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Shear strength characteristics of cadmium-contaminated red clay following the analysis of dry-wet cycles and water content

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ABSTRACT

The purpose is to study the influence of water content on the shear strength of red clay under heavy metal pollution and dry-wet cycles. The red clay in Guilin is taken as the research object. Direct shear tests are carried out on red clay under different initial environments. Meantime, cadmium-contaminated red clay is artificially prepared through cadmium chloride in the laboratory. Then, with the aid of the triaxial shear test, the variation characteristics of the shear strength of the red clay with different cadmium concentrations under dry-wet cycles are studied. According to the results of the direct shear test, the relationships between water content and cohesion, and internal friction angle of red clay is explored. Also, the changes of cohesion and internal friction angle under different cadmium ion concentrations and dry-wet cycles are analyzed, and the relationship between shear strength and dry-wet cycles, as well as between peak shear strength and pollutant concentration is revealed. The results show that the cohesion and internal friction angle generally decrease with the increase of water content. Under different dry-wet cycles, the shear strength decreases with the increase of pollution concentration. The results of the triaxial test show that the lower the metal pollution on the soil is, the more obvious the effect of dry-wet cycles on the shear strength of contaminated red clay is. On the contrary, when the pollution concentration increases, the internal structure of red clay is significantly damaged, and the increase of the number of the dry-wet cycles has a less obvious effect on the enhancement of shear strength. This proves that when red clay is polluted by a low concentration of cadmium, the water evaporation cycle formed by natural rainfall can significantly improve the shear strength of red clay. This study can provide a theoretical reference for seismic disaster prevention and control of the pollution of red clay in heavy metal contaminated areas.

Keywords: Dry-wet cycle; Shear strength; Water content; Red clay

1. Introduction

Red clay is distributed everywhere in China, especially in the south of the Yangtze River. Compared with other kinds of clay, red clay has higher water content, pore ratio, and stronger mechanical properties, and the mechanical strength of red clay has significant vertical distribution [1,2]. Because the formation process of red clay needs to undergo a series of physical and chemical changes, like weathering and micronization. Meanwhile, red clay shows significant engineering geological differences in different soil-forming stages and different geographical environments. The compressibility of red clay is low and its mechanical strength is high. And it is easy to shrink and its internal structure is easy to crack because of its complex engineering properties, which often brings various security risks to construction projects. Furthermore, the high water sensitivity of red clay makes its soil structure easy to contract due to the changes in groundwater level, natural rainfall evaporation, and other effects, resulting in building settlement, slope instability, subgrade damage, and other engineering disasters [3,4].

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In recent years, with the accelerating process of industrialization, heavy metal pollution becomes one of the most serious problems in soil pollution in China. The most serious pollution sources include Pd, Zn, Cd, Cr, and Cu, and is often composed of these heavy metals. Industrial wastewater often contains heavy metal ions, and these heavy metal ions are penetrated into the soil and precipitated in the soil over time, changing the microstructure of soil and affecting its mechanical properties. In addition, groundwater seepage, repeated natural rainfall and evaporation, high temperature and drought in summer, and other effects affect the mechanical properties of soil, resulting in many engineering accidents, which will not only seriously destroy the ecological balance, but also threaten the safety of human life [5].

Many factors affect the shear strength of red clay. Because of the obvious regional characteristics of red clay, scholars have not yet formed a unified conclusion on the influence mechanism of water content on the shear strength of red clay and the influence mechanism of dry and wet cycles on the shear strength of red clay under different pollution concentrations. Therefore, the typical representative of red clay in Guilin is taken as the research object, and the red clay under different initial environments is selected to carry out direct shear tests to explore the various characteristics of shear strength of red clay under different water contents. At the same time, triaxial tests are carried out on red clay polluted by cadmium under different dry and wet cycles and pollutant concentrations. The influence mechanism of shear strength under different dry and wet cycles and pollutant concentrations is analyzed, and the corresponding functional relationship is established, which provides theoretical guidance for the research and related engineering problems of red clay in Guilin.

2. Method

2.1. Test materials

2.1.1. Selection of direct shear test sample soil

The red clay used in this experiment is taken from the east of Hongqiao Street and the south of Wenxin Avenue in Xiangshan District of Guilin City, Guangxi. The soil depth of the sample soil is 3.5 m. The original red clay is dried by air after sampling, and then impurity is removed and finally crushed for further use.

2.1.2. Physical properties of sample soil

According to the analysis of soil particles and the procedures of screening, the diameters of the particles of red clay in Xiangshan District of Guilin City are as follows: generally, the diameters of the participles are below 20 mm, of which the diameter less than 0.002 mm accounts for the highest proportion, reaching 44.7%. The diameter which is between 0.075 and 0.001 mm accounts for 23.53%. The proportion of particles with a diameter of 0.005–0.002 mm is 15.97%, the proportion of particles with a diameter of 0.01–0.005 mm is 7.6%, the proportion of particles with a diameter of 0.25–0.075 mm is 5.72%, and the proportion of particles with a diameter of 20–0.25 mm is 2.48%. And a series of physical property tests are carried out on the sample soils indoor, and their physical properties are obtained, as shown in Table 1.

2.2. Sample preparation and selection

2.2.1. Pollutant selecting

The selected pollutant in this experiment is cadmium chloride ($CdC1_2$) (analytically pure). Cadmium chloride is a colorless crystal that is extremely soluble in water. Its melting point is 568°C, the boiling point is 960°C, and the density under standard conditions is 4.05. And it is mainly used in photography, printing, metal plating, and other fields. The high solubility of cadmium chloride is the significant difference between cadmium chloride and other cadmium compounds, that is, cadmium chloride can be quickly dissolved in water and form colorless and transparent cadmium chloride solution [6,7]. The technical conditions of the pollutant are detailed in Table 2.

2.2.2. Evaluation of the concentration of cadmium pollution solution

In recent years, cadmium pollutes more and more soils in various districts of Guilin. Some scholars sample and analyze the industrial discharge wastewater in Xiufeng District based on heavy metal pollution, and the results show that the cadmium content varies from 0.012 mg kg^{-1} to 0.24 mg kg^{-1}, which has certain ecological risks. If industrial drainage contains heavy metal pollution, heavy metal ions will gradually deposit in the soil, and eventually cause potential harm to the ecological environment and human health. Based on the above analysis, the concentrations of cadmium pollution of red clay are set to 0%, 0.1%, 0.5%, and 2.5% respectively, and the concentration of cadmium is the mass ratio of cadmium ion to the corresponding solution [8,9].

2.2.3. Sample preparation under different water content conditions

The soil samples are fully crushed, screened by the 2mm standard sieve, and dried in the oven of 100°C~110°C. The water contents of four soil samples are tested according to the six conditions of θ = 18%, 22%, 25%, 28%, 32%, and 36%. Under various water contents, the dry soil mass required for the four ring-knife samples is weighted according to their initial dry density, and the water mass required under different water contents is calculated. Then, the water is added to make the soil sample hygroscopic. After the samples are uniformly stirred, the soil samples are put into the fresh-keeping bag and stored for 24 h. After the water is fully absorbed, an appropriate amount of soil is weighed and layered into the sampler, and the sample is pressed with a jack.

2.3. Relevant tests

2.3.1. Direct shear test

The test instrument used in the direct shear test is a new strain-controlled direct shear apparatus. After each group

Table 1
Physical properties of sample soils

Sample number	Water content (%)	Void ratio	Degree of saturation (%)	Dry density (g/cm^{-3})
1	34.7	0.94	94	1.33
2	34.1	0.95	94	1.42
3	34.3	0.96	97	1.45
4	35.3	0.98	93	1.38

Table 2
Technical conditions of the pollutant (%)

Ratio of $CdC1_2$	≥98.0
Ratio of nitrogen compounds	0.002
Ratio of insoluble substances	0.004
pH	4.3–6.6
Ratio of sulfate	0.01

of samples is prepared, the sample soils are placed in a direct shear box for the undrained shear test. The samples are imposed to 100, 200, 300, and 400 kPa vertical compressive stress, respectively. The shear rates are 0.9 mm/min. The test instrument is shown in Fig. 1.

Fig. 1. New strain-controlled direct shear apparatus.

2.3.2. Triaxial test

The recovered sample soil is first air-dried and then crushed. The standard sieve is used for soil screening. After the sample soil is screened, the solution containing cadmium ions is artificially sprayed, and then stirred to prepare cadmium-contaminated red clay with 0%, 0.1%, 0.5%, and 2.5% cadmium ions. The final water content of the contaminated red clay is tested 24 h later. The initial water content of the test sample soil is controlled to 30%, and the initial dry density is 1.40 g/cm^{-3}. In the triaxial compression shear test, the specimen with a height of 80 mm and a diameter of 39.1 mm is prepared according to certain standards. At the same time, the specimen is saturated by vacuum for 24 h. Subsequently, it is dried for 24 h at 40°C and then saturated by vacuum for 24 h. The above is a complete dry-wet cycle. In the experiment, the concentration of each polluted sample is carried out in 0 cycles, 1 cycle, 2 cycles, 3 cycles, and 4 cycles.

The instrument used in the triaxial test is the TSL-1 automatic triaxial shear penetrometer developed by an instrument and equipment company. As shown in Fig. 2, the saturation of each sample is measured after the dry-wet cycle. The triaxial test can be carried out when the saturation reaches more than 93%.

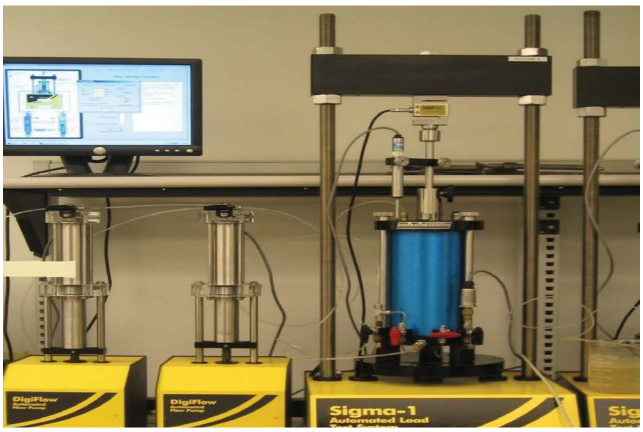

Fig. 2. TSZ-1 automatic triaxial shear penetrometer.

3. Analysis of the results

3.1. Effect of different water content on shear strength

3.1.1. Analysis of the results

According to the test results, the changes of cohesion and internal friction angle with the water content of red clay can be drawn, as shown in Figs. 3 and 4. Fig. 3 shows that the cohesion of four different red clays decreases with the change of water content. When the water content is within the range of 18%~22%, the cohesion of each soil sample decreases with the increase of water content, and the decrease is obvious, and the maximum decrease is 103 kPa. When the water content continues to increase to 28%, the cohesion value continues to decrease, but the decrease tends to be flat. When the water content is within the range of 28%~32%, the cohesion of four kinds of soil samples increases slightly with the increase of water content, and the growth rate is relatively flat. When the water content is 32% or so, the cohesion of four kinds of soil samples reaches a small 'peak'. The cohesion of each soil sample decreases slightly with the increase of water content, and the changing trend of different soil samples is consistent when the range of water content is 32%~36%.

Fig. 4 shows that when the water content increases from 18% to 22%, the internal friction angles of the four soil samples decrease with the increase of water content, and the decrease is significant. Subsequently, when the water content increases to 22%–30%, the internal friction angles of the four soil samples increase first and then decrease with the increase of water content. When the water content increases from 30% to 32%, the internal friction angle of each soil sample decreases with the increase of water content, and the decrease is obvious. With the further increase of water content, the internal friction angle of each soil sample increases, and the variation law is consistent [10].

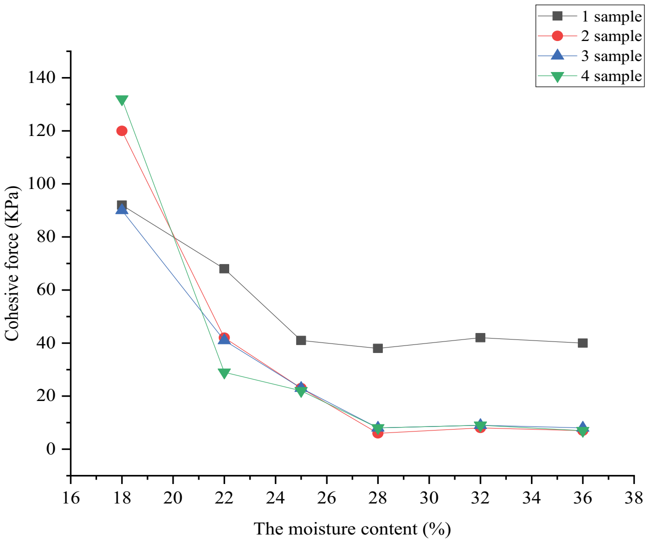

Fig. 3. Relationship between cohesion and water content.

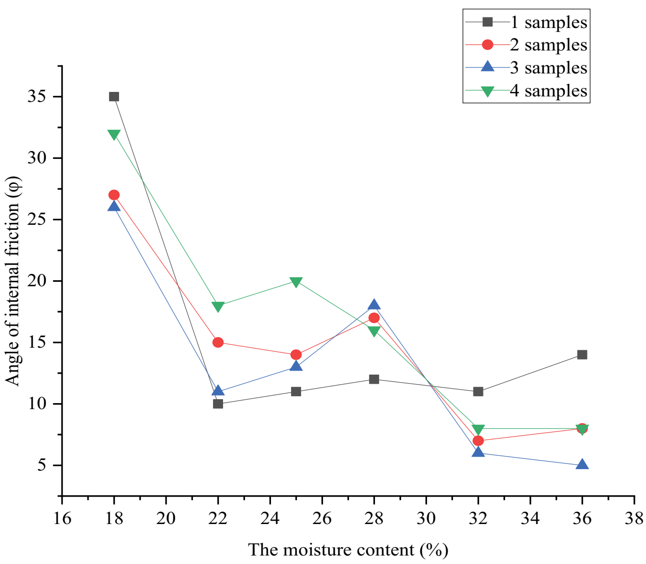

Fig. 4. Relationship between internal friction and water content.

3.1.2. Experimental results and mechanism analysis under different water contents

Based on the variation of cohesion and internal friction angle of red clay under different water content conditions in the above tests, the analysis is conducted from the following aspects:

- The experimental data in Fig. 3 indicate that the least square method in Matlab software is used to fit the relevant experimental data. The relationship between cohesion and water content of red clay can be approximated by the following equation:

$$C = -121,824\theta^3 + 106,571\theta^2 - 30,721\theta + 2,931.7 \quad (1)$$

where C is the cohesion and the correlation coefficient R^2 = 0.9872. The cohesion mainly comes from the mutual attraction between soil particles, water film connection, and cementation [11]. Fig. 4 shows that the cohesion of red clay changes with the change of water content. When the water content is within the range of 18%~22%, the decrease range of the cohesion is the most obvious. When the water content is close to 32%, the soil is nearly saturated, and the cohesion tends to be stable and the change is slight. One reason for this phenomenon is that the high strength of red clay is mainly caused by the cementation of free oxides, and this connection is water-stable [12,13]. The other is that with the increase of water content, the water film on the surface of soil particles is thickened, and the particle spacing is increased, which leads to the weakening of water film connection between particles and the decrease of cohesion.

- The experimental data in Fig. 4 shows that the least square method in Matlab software is used to fit the data. The relationship between the internal friction angle and the water content of red clay can be expressed by the following equation:

$$\phi = 6,603,45\theta^4 - 7,344,38\theta^3 + 3,030,89\theta^2 - 549,49\theta + 3,701.5 \quad (2)$$

The correlation coefficient is R^2 = 0.9999. In Fig. 4, the internal friction angle of red clay decreases first and then increases and then decreases and then increases with the increase of water content, and the overall trend is downward. The main factors affecting the internal friction angle of red clay are particle structure, size, and density [14]. Free iron oxide in red clay exists in the crystalline and cemented state, and the relative change of the content of the two can analyze the relationship between friction strength and water content. When the water content is low, the soil particles of red clay form a stable granular structure under the oxide connection with cementation, and the red clay iron oxide mainly exists in the form of cementation. At this time, the common water film between soil particles is thin, and the water film connection force is large, and the number of fine particles of red clay soil is large. Under the action of bonding force and water film connection force, the contact surface of each soil particle increases, and the overhead pores are filled with fine particles, forming a solid agglomeration structure. The soil is dense and integral, and its internal friction angle is large [15,16].

3.2. Effect of different dry-wet cycles on shear strength

3.2.1. Statistics of experimental results

According to the experimental results, the relationships between the cohesion and the internal friction, the number of dry-wet cycles of red clay under different cadmium ion concentrations are obtained, as shown in Figs. 5 and 6.

3.2.2. Experimental results and mechanism analysis under different dry-wet cycles

The relationship between the shear strength and the number of dry-wet cycles, as well as the relationship between the peak shear strength and the concentration of cadmium ion, is fitted by exponential function for red clay contaminated with different concentrations of cadmium ion under different dry-wet cycles, as shown in Eqs. (3) and (4):

$$\tau_{fN} = a_3 + b_3 e^{-k_3 N} \tag{3}$$

$$\tau_{fn} = a_2 + b_2 e^{-k_2 n} \tag{4}$$

where N is the number of dry and wet cycles, n is the concentration of cadmium ions, a_2, b_2, k_2, a_3, b_3, k_3 are fitting constants, and the correlation coefficient $R^2 = 0.998$.

Figs. 5 and 6 show that the cohesion of Cd-contaminated red clay decreases first and then increases with the increasing number of dry-wet cycles. For red clay with the Cd pollution concentration of 0, the cohesion shows a downward trend. The internal structure of contaminated soil is damaged due to the infiltration of cadmium ions. When a dry-wet cycle is completed, the shrinkage volume of the soil sample decreases. At this time, the polymer in the sample soil is further close, and its contact is denser, which makes the cohesion and internal friction angle of soil will increase [17]. When the number of cycles is increased, the small cracks generated inside the soil will continue to expand, and some small cracks developed on the surface will also expand. Therefore, it is difficult to restore the soil to the original structure based on the internal cracks filled by water, and the cohesion will decrease further after multiple cycles are conducted, but it is not significant. During the dry-wet cycle of the red clay sample with the pollution concentration of 0, the original structure of the soil will change with the continuous hydrolysis of the internal free oxide colloid, resulting in the corresponding decrease of soil cohesion and the corresponding increase of internal friction angle. After four dry-wet cycles, the internal friction angle of cadmium contaminated red clay is significantly smaller than that of non-cadmium contaminated red clay. This is mainly because the free oxide colloid in the red clay without cadmium pollution will be hydrolyzed with the increase of the number of dry-wet cycles, so that the friction and affinity between the soil particles are increasing, and thus the internal friction angle of the red clay without pollution is also increasing with the increase of the number of dry-wet cycles. For the red clay with cadmium pollution, the thickness of the water film on the surface of the red clay is changed, which plays a certain 'lubrication' role in the soil, decreasing the friction between the soil particles. Based on the above analysis, the closer contact between soil particles is caused by the dry-wet cycle effect on the shear strength of cadmium-contaminated red clay. Therefore, the increase of internal friction angle of cadmium-contaminated red clay is not significant with the increase of dry-wet cycles [18–25].

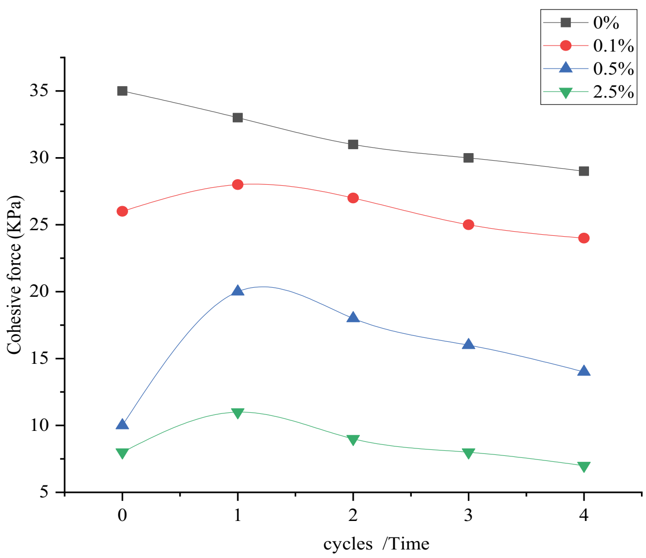

Fig. 5. Relationship between cohesion and dry-wet cycles under different pollution concentrations.

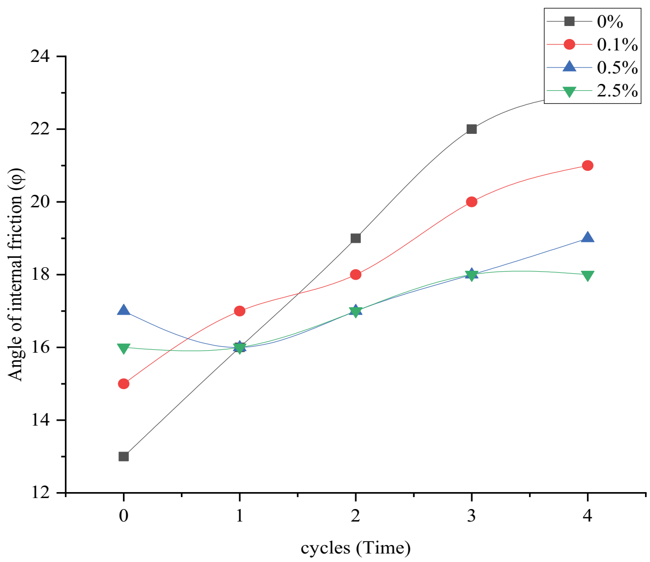

Fig. 6. Relationship between internal friction and dry-wet cycles under different pollution concentrations.

4. Conclusion

Under the same initial conditions, with the increase of water content, the cohesion and internal friction angle of red clay show a downward trend as a whole, and the decrease is more obvious in the range of low water content (less than 22%). When the soil is close to a saturated state, the cohesion of red clay tends to be stable and the change is small. Compared with cohesion, water content has little effect on the internal friction angle of red clay. The main mechanism is that the 'water stability' of cement bond based on free iron oxide is the main reason affecting the cohesion of red clay. The change of internal friction angle mainly depends on the relative content of the crystalline and cemented state. When the pollution concentration of red clay is low or there is no pollution, the increase in the number of dry-wet cycles will significantly enhance the shear strength of red clay. When the pollution concentration is high, the strong structure of the soils will be seriously damaged, and the increase of dry-wet cycles does not significantly enhance the shear strength. Thus, when the red clay is not seriously polluted by cadmium, the dry-wet cycle based on natural precipitation evaporation can effectively enhance the shear strength of red clay.

Several factors such as water content, different dry-wet cycles, and different pollution concentrations are selected to study the shear strength of red clay. In practice, the shear strength is also affected by other factors, such as different confining pressures, and dry densities. And these factors also affect the internal structure of red clay. Therefore, the subsequent research can be focused on the influence of water content on the shear strength and internal structure of red clay under different dry densities. Besides, the variation characteristics of the shear strength of red clay should also be discussed under different confining pressures with pollution concentrations and dry-wet cycles.

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