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Experimental Study on the Effect of Moisture Content on Shear Strength of Unsaturated Silty Clay

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Abstract

Most soils in the natural state are unsaturated. At present, the theoretical formulas for the shear strength of unsaturated soils are difficult to apply in engineering practice due to the difficulty in obtaining the physical parameters. While one of the factors determining the fundamental physical indices of soils is moisture content, is convenient to be obtained. Based on the indoor consolidation undrained shear test, analysis was done on how changing moisture contents and confining pressure affected the strength and deformation traits of remolded silty clay. Results show that the shear strength is affected by the combined effect of moisture content and confining pressure, the increase of confining pressure can significantly improve the shear strength of soil. Under the condition that the moisture content is maintained constant, the perimeter pressure has a positive relationship with the percentage increase in shear strength of unsaturated chalky clay. So, the formula for the total stress strength of unsaturated soil with the moisture content as the independent variable is established by curve fitting. The findings of this study can serve as a valuable guide for estimating the shear strength produced by the local change in groundwater level in silty clay layers.

Keywords: Unsaturated soil, Silty clay, Shear strength, Triaxial test, Moisture content

1. Introduction

Shear strength, which primarily varies by soil type, is the most intuitive way to characterize the mechanical properties of soils [1], particle fraction [2-4], compactness and moisture content [5], which final one is most closely tied to soil strength and is influenced by outside variables. Naturally, the status of the soil shifts from being unsaturated to being saturated. Mohr-Coulomb theory solves the problem of the shear strength of saturated soil very well, while the joint action of pore water and pore gas affect the shear strength of unsaturated soils, these soils' strength hypothesis is more intricate.

Many scholars have presented various formulas for the investigation of shear strength of unsaturated soil, based on soil-water characteristic curves [6], mathematical fitting, segmentation functions [7]. At present, there are two representative formulas for unsaturated soil strength: the Bishop effective stress formula and the Fredlund double stress variable formula [8, 9]. However, these formulations require experimental determination of matrix suction and other parameters, making it challenging to obtain and use them in engineering practice. These parameters that are tricky to get and tricky to use in engineering practice.

Moisture content and saturation, as parameters characterizing the basic physical index of soil, are easy to obtain. Additionally, some researchers have examined the equation for unsaturated soil shear strength using moisture content and saturation as independent variables based on the saturated soil shear strength total stress index. [10-14]. The shortcomings of the prior related model, which was only appropriate for a narrow range, were overcome by Ma et al.'s shear strength formula, which is based on the total stress strength index of saturated soil [10, 11]. Miao et al. devised the total stress strength formula of unsaturated expansive soil using moisture content as an independent variable based on direct shear testing of expansive soil[11]. Yang et al. demonstrated the feasibility of the total stress intensity formula for unsaturated soils with moisture content [12]. These above mentioned study avoid the cumbersome measurement of matrix suction and has practical engineering significance for predicting the change in strength characteristics of soils due to changes in moisture content and for pre-engineering investigation and design.

2. State of the art

Unsaturated soil is a three-phase system that consists of solid, liquid, and gas. The composition of the soil and the amount of water in the pore spaces have a major impact on the strength of the soil. A critical factor in the investigation of the properties of the soil body and engineering applications is the shear strength of unsaturated soils, but its test method is a problem for many engineers. Determining the shear strength of soil has been determined using a variety of methods. These techniques can be broadly classified into two categories: forced shear method (direct shear method) and free shear surface method (indirect shear method). As the example, such as the direct shear test, double direct shear test, ring shear test [15-18]. The indirect shear test primarily consists of compression tests and indentation tests, for instance, the triaxial test, the biaxial compression test, and

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the unconfined compression test [15, 19], and permeability test technique [20, 21]. By adjusting suction and fitting a soil-water characteristic curve, some researchers investigate how soil strength is indirectly affected by moisture content, but the matrix suction test is complicated, making it much less practical than controlling moisture content in practical application. Direct shear tests and triaxial testing are the main methods used to determine the impact of moisture content (saturation) on soil shear strength. The shear strength of soil is assessed using a strength equation.

In order to create a strength formula, to investigate how changes in saturation and moisture content affect soil cohesion, internal friction angle, and strength, indoor test analysis is widely employed. Straight shear tests performed by Bian et al. on silty clay with varying moisture contents revealed that internal friction angle was roughly linear while moisture content and cohesiveness were nearly quadratic [22]. In unsaturated red clay, Chen et al. discovered that when moisture content rose, the cohesiveness of the clay reduced [23]. Unsaturated loess was subjected to straight shear testing by Cai et al., who found that the shear strength of soil decreased as the moisture content rose [24]. According to Wang et al., the effective cohesiveness was strongly positively associated with the moisture content, also increasing matrix suction led to a rise in the shear strength of unsaturated soil [25].

While numerical analysis methods can overcome the environment and the sample preparation of the test error, and the indoor experimental research is limited by the test conditions [26-28]. Kim et al. therefore investigated the shear strength properties of compacted kaolin under infiltration conditions using SIGMA/W and the program YS-Slope [29]. Zhang et al. studied the impact of suction on the red clay's shear strength while confirming the experimental findings by PFC3D inversion [30]. Cai et al. modelled triaxial testing of unsaturated soils under tension-shear settings to examine the impact of moisture content on peak strength and swelling processes at different perimeter pressures [31]. For unsaturated soils, Liu et al. suggested a DEM-based micromechanical model [32]. Using PFC3D, Ma et al. developed a model of unsaturated silt based on Hill's contact [33].

According to research on how moisture content affects how strong unsaturated soils are, most scholars have concluded that shear strength declines as moisture content rises, whereas angle of internal friction and cohesiveness differ slightly depending on factors like soil type, test procedures, and regional differences. However, no further analysis has been done on the trend of soil strength decay and increase, and no further research has been done on the relationship between these two trends. In this study, the stress-strain characteristics and shear strength of unsaturated silty clay under different moisture content and confining pressure are investigated based on indoor consolidation undrained shear test for silty clay in a construction area in Jiyuan, With the use of experimental analysis, it is demonstrated how changing moisture contents and confining pressures affect the silty clay's deformability and tensile strength.

The rest sections of this study are structured as follows. The source of test materials, fundamental physical indices, and the composition of grain size are initially introduced in Section 3. then goes on to detail the test technique, test tools, and test process. Finally, the conclusions are outlined in Section 5 after the results analysis and discussion are presented in Section 4.

3. Methodology

3.1 Test material

The test dirt was dug out from a Jiyuan building site and buried at a depth of 4.5 m. The basic physical parameters and particle composition are shown in Tables 1 and 2.

Table 1. Basic physical indexes of specimens.

Density	Moisture content	Specific gravity of particles	Liquid limit	Plastic limit	Plasticity Index
1.91	23.20	2.71	28.10	17.70	10.40

Table 2. Particle composition of specimens.

Different soil grain contents (%)				Coefficient of nonuniformity	Coefficient of curvature
Grain size ≥ 0.075 mm	Grain size < 0.075 mm	Grain size < 0.05 mm	Grain size < 0.005 mm		
12.80	87.20	75.60	14.30	1.39	9.62

3.2 Sample preparation

The China Standard for Soil Test Method (GB/T 50123-2019) is followed in the fabrication of remolded specimens with a defined moisture content. method for creating disturbed soil sample. The soil was remolded, and the dry density was adjusted to match the in-situ dirt in order to prepare the specimens, and the preparation process was divided into the following 4 steps: (i) drying the soil sample in an electric blast dryer. (ii) crushing the dried soil sample through a 2 mm sieve. (iii) adding distilled water evenly according to the required moisture content to make a corresponding moisture content soil sample, placing it in a plastic bag and sealing it, and leaving it for 72 h so that the moisture in the soil sample is evenly distributed for use. (iv) according to the sample's height, weigh the appropriate soil mass according to its moisture content, compact it in five layers with equal masses, and then compact each layer to the necessary density. When the final layer is compacted, the ends of the specimen are leveled, and the mass is weighed to keep the error within the allowed range. Each layer is compacted to the necessary height, the surface is scraped, and the procedure is repeated. The main operating procedure is shown in Fig. 1.

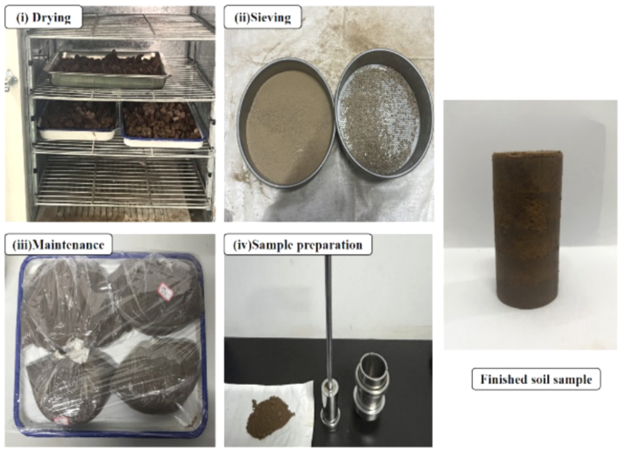


Fig. 1. Flow chart for preparation of remolded soil specimens.

3.3 Test process

For the consolidation undrained (CU) test, the TSZ-3A triaxial apparatus was used, Fig. 2 shows the test apparatus. The test was designed with 5 groups of different moisture contents, namely 15%, 18%, 21%, 24%, and 27%, using parallel tests. For each group, six samples were made, Moreover, three stages of 100, 200, and 300 kPa were used to divide the confining pressure., with a loading rate of 0.08 mm/min. Two stages comprised the test procedure: (a) The specimens were condensed at equal pressure under the predetermined confining pressure, and the end of condensing was defined as pore pressure dissipation being at least 95%; (b) The shear test under the set loading rate, axial deformation of 15% when the test was stopped.

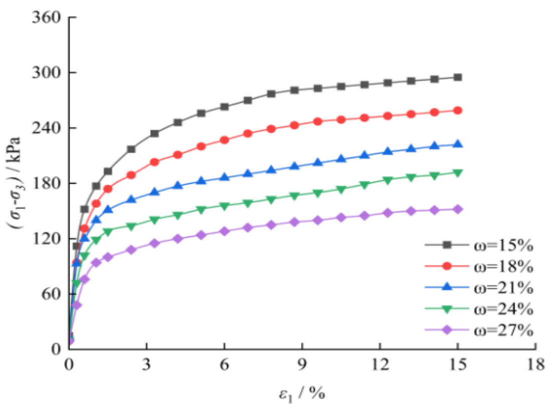
Fig. 2. TSZ-3A automatic strain-controlled triaxial instrument.

4. Results analysis and discussion

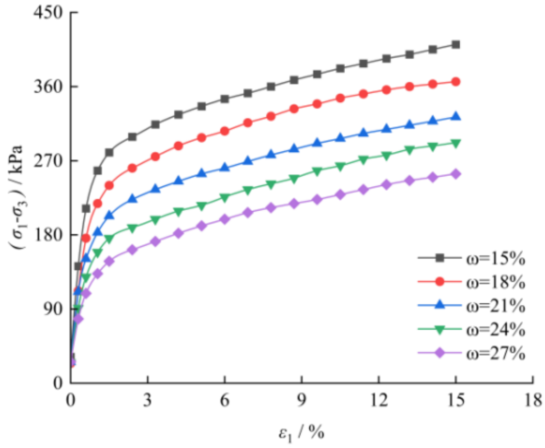
Peak deviatoric stress and stress-strain relationship curves are shown for various moisture contents and confining pressures using the axial strains as the horizontal coordinate and the deviatoric stress as the vertical coordinate, as illustrated in Figs. 3 and 4.

4.1 Stress-strain curves and characteristics of peak bias stress variation

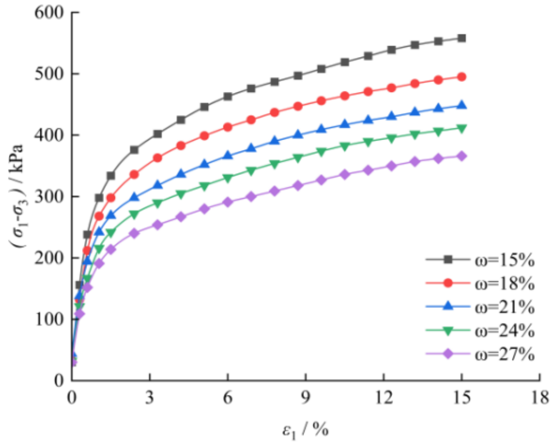
As demonstrated in Fig. 3, the stress-strain curves harden at various confining pressures and moisture contents. The shearing process is divided into 2 stages according to the curve morphology: (i) linear deformation stage, the axial deformation is very small, the deviatoric stress increases rapidly, It is linear for the stress-strain curve, the specimen under the action of compression density, the pore space decreases, the density increases. (ii) stage of non-linear deformation: the specimen under shear results in bulging deformation, there is a parabolic form to the stress-strain curve, while axial strain increases, the deviatoric stress tends to stabilize.



(a) 100 kPa



(b) 200 kPa



(c) 300 kPa

Fig. 3. Stress-strain curves at different confining pressures.

4.2 Confining pressure effect on the peak partial stresses

According to Fig. 4, the maximum deviational stress continuously lowers as moisture content rises while being constrained by the same pressure, and the maximal deviatoric stress falls more quickly the greater the confining pressure, for example, when the confining pressure is 100 kPa, the corresponding peak deviatoric stress decreases from 558 kPa to 366 kPa when the amount of moisture rises from 15% to 27%, with a drop ratio of 34.41%. 200 and 300 kPa are the confining pressures, the corresponding peak stress drop ratio is 38.19% and 48.47%, respectively. When confining pressure is increased, soil strength diminishes more quickly as moisture content rises.

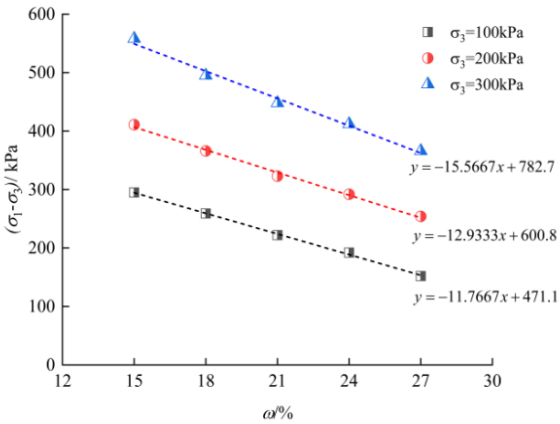


Fig. 4. Peak deviation stress variation with moisture content.

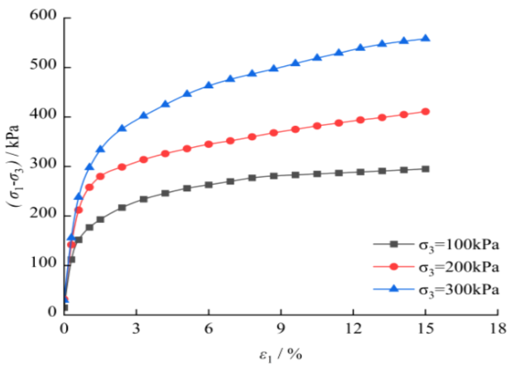
The deterioration of soil strength due to increased moisture content is mainly reflected in two aspects: (i)

Within soil particles' exterior, there are water films of varying thicknesses made up of both firmly and weakly bound water, of which the strongly bound water is tightly bound to soil particles and difficult to separate, but the weakly bound water at the periphery can be separated from soil particles under simple conditions. As the moisture content rises, weakly bound water has a larger role while firmly bound water plays a smaller role, a thickening water layer developed on the soil particles' surface, the linkage between particles is reduced, the dispersion increases, the viscous resistance is reduced, in shear, the thickening of the weakly combined water film on the relative movement of soil particles play a lubricating effect, macroscopically realized as a reduction in shear strength. (ii) soil body in the consolidation effect is compressed, decreased pore space, and the degree of compression and the confining pressure when the moisture content becomes saturated, unsaturated soils' shear resistance gradually approaches that of saturated soils, showing that the higher the moisture pressure, the greater the degree of attenuation of the peak deviatoric stress with increasing moisture content.

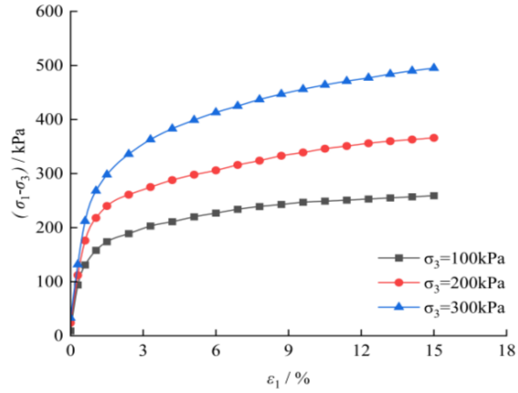
4.3 Shear strength characteristics of unsaturated silty clay with different moisture contents

According to Figs. 5 and 6, for the same moisture content, the peak deviatoric stress, initial tangential modulus (also known as linear deformation stage tangential modulus), and confining pressure are all positively correlated. Peak deviation stress increases more quickly the higher the confining pressure. The soil's strength can be greatly increased by raising the confining pressure. For example, when there is 15% moisture content, and confining pressures is 100, 200, and 300 kPa, the peak values of deviatoric stress are 295, 411, and 558 kPa, respectively, increasing by 39.32% and 89.15%, respectively. Accordingly, when the moisture content is 27%, the peak value of deviatoric stress increases by 67.11% and 140.08%, respectively. With a rise in confining pressure, greater proportionate increases in soil strength occur at higher moisture content levels.

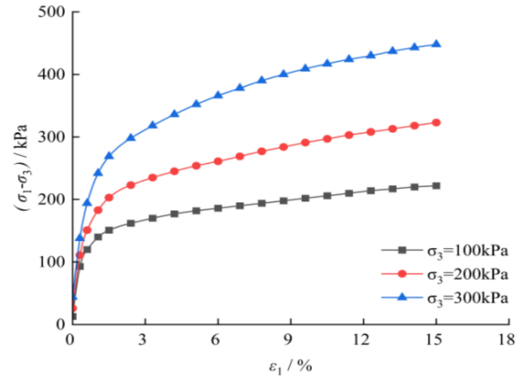
The enhancement of the soil strength by the confining pressure is mainly reflected in two aspects: (i) the internal and external equilibrium of the soil body is disrupted under consolidation, and the internal pore space and stress field are redistributed. The soil body's pore space diminishes as the confining pressure rises, the compactness increases, the association between soil particles is enhanced, the arrangement of soil particles is encrypted, and the frictional resistance and bite force increase. (ii) In the process of shear, the soil deformation not only needs to overcome the inter-particle resistance but also needs to overcome the external pressure generated by increasing the confining pressure, which, on a macroscale, is a rise in shear strength.



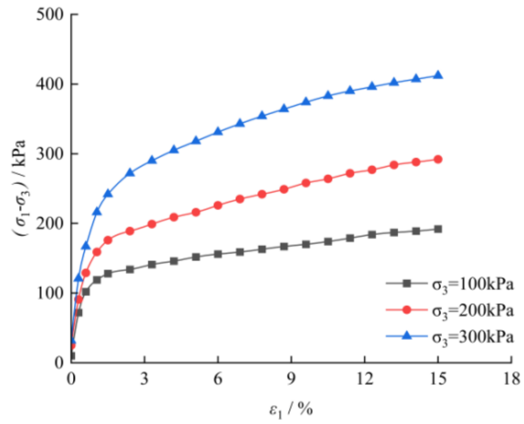
(a) 15%



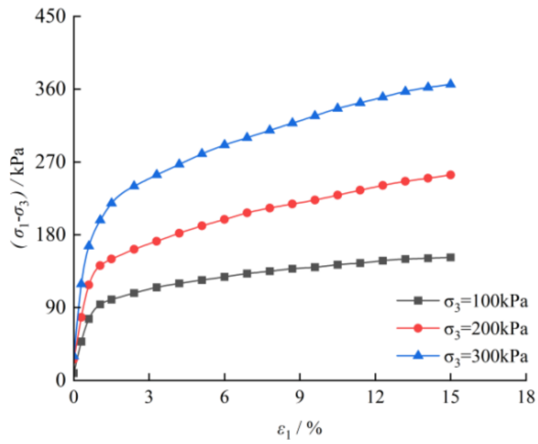
(b) 18%



(c) 21%



(d) 24%



(e) 27%

Fig. 5. Curves of stress-strain at various moisture contents.

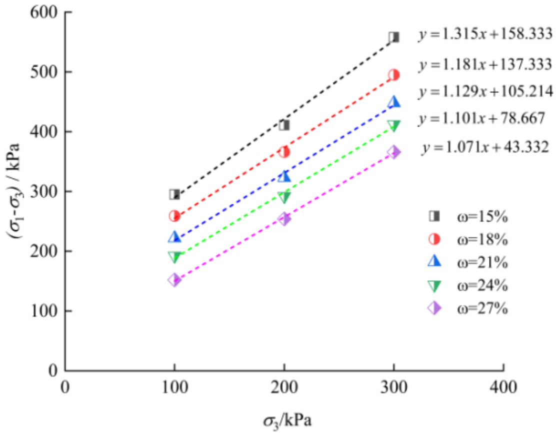


Fig. 6. Variation curve of peak partial stress with confining pressure rate at different moisture contents.

All of the stress-strain curves are of the sort that hardens, as seen in the figure. As a breaking strength, 15% axial strain and the deviatoric stress value were applied. The Coulomb-Mohr circle was drawn with the center and radius, and the shear strength envelope at various moisture contents is shown in Fig. 7. The strength envelope equation and shear strength indices were obtained, as shown in Table 3, after which it became required to create internal friction angle care curves with moisture content for cohesiveness, as shown in Figs. 8 and 9.

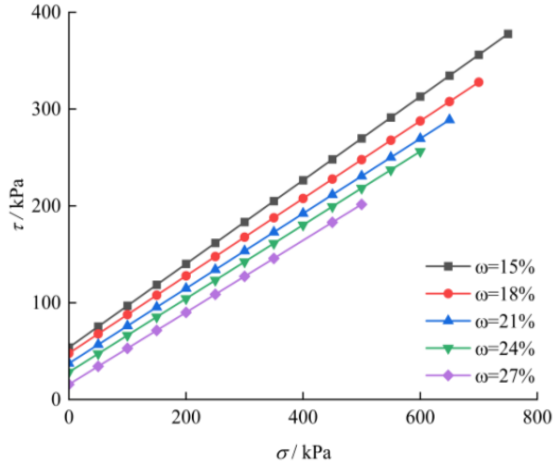


Fig. 7. Shear strength wrap at different moisture contents.

Table 3. Basic physical indexes of specimens.

Moisture content (%)	Total stress failure envelope equation	Internal friction angle (°)	Cohesive force (kPa)	Effective internal friction angle(°)	Effective cohesive intercept (kPa)
15	$\tau = 0.432\ \sigma + 53.73$	23.37	53.73	28.29	40.23
18	$\tau = 0.401\ \sigma + 47.75$	21.78	47.75	27.92	38.72
21	$\tau = 0.387\ \sigma + 37.34$	21.16	37.34	28.35	28.48
24	$\tau = 0.381\ \sigma + 28.29$	20.78	28.29	28.30	28.26
27	$\tau = 0.372\ \sigma + 15.64$	20.40	15.64	28.26	27.16

The internal friction decreases linearly as the moisture content increases, as seen in Figure 8, while the effective internal friction angle stays constant. The cohesion force and inter-particle friction force make up the soil's internal friction angle. when there is little moisture content, the clay particles are closely connected by strong bound water, and the viscous resistance is large. The loosely bound water layer on the surface of soil particles increases as moisture content rises, the cohesion between particles weakens, and the large viscous particles are dispersed into small viscous particles. Dissociated in pore water, the soil's deformation is gradually transformed from interparticle occlusion to sliding friction. Reduced angle of internal friction is a macroscopic result of higher moisture content. The effective internal friction angle only considers the occlusal action between soil and aggregate, which is approximately a stable value. The linear formula is used to fit the relationship between the friction angle and effective internal friction angle with moisture content. The fitting curve is shown in Fig. 6. The fitting result is as follows:

$$\begin{cases} \varphi_{cu} = 26.3605 - 0.2315 \\ R^2 = 0.8895 \end{cases} \quad (1)$$

$$\begin{cases} \varphi' = 27.9941 + 0.0109\omega \\ R^2 = 0.0909 \end{cases} \quad (2)$$

Effective internal friction and moisture content do not significantly correlate, according to a comparison of fitted equation correlation coefficients.

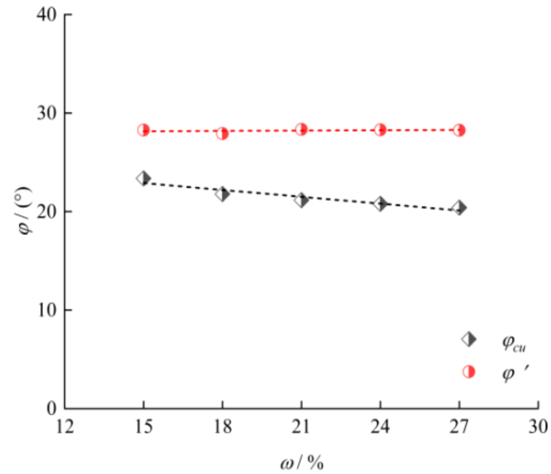


Fig. 8. φ' and φ_{cu}'s curved with moisture content.

As seen from Fig. 9, With a rise in moisture content, the cohesiveness falls, and the fitted curve is parabolic; the effective cohesion increases with the increase of moisture content in a non-linear curve distribution, when there is less than 21% moisture content, the effective cohesion drops as the moisture content rises, but when there is more than 21% moisture content, the effective cohesion remains stable. Effective cohesion mainly results from the attraction of cohesion between soil particles and is related to the consistent state of the soil [34].

According to the correlation between consistency index and moisture content, when the consistency index is 0.25, the corresponding moisture content is 20.3%. When the moisture content is near to the plastic limit (17.7%) or less than, the soil is in a solid or semi-solid, hard plastic state and the association between soil particles is mainly based on strong bound water binding, and as moisture content rises, the effective angle of internal friction steadily decreases. Whenever the moisture content exceeds 21%, the soil is in a plastic state, the association between soil particles is based on weakly bound water, the dispersion of soil particles increases, and the effective cohesion decreases rapidly; as the amount of moisture keeps rising, The degree of soil particle dispersion has a significant impact on effective cohesiveness, and in a constrained space, the amount of dispersion steadily decreases but the effective internal friction angle largely keeps the same as moisture content increases. [35].

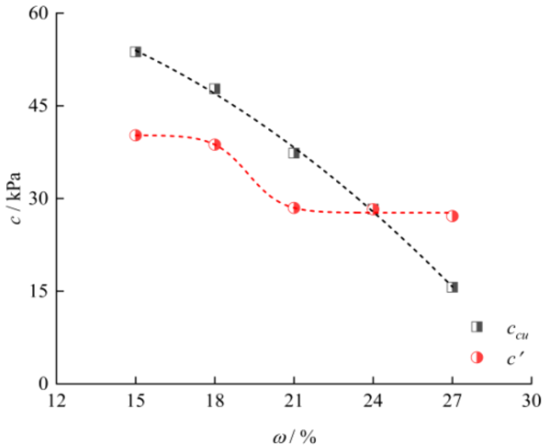


Fig. 9. Cohesion and effective cohesion as a function of moisture content.

In contrast, the cohesion of unsaturated soils is mainly influenced by the combined effect of cohesion and matrix suction, with matrix suction gradually decreasing with increasing saturation, and when the moisture content is greater than 21%, the cohesion is mainly influenced by matrix suction. To fit the connection between cohesion and effective cohesion with moisture content, the quadratic polynomial and Boltzmann distribution are utilized. As seen from Fig. 7, the fitting curve is displayed. The outcomes of the fitting are as follows:

$$\begin{cases} c_{cu} = 63.2420 + 0.8090 - 0.0950\omega^2 \\ R^2 = 0.9982 \end{cases} \tag{3}$$

$$\begin{cases} c' = 27.7006 + \dfrac{12.5512}{1 + e^{(\omega\text{-}19.2644)/0.6422}} \\ R^2 = 0.9581 \end{cases} \tag{4}$$

4.4 Derivation of total stress intensity formula for unsaturated soil with moisture content as independent variable

According to the total stress strength formula proposed by Mohr-Coulomb, it is expressed as:

$$\tau = \sigma \tan\varphi + c \tag{5}$$

Shear strength is denoted by the letter τ in the formula, normal stress by the letter σ, cohesiveness by the letter c, and internal friction by the letter φ. The test results clearly show a functional relationship between changes in moisture content and cohesiveness and angle of internal friction, the approach that employs moisture content as the independent variable may then be used to compute the overall stress intensity of unsaturated soil and is denoted as follows.:

$$\tau = \sigma \tan\varphi(\omega) + c(\omega) \tag{6}$$

Substituting the resultant Eq. (1) and Eq. (3) into Eq. (6), the equation for the total stress intensity of unsaturated soil is expressed as:

$$\tau = \sigma \tan(26.3605 - 0.2315\omega) + 63.2418 + 0.8090\omega - 0.0952\omega^2 \tag{7}$$

5. Conclusions

By preparing remodeled soil samples with varying moisture contents, conducting indoor consolidation undrained shear tests using the TSZ-3A type fully-automatic strain-controlled triaxial instrument, and analyzing how the laws of moisture content and confining pressure relate to the shear strength qualities of powdered clay, we examine the strength change of the powdery clay stratum caused by the change in groundwater level and arrive at the following three judgments:

(1) Changes in effective cohesion with moisture content are related to changes in soil consistency. The effective internal friction angle reduces gradually as the moisture content rises when the consistency index is less than or close to 0. The soil transitions from a hard plastic to a plastic state, and the effective cohesion sharply declines, when the consistency index is close to or higher than 0.25, the effective cohesiveness gradually declines and is mostly influenced by the degree of dispersion between soil particles.

(2) Combining the effects of confining pressure and moisture content has an impact on soil's shear strength, and raising confining pressure can greatly enhance soil's shear strength. The percentage increase in soil shear strength and the rate of decay are positively associated with the confining pressure with increasing moisture content.

(3) The development of an equation for the strength of unsaturated soils using moisture content as the independent variable was based on fitting equations for the fluctuation of how internal friction and cohesiveness change with moisture content.

Since silty clay is widely distributed, and the particle components and properties of powdery clay vary from region to region, the experimental analysis of powdery clay in the study is limited by the required moisture content interval, and further discussion about the relationship between the effective internal friction angle of unsaturated soils and the soil's consistency state is still necessary.

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