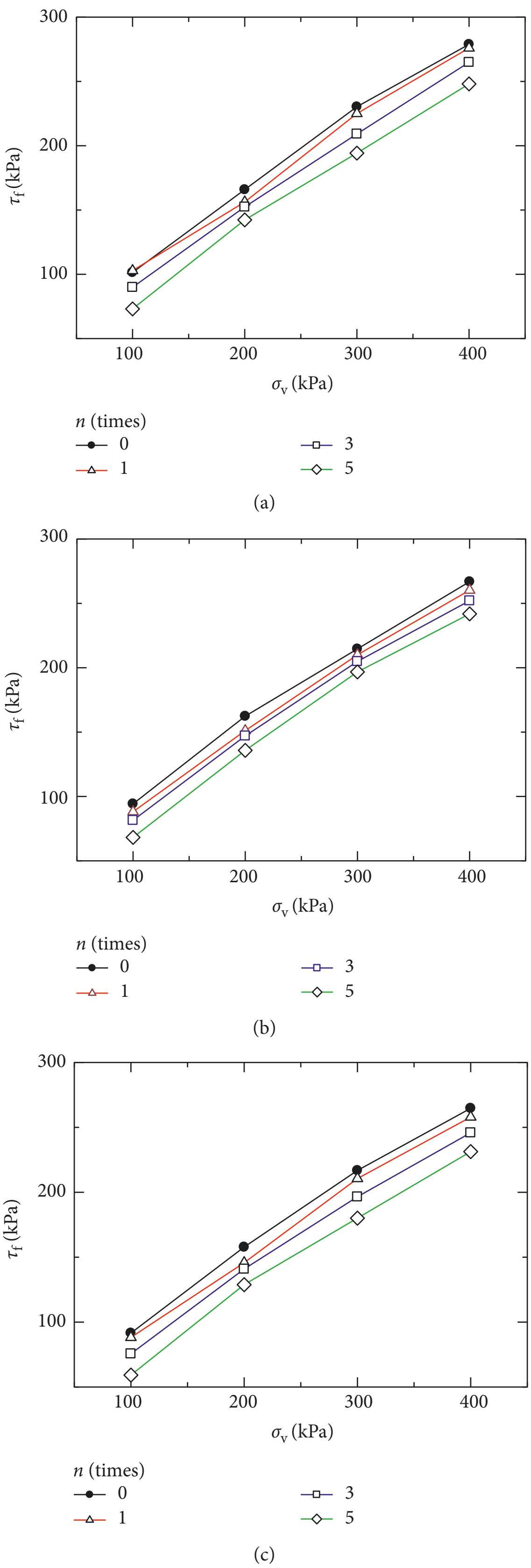

Figure 8: Relationships between shear strength and normal stress at different compaction degrees and drying-wetting cycles. Compaction degree: (a) 98%; (b) 96%; (c) 94%.

Table 6: Initial state and strength parameters of saturated Yudong silt.

d (%)	n (times)	c (kPa)	φ (°)
94	0	37.76	30.04
	1	31.31	29.83
	3	22.1	29.65
	5	8.29	29.48
96	0	41.44	30.34
	1	35.91	30.09
	3	27.63	30.04
	5	14.73	29.78
98	0	44.92	30.77
	1	42.36	30.56
	3	33.15	30.21
	5	20.26	29.96

As shown in Figure 6, the relationship between the initial water content and cohesion for Yudong silt can be fitted by a parabolic curve. The mathematical expression for the relationship is as follows:

$$c = -0.43w_0^2 + 13.43w_0 - 36.38, \quad (3)$$

where c is the cohesion in kPa and w_0 is the initial water content in %.

4.3. Effects of Drying and Wetting Cycles and Degree of Compaction on Shear Strength of Saturated Yudong Silt. The relationship between the shear strength and normal stress for saturated silt specimens under different degrees of compaction and different numbers of wetting and drying cycles is shown in Figure 8. The shear strength line of Yudong silt moves down as the number of drying and wetting cycles increases when the initial degrees of compaction are the same. The shear strength line of Yudong silt moves up with increasing the initial degree of compaction when the number of drying and wetting cycles was the same.

The strength indexes were determined by fitting test data using the least squares method under different testing conditions. As shown in Table 6, the cohesion decreases obviously as the number of drying and wetting cycles increases, while the cohesion increases as the initial degree of compaction increases, as shown in Figure 9. The wetting and drying cycles and the initial degree of compaction have little effect on the internal friction angle, which changes only between 29° and 31°, as shown in Figure 10.

The drying and wetting cycles have a significant effect on the cohesion of Yudong silt. During the drying and wetting process, the soil microstructure changes and the intergranular joints are weakened by small fissure channels or salt solute, resulting in a lower cohesion. The cohesion of silt is also influenced by the degree of compaction because the cohesion is mainly a function of electrostatic attraction and the adhesion between soil particles. When the degree of compaction increases, the distance between the soil particles decreases, the interaction between the particles becomes stronger, and the cohesion increases [39]. The internal friction angle is caused by the friction, including occlusal

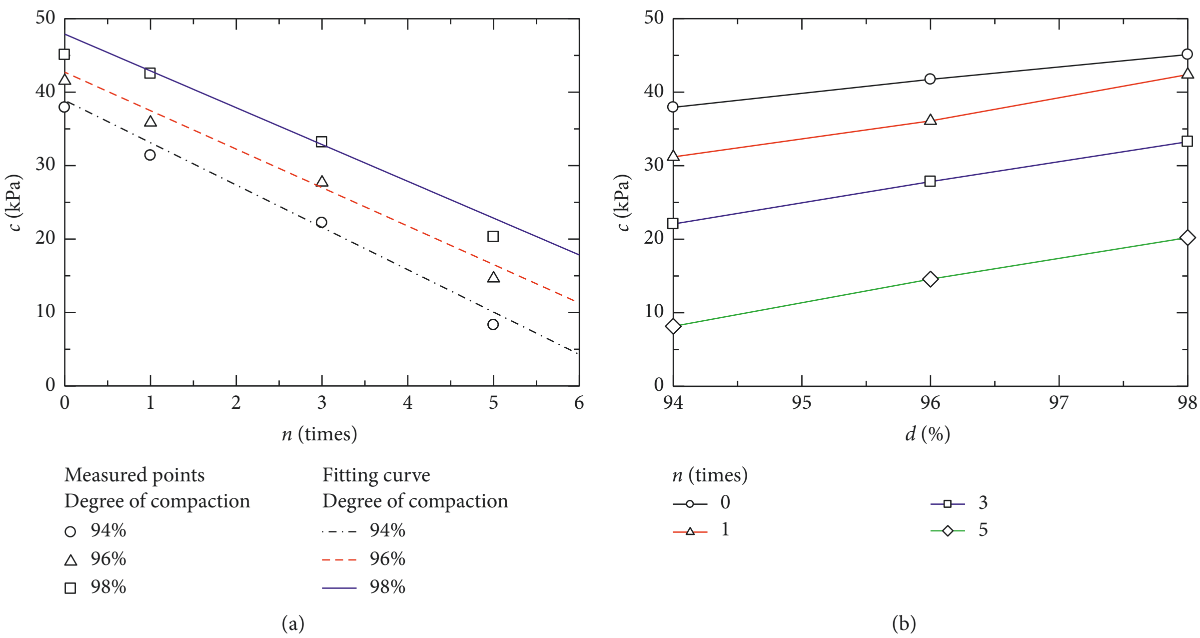

FIGURE 9: Effects of drying and wetting cycles and compaction degree on cohesion. Relationship between (a) cohesion and number of drying and wetting cycles; (b) cohesion and degree of compaction.

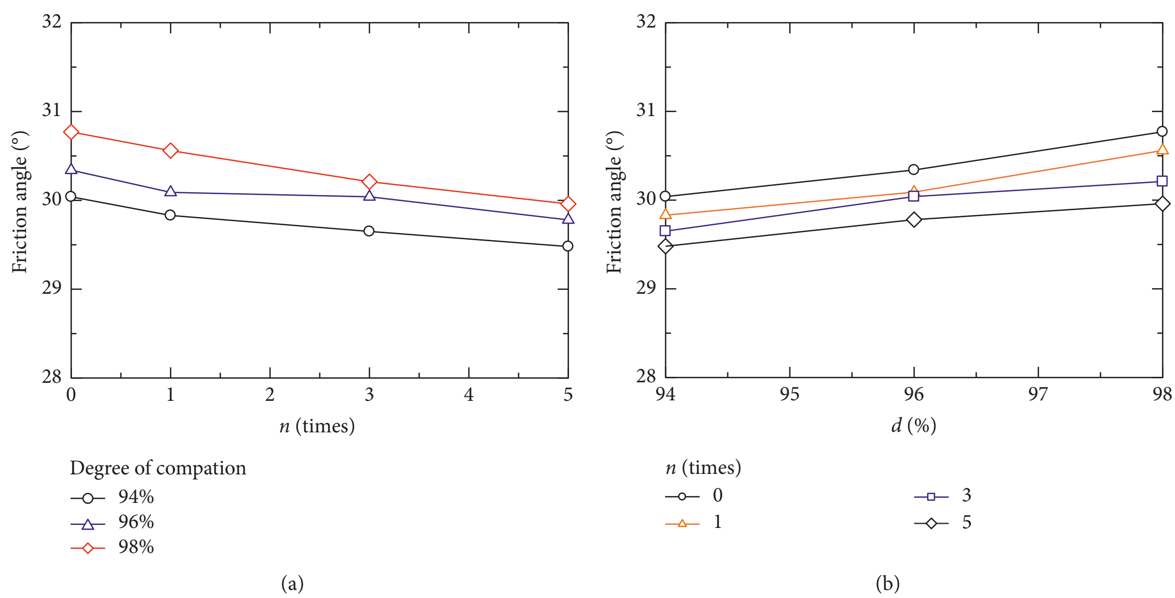

FIGURE 10: Effects of drying and wetting cycle and compaction degree on friction angle. Relationship between (a) friction angle and number of drying and wetting cycles; (b) friction angle and degree of compaction.

friction and sliding friction, between the particles; the size of which depends on the particle morphology, pore pressure, and the soil structure and other factors. The drying and wetting cycles cause irreversible damage to the connection between the particles, and subtle cracks appear that reduce the integrity of the sample. Silt has a uniform particle size, and the clay content is very low, which means that the changes in the soil structure after the drying and wetting cycles are limited, and so, while the friction angle has decreases, the decrease is not obvious. The uniform particle size of silt is uniform, which means that it is dense and difficult to shape. As the degree of compaction increases, the pores of the silt are not really filled but are shaped into a type of building block framework, so any increases in the internal friction angle are not obvious.

Cohesion of Yudong silt is plotted against the number of drying and wetting cycles and degree of compaction in Figures 9(a) and 9(b), respectively. There were clear linear relationships between the cohesion and the number of drying and wetting cycles and the degree of compaction. The

Table 7: Fitting parameters a and b for different degrees of compaction.

Compaction degree, d (%)	Fitting parameter		
	a	b	Fitting degree
94	37.79	−5.74	0.99
96	41.66	−5.21	0.98
98	46.38	−4.98	0.97

linear relationship between the degree of cohesion and the number of drying and wetting cycles in Figure 9(a), can be expressed as:

$$c = a + bn, \tag{4}$$

where c is the cohesion, n is the number of drying and wetting cycles, a is the intercept, and b is the slope. The fitting parameters a and b for different initial compaction conditions are listed in Table 7.

There is a linear relationship between the parameter a and the degree of compaction, as shown in Table 6, while there is a reciprocal-type function between the parameter b and the degree of compaction, which are expressed as follows:

$$a = 214.8d - 164.2, \tag{5}$$

$$b = \frac{1}{0.47 - 0.69d}. \tag{6}$$

Substituting (5) and (6) into (4) results in the following equation:

$$c = 214.8d - 164.2 + \frac{n}{0.47 - 0.69d}. \tag{7}$$

The cohesion of saturated Yudong silt for any degree of compaction and any number of drying and wetting cycles can be predicted by (7).

According to the program of the direct shear tests on saturated and unsaturated silt specimens, the tests are orthogonal to the group saturated specimen with the compaction degree of 96% and the drying and wetting cycles of 0. The cohesion of specimens of this group obtained by the direct shear tests is 41.44 kPa. (3) is divided by 41.44 kPa and then is multiplied by (7) as follows:

$$c\left(w_0,\ d,\ n\right) = \frac{c\left(w_0\right)}{41.44} \times c\left(d,\ n\right). \tag{8}$$

Substituting (3) into (8) results in the following equation:

$$c = \left(-0.43w_0^2 + 13.43w_0 - 36.38\right) \times \left[5.18d - 3.96 + \frac{n}{19.48 - 28.59d}\right]. \tag{9}$$

With (9), the cohesion can be predicted for Yudong silt with different initial water contents and for different degrees of compaction and different numbers of drying and wetting cycles in the range of test conditions.

4.4. Predicting Strength of Yudong Silt Using SWCC. The strength theories for unsaturated soils are mostly based on the Mohr–Coulomb criterion. Numerous formulae for the strength of unsaturated soils are recognized by geotechnical community, including the strength formulae proposed by Bishop [40] and Fredlund and Morgenstern [41].

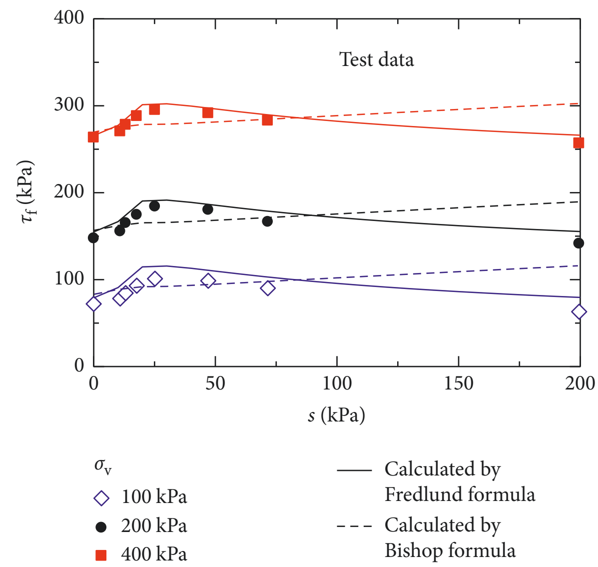

Figure 11: Measured and predicted shear strength versus suction under different vertical stresses.

Bishop [40] proposed a univariate effective stress formula, which can be written as

$$\tau_f = c' + \left[\sigma - u_a + \chi\left(u_a - u_w\right)\right]\tan\varphi'. \tag{10}$$

Fredlund and Morgenstern [41] proposed a bivariate formula, which can be written as

$$\tau_f = c' + \left(\sigma - u_a\right)\tan\varphi' + \left(u_a - u_w\right)\tan\varphi^b. \tag{11}$$

From the corresponding values of suction obtained under different initial water contents from the drying curve (Figure 4(a)), the relationships between the shear strength and suction for net normal stresses of 100, 200, and 400 kPa can be calculated with (10). The relationship between χ and the saturation degree of noncohesive silt was determined by Bishop and Donald [42], and the value of χ is approximately equal to the value of the saturation degree (Figure 4(b)). The data were input into (11), and the relationships between the shear strength and suction for net normal stresses of 100, 200, and 400 kPa were also obtained. The measured net normal stresses in the tests were 100, 200, and 400 kPa, and the relationship between the shear strength and the suction of the Yudong silt is shown in Figure 11.

There were very large deviations between the shear strength calculated by (10) and the measured values, as shown in Figure 11. The shear strength calculated by the Bishop formula did not decrease but always increases with increasing the suction when the suction value is greater than 30 kPa. Therefore, there are still certain limitations associated with applying the shear strength formula for unsaturated soils proposed by Bishop [40] to the Yudong silt. There were small deviations between the shear strength calculated by (11) and the measured values, as shown in Figure 11.

The measured shear strength versus suction shows that when the water content is close to the optimum water content, the suction is 30 kPa, and the peak shear strength also occurred at the water content. The soil used in this study has a uniform particle size distribution and has many pores. When the suction decreases from 30 kPa, the silt specimen tends to be saturated rapidly. Part of water weakens the interactions between the soil particles and reduces the bonding between the particles, resulting in a decrease in shear strength [41]. When the suction exceeds 30 kPa, the silt is relatively dry with little capillary water, and then, some small cracks exist in the silt specimens, which have small shear strength.

From the above discussions, (1), (9), and (11) can quickly provide the technical parameters for the design and construction of the road subgrade or fill materials.

5. Conclusions

(1) The cohesion of saturated Yudong silt decreases with increasing the number of drying and wetting cycles, increases with increasing the degree of compaction, and increases first and then decreases as the initial water content increases. An empirical formula was given according to the experimental data. The formula can predict the cohesion of the saturated Yudong silt under different degrees of compaction or different numbers of drying-wetting cycles in the range of test conditions.

(2) The internal friction angle of Yudong silt, which changes between 29° and 31°, was only slightly influenced by the number of drying and wetting cycles, the initial compaction degree, and the initial water content.

(3) According to results of the direct shear tests and the soil-water characteristic curve of Yudong silt, the shear strength formula proposed by Bishop is not applicable, while an alternative method based on the Fredlund formula is appropriate.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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