Microstructure and Mechanical Properties of Expansive Clay under Drying–Wetting Cycle

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Abstract: Expansive clay is one of the most widely distributed soils in the world. Due to its rich content of strongly hydrophilic minerals—such as montmorillonite—expansive clay exhibits substantial swelling and shrinkage properties, and overconsolidation. The formation process of undisturbed expansive clay has a long and complicated geological history and innumerable drying–wetting cycles, resulting in the formation of special internal structures. In this study, the mud-to-natural-consolidation deposition process was simulated using a saturated mud-remolded sample preparation device, and then, mud-remolded soil under a certain consolidation pressure was prepared. Subsequently, the effects of the stress history and drying–wetting cycle on its mechanical properties and microstructure were examined through uniaxial consolidation compression experiments, $K_0$ consolidation experiments, and pressure plate experiments of undisturbed soil, mud-remolded soil, and a drying–wetting cycle sample. The results showed that the mud-remolded soil completely broke the natural structure of the undisturbed soil, with the structural characteristics of the remolded soil being restored to a certain extent after the drying–wetting cycle. This not only reduced the void ratio of the soil sample, but also changed its compressibility and water retention characteristics, revealing the role of atmospheric drying–wetting cycles in the natural overconsolidation state of expansive clay and providing a theoretical basis for understanding their overconsolidation characteristics.

Keywords: expansive clay; drying–wetting cycle; mechanical property; microstructure

1. Introduction

The instability of expansive clay slopes is a common problem globally. Highway and railroad projects built in expansive clay areas often collapse; this damage is often repeated and potentially harmful in the long term [1,2]. Expansive clay is a geological body with multiple fissures, and considerable expansion and shrinkage can occur during the natural geological-formation process. The clay composition of expansive clay is primarily that of montmorillonite—a strong hydrophilic mineral—and its mixed-layer clay mineral counterparts, which exhibit swelling and shrinkage, fissure, and overconsolidation properties. Such clays are extremely sensitive to external factors such as climate change and human activities, resulting in frequent disasters on expansive clay slopes [3]. The swelling and shrinkage, fissure, and overconsolidation properties of expansive clay are not independent but interact and promote one another. Moreover, these three properties tend to work together to render the engineering properties of expansive clay extremely poor, resulting in frequent disasters.

Expansive clays are widely distributed, with their existence having been found in more than 40 countries worldwide so far [4–7], spread over six continents. Furthermore, China is one of the countries with the widest distribution of expansive clays (rock) in the world. Consequently, several experimental and theoretical studies have been conducted...
on the stability of expansive clay slopes. Ng et al. [8] and Zhan et al. [9] conducted long-term rainfall infiltration monitoring on prototype slopes of expansive clays and performed detailed analyses of their slope deformation and failure modes. Greco et al. [10] studied the stability of expansive clay slopes under rainfall infiltration conditions and conducted a systematic analysis of their depth, the relationship between landslides and water content, and the infiltration line extension. To overcome the influence of sampling disturbances and specimen size limitations in laboratory tests, Li et al. [11,12] conducted field tests of expansive clay to determine its in situ mechanical properties, and analyzed its pore structure evolution characteristics and the connection between the pore structure and macroscopic mechanical properties. Phanikumar et al. [13] revealed the role of the particle size of expansive clays in swelling and shrinkage: clay lumps and clay powder had the same placement conditions, whereas clay powder had a higher potential for heave and swelling. This is because water has difficulty reaching the pockets of unsaturated clay, and clay powder has a higher compression index than clay lumps. Expansive clay is a typical unsaturated soil, and its basic properties—that is, its swelling, shrinkage, and fissure properties—can be greatly affected by water content [14–17]. Consequently, the repeated uneven swelling and shrinkage of expansive clays under the strong alternating action of drying and wetting can induce disasters, including slope erosion, collapse, and landslides. Many researchers have studied the stability of expansive clay slopes using centrifugal model tests [18,19]. Cai et al. [18] studied the fissure evolution law of canal slopes and deformation via two sets of expansive clay canal drying–wetting cycle centrifugal model tests; they examined the development of soil fissures and the law of canal water infiltration, and its influence on the deformation and stability of canal slopes under the action of such cycles. Using model tests and theoretical calculations on the stability of expansive clay slopes under the action of drying–wetting cycles, scholars worldwide have recognized that swelling and shrinkage, and fissure properties, as well as the action of drying–wetting cycles, are the main factors inducing the instability of expansive clay slopes [20–22].

A common overconsolidation formation mechanism is that the soil is subjected to greater loading than the overlying pressure during its geological history, with the pre-consolidation pressure (Pc) of the soil reflecting the influence of its geological history. For example, Nanyang expansive clays formed at an early age experienced compaction and consolidation in their geological history, and were later exposed to the surface owing to denudation of the overlying strata through crustal uplift. Consequently, these expansive clays are often overconsolidated [23], which can cause the unloading effect to be greater than that of normally consolidated clay, making it easier for the original closed fissures to open, loosening the soil structure, and reducing its strength. This characteristic can have a particular effect on the stability of expansive clay slope excavations [24].

Much research has been conducted on the influence of fissures and humidity on the properties of expansive clay and the stability of slope engineering. However, few studies have investigated the influence of drying–wetting cycles on overconsolidation during the natural formation of expansive clay. Most previous studies have been conducted on the drying–wetting cycles under unloaded conditions—where the soil tends to become loose—whereas in situ drying–wetting cycles often occur under a certain stress state. Fissures are a key factor in the instability of expansive clay slopes, with the clay’s expansion and shrinkage properties being the internal causes of fissures, and its overconsolidation property being a promoting factor. Moreover, overconsolidation results in a small natural void ratio, high dry density, and high initial structural strength in expansive clays.

The formation of undisturbed expansive clay has a long and complex geological history and innumerable drying–wetting cycles. However, whether the overconsolidation of expansive clay is caused by the pre-consolidation pressure (Pc) generated by the compaction effect during the natural formation of clay particles, or by the drying–wetting cycle effect, resulting in a low void ratio and high strength, remains unclear, as few comparative studies have been conducted. Consequently, this study simulated the sedimentation
process from mud to natural consolidation under a certain consolidation pressure by preparing mud-remolded soils. On this basis, the influence of stress history and drying–wetting cycles on the mechanical properties of expansive clay was examined. By comparing the mechanical properties and microstructure, the effects of stress history and drying–wetting cycles were analyzed, revealing the role of atmospheric drying–wetting cycles in the overconsolidation state of expansive clay and providing a theoretical basis for understanding their overconsolidation characteristics and considering the influence of overconsolidation on the long-term stability of slopes after excavation.

2. Materials and Methods

2.1. Test Material

The object of this study was the brown–yellow expansive clay found in the Nanyang area, which was taken from the side of the Nanyang Neixiang–Dengzhou Expressway at a depth of 3–4 m (Figure 1a). The clay contained ferromanganese nodules and ginger stones, and undisturbed soil samples were taken from the same layer using the pit method (Figure 1b).

The basic physical parameters of Nanyang expansive clay are listed in Table 1, according to the Standard for Soil Test Method (JTG 3430-2020) [25]. The liquid and plasticity limits for the soil were 55.4% and 26.2%, respectively. The free expansion rate $\delta = 61\%$. X-ray diffraction analysis was used to test its composition; the mineral composition of Nanyang expansive clay is listed in Table 2. The plastic index, clay content, and free expansion rate of the soil all satisfied the ranges set out in the evaluation standards for expansion potential, so the soil was categorized as a medium expansive clay [25,26]. Uniaxial consolidation compression tests were conducted on the undisturbed expansive clay.
Based on the Casagrande method [27], the $P_c$ of the expansive clay was determined to be approximately 200 kPa, with the overlying pressure of the undisturbed expansive clay being approximately 80 kPa. It was evident that the $P_c$ was greater than the overlying pressure, indicating that the undisturbed soil had certain overconsolidation properties.

Table 1. Basic physical parameters of Nanyang expansive clay.

<table>
<thead>
<tr>
<th>Density (g·cm$^{-3}$)</th>
<th>Specific Gravity</th>
<th>Free Expansion Rate (%)</th>
<th>Liquid Limit (%)</th>
<th>Plastic Limit (%)</th>
<th>Plastic Index (%)</th>
<th>≥0.005 mm</th>
<th>&lt;0.005 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.98</td>
<td>2.81</td>
<td>61</td>
<td>55.4</td>
<td>26.2</td>
<td>29.2</td>
<td>40.6</td>
<td>59.4</td>
</tr>
</tbody>
</table>

Table 2. Mineral composition of Nanyang expansive clay.

<table>
<thead>
<tr>
<th>Mineral Content (%)</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Montmorillonite</th>
<th>Chlorite</th>
<th>Illite</th>
<th>Kaolinite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
<td>8</td>
<td>15.6</td>
<td>18.2</td>
<td>7.8</td>
<td>10.4</td>
</tr>
</tbody>
</table>

2.2. Preparation of Remolded Soil

Because the undisturbed expansive clay has had a long and complex geological history and drying–wetting cycle, it has formed a special internal structure. To study the influence of this on its physical and mechanical properties, remolded soil samples were prepared, and the differences in basic characteristics between the remolded and undisturbed soil were compared and analyzed. Generally, compaction or static pressure methods are used to prepare remolded soil, but these two methods can neither control the consolidation pressure during sample preparation nor prepare saturated remolded soils with consistent density and moisture content above and below the sample. In this study, remolded soil was prepared using the mud consolidation method, simulating the clay particles completing the natural consolidation sedimentation process from mud to soil under a certain consolidation pressure.

To prepare saturated remolding samples with different $P_c$ values, a saturated mud-remolded sample preparation device (Figure 2) was designed based on CBR (California bearing ratio) test equipment—which could control the sample preparation pressure—as well as a sample preparation cylinder with a height of 170 mm and an inner diameter of 152 mm, a square top cover, and a bottom plate with a side length of 210 mm. The top cover and the bottom plate had holes at the four corners, and the top and bottom plates were fixed to the sample preparation cylinder with screw rods. After the mud was poured into the sample preparation cylinder, a permeable plate with a guide rod in the middle was placed on the soil sample, on top of which an air bag was placed. The guide rod was passed through the top plate and the consolidation deformation of the sample was measured using a dial indicator at the top of the guide rod. Air pressure was applied to the airbags to consolidate the soil. The device was immersed in a water tank to ensure that the soil samples remained saturated. The air compressor was connected to a precision pressure-regulating valve and a pressure gauge, and used to adjust the pressure in the airbag. To prepare the samples in batches, the sample preparation device was connected in parallel with a t-branch pipe so that the entire device could simultaneously prepare multiple sets of samples with different controlled consolidation pressures. Air pressure was applied to the airbags to consolidate the soil in the device. To ensure the accuracy of actual pressure applied to consolidate the soil, calibration of the actual pressure exerted by the air bag was conducted on a platform balance high-pressure consolidation instrument, the air pressure in the air bag was adjusted, and the actual pressure on the consolidation instrument was balanced by weights. The calibration curve of the air pressure and the actual pressure could then be obtained.

The materials of the mud were the same as those of the undisturbed expansive clay listed in Table 2. When preparing the mud, the expansive clay was dried and screened.
using a 2 mm sieve, and the soil and water were mixed until the moisture content reached the liquid limit. The soil particles were thoroughly mixed with water via stirring, and soil structure was completely destroyed. Subsequently, a mud remolding sample preparation device was used to prepare samples with consolidation pressures of 200, 400, and 600 kPa, respectively. The remolded samples were uniform, without fissures, and distinct from natural expansive clay, as shown in Figure 2. The water contents of three layers from the top to the bottom of the sample with a consolidation pressure of 200 kPa were tested. Horizontal coordinates 1, 2, and 3 represent the upper, middle, and lower layers of the sample, respectively. It can be seen from the figure that the measured moisture contents of the remolded samples were uniform (Figure 3).

![Figure 2](image_url)

**Figure 2.** Saturated mud-remolded sample preparation device and sample. (a) Sample preparation device. (b) Structure of sample preparation cylinder (diameter 152 mm). (c) Natural expansive clay (diameter 61.8 mm). (d) Mud-remolded sample (diameter 61.8 mm).
3. Results and Discussion

3.1. Compression Curves of Mud Paste

Mud paste with a moisture content of approximately 57% was prepared on the consolidation instrument using a Φ61.8 × 20 mm cutting-ring sample, after which a uniaxial consolidation compression experiment [25] was conducted by applying a load step-by-step as follows: 12.5 → 25 → 50 → 100 → 200 → 300 → 400 → 600 → 800 → 1200 kPa, and an appropriate compression curve was obtained. Based on the Casagrande method, the $P_c$ was determined to be approximately 10 kPa, which is consistent with the state of mud paste without structure or stress history. Comparing the compression curves of the mud paste and undisturbed soil (Figure 4), it is evident that although the $P_c$ of the undisturbed soil is approximately 200 kPa, the initial void ratio is very low. The expansive clay in the Nan-yang area is mainly lacustrine sedimentary and alluvial expansive clay. The void ratio of the mud-remolded expansive clay after consolidation under a consolidation pressure of 200 kPa is much higher than that of the undisturbed soil. When the pressure gradually increases, the compression curves of the mud-remolded and undisturbed soils gradually converge. Comparing the compression curves of the mud-remolded soil and undisturbed soil, it is evident that to compress the void ratio of the soil to 0.71, the axial pressure of the undisturbed soil is 200 kPa, whereas that of the mud-remolded soil is as high as 800 kPa.

Consequently, it can be inferred that the initial high density and low void ratio of the undisturbed soil are not caused by large loads alone but are also influenced by external environmental factors such as temperature and climate, which have a great influence on the formation of its special structure.
3.2. Drying–Wetting Cycle Test of Mud-Remolded Soil

Mud with a moisture content higher than the liquid limit was prepared and consolidated at 200 kPa using a sample preparation device. The first drying–wetting cycle was conducted after unloading and expansion in a constant-temperature and -humidity chamber. The soil sample was dehydrated to a moisture content of approximately 10%, after which the moisture absorption of the soil sample was made uniform through continuous spraying with water, before being soaked in water for a day and night to complete the drying–wetting cycle. As shown in Figure 5, after the drying–wetting cycle, a large quantity of soil on the side wall of the sample disintegrates, filling the gap between the soil sample and the sample cylinder, with the overall soil sample bulging upward.

Figure 4. Compression curves of mud paste and undisturbed soil.

Figure 5. Sample after the drying–wetting cycle (diameter: 152 mm).
An in situ drying–wetting cycle is often performed under a certain stress state. Consequently, after the first drying–wetting cycle (the red arrow), the sample was consolidated under a pressure of 200 kPa (the blue arrow), and the second drying–wetting cycle was performed after unloading and expansion, with the above process being repeated. After five drying–wetting cycles, the soil samples were produced as drying–wetting cycle samples. The changing heights of the samples during the preparation process are shown in Figure 6.

![Figure 6. Changing height of the samples during the preparation process.](image)

It is evident that the consolidation settlement deformation of soil under a consolidation pressure of 200 kPa after the drying–wetting cycle decreases with an increase in the number of cycles. The expansion of the soil after the drying–wetting cycle also decreases with increasing cycles. After three drying–wetting cycles, the final height of the sample after consolidation gradually stabilizes.

3.3. Influence of Drying–Wetting Cycles on Compression Characteristics

Uniaxial consolidation compression experiments were conducted on mud-remolded soils with consolidation pressures of 200, 400, and 600 kPa, a drying–wetting cycle sample, and undisturbed soil to analyze the influence of drying–wetting cycles on the soils’ compression characteristics (Figure 7). Additionally, a secondary consolidation sample was prepared after the primary consolidation was completed under a consolidation pressure of 200 kPa (the secondary consolidation time was 14 d) to compare and study the differences in the effects of secondary consolidation and drying–wetting cycles on the compression characteristics of expansive clay.
Compression tests of different soils can be used to determine the differences between their compression characteristics using $\Phi 61.8 \times 20$ mm cutting-ring samples. The results show that for the mud-remolded soils consolidated under consolidation pressures of 200, 400, and 600 kPa, the $P_c$ is approximately 200, 400, and 600 kPa, respectively, determined based on the Casagrande method, which is consistent with the consolidation pressure in the actual sample preparation process.

The initial void ratio of the secondary consolidation sample is smaller than that of the remolded soil without secondary consolidation under the same consolidation pressure of 200 kPa, but the straight-line segments in the latter part of the compression curve are still parallel to one another, indicating that secondary consolidation can continue to compact the soil after the completion of the primary consolidation process. The creep effect of the soil skeleton further reduces the void ratio of the soil; however, when the consolidation pressure reaches its $P_c$, the compression characteristics of the secondary consolidation soil—namely, the compression index—are similar to those of the normal consolidation mud-remolded soils.

Comparing the compression curves of the undisturbed soil and mud-remolded soil with different consolidation pressures, it is evident that although the $P_c$ of the undisturbed soil is smaller than that of the mud-remolded soil, the initial void ratio is considerably smaller than that of the mud-remolded soil with a 600 kPa consolidation pressure. Moreover, the compression modulus of the undisturbed soil is much larger than that of the mud-remolded soil, which is related to the long geological history and climate changes experienced during the formation of the undisturbed soil. Comparing the compression curves of the drying–wetting cycle sample and the mud-remolded soil with different consolidation pressures, it is evident that the drying–wetting cycle sample can achieve a lower void ratio under the same consolidation pressure of 200 kPa, with its initial void ratio being even lower than that of the mud-remolded soil with 600 kPa consolidation pressure, gradually approaching the initial void ratio of the undisturbed soil. The slope of the straight line segments in the latter part of the compression curve of the drying–wetting cycle sample is clearly smaller than that of the mud-remolded soil without a drying–wetting cycle, but closer to the compression characteristics of the undisturbed soil.

The undisturbed soil is affected by various factors in its long-term formation history, finally forming its unique structural characteristics. The mud-remolded soil completely breaks the natural structure of the undisturbed soil, whereas the drying–wetting cycle sample restores its structure to a certain extent, not only reducing the void ratio of the sample but also changing its compressibility. It can be inferred that the drying–wetting
cycle caused by climate change is the main reason for the overconsolidation of undisturbed expansive clay. The low void ratio and high strength of undisturbed expansive clay are caused primarily by the fabric changes in clay particles after drying–wetting cycles, and not by the compaction effect owing to the large stress history or secondary consolidation effect owing to the earlier formation period.

3.4. Effect of Drying–Wetting Cycles on the Lateral Stress of Expansive Clay

It is well known that the coefficient of the lateral earth pressure of overconsolidated soil ($K_0$) is larger than that of normal consolidated soil. The $K_0$ also increases with increasing overconsolidation; consequently, high lateral earth pressure makes overconsolidated expansive clay more prone to instantaneous damage than normal consolidated soil after lateral unloading during slope excavation.

To understand the effect of the drying–wetting cycle on the lateral stress of expansive clay, a $K_0$ consolidation instrument [25] was used to test the lateral stress of the drying–wetting cycle sample, after which we compared it with the mud-remolded soil under 200 kPa consolidation pressure and the undisturbed soil using $\Phi 61.8 \times 40$ mm cutting-ring samples. The axial stress–lateral stress relationship curves of the different soils are shown in Figure 8.

![Figure 8. Comparison of the axial stress–lateral stress relationship curves of different soils.](image)

Based on the axial stress–lateral stress relationship curve, in the initial stage of loading, the $K_0$ (the ratio of lateral stress to axial stress) of the three soils is maintained at a low level. With an increase in axial load, $K_0$ also increases and gradually stabilizes. Under the same axial stress, the $K_0$ value of the mud-remolded soil is the largest, followed by that of the drying–wetting cycle sample, with that of the undisturbed soil being the lowest. Under axial unloading conditions, the soils are in an overconsolidated state. Under the same axial stress, the lateral stress during unloading is considerably higher than that during loading. With an increase in unloading—that is, the overconsolidation ratio—$K_0$ gradually increases. The $K_0$ values of the three soils during unloading maintain their size relationship during loading. Moreover, when the axial stress is unloaded to a lower level, the $K_0$ values of the three soils are very close.

The in situ monitoring of over-consolidated expansive clay slopes conducted by Zhan et al. [9] showed that unsaturated expansive clays tended to expand after absorbing water; however, under lateral constraints, this expansion potential was expressed in the form of an expansive force, and the horizontal lateral stress increased considerably, but decreased with the local softening of the soil. It is evident that the lateral stress of the expansive clay
increases during the drying–wetting cycle, but the $K_0$ of the soil decreases after the drying–wetting cycle as the fabric of the remolded soil changes owing to the drying–wetting cycle itself. Subsequently, the void ratio decreases and the density increases. Moreover, the drying–wetting cycles without loading result in the soil loosening as the number of drying–wetting cycles increases. However, for the soil undergoing drying–wetting cycles and re-consolidation, combined with the results of the uniaxial and $K_0$ consolidation experiments, the soil is compacted and its $K_0$ decreases.

The change in the remolded soil fabric caused by the drying–wetting cycle does not increase the lateral stress of the soil, which decreases after the drying–wetting cycle owing to an increase in the soil density. Moreover, the $K_0$ of the undisturbed soil is always the smallest during the loading and unloading stages.

3.5. Influence of Drying–Wetting Cycles on Water Retention Characteristics of Expansive Clay

To study the influence of different overconsolidation stress histories on the water retention characteristics of expansive clay, a pressure plate instrument produced by the Soil Moisture Company was used to test the soil–water characteristic curves (SWCCs) of expansive clay samples with different stress histories. Six groups of $\Phi 61.8 \times 20$ mm cutting-ring samples fully absorbed water, including mud-remolded soil with preconsolidation pressures of 200, 400, and 600 kPa, remolded soil with five drying–wetting cycles, remolded soil with the same void ratio as the undisturbed soil, and undisturbed soil. After the expansion had stabilized, the soil samples were placed into a pressure plate instrument for the SWCC test by applying pressure in a stepwise manner. After the suction balance of 600 kPa was reached, the soil samples were removed and placed in the oven, dried at 106 °C to a constant weight, and the dry soil mass was weighed. After measuring the gravity water content of the remolded soil and undisturbed soil under different suction levels with different historical stresses, the SWCC represented by the gravity water content could be plotted in a semi-logarithmic coordinate system, as shown in Figure 9.

![Figure 9. Comparison of the soil–water characteristic curves (SWCCs) of different soils.](image-url)

Owing to the difference in stress histories, the initial water content of the remolded soil also differs. The larger the stress history, the smaller the initial water content. Consequently, the entire SWCC of the sample with a high-stress history is below that of the sample with a low-stress history, with the effects of different stress histories on the water retention characteristics of the remolded soil being reflected mainly in their air-entry values. The air-entry value of the remolded soil increases considerably with increasing stress.
history, with the decrease in the initial void ratio making it more difficult for air to enter the soil. Additionally, with an increase in suction, the influence of stress history gradually weakens, the gravity moisture content of samples with different stress histories gradually approach one another, and the SWCCs converge. Comparing the slope of the SWCC of the remolded soil after obtaining the air-entry value (water storage coefficient), it is evident that the water storage coefficient of the remolded soil with a $P_c$ of 600 kPa is smaller than that of the remolded soil with $P_c$ values of 200 and 400 kPa, indicating that when the matric suction exceeds the air-entry value, the dehumidification rate of the samples subjected to a low-stress history is much faster than that of the samples subjected to a high-stress history, even though the samples subjected to a low-stress history have a high water retention capacity under a specific matric suction.

For undisturbed soil, the air-entry value and water storage coefficient are low. The consolidation pressure of the remolded soil can be calculated using the compression and expansion coefficients to eliminate the influence of the void ratio, which is similar to that of the undisturbed soil, after which the influence of the soil structure on the water retention characteristics of the expansive clay can be analyzed. Comparing the SWCCs of the undisturbed soil and the remolded soil with similar void ratios (Figure 8), it is evident that the SWCC of the remolded soil with a similar void ratio has an obvious turning point, which can be regarded as comprising two straight-line segments. The former section is essentially horizontal, suggesting that it could be difficult to dehumidify the soil sample. The latter section is an oblique line corresponding to the internal connection state of the unsaturated soil.

The air-entry value of the undisturbed soil is small, and the moisture content decreases rapidly with increasing suction. The soil particles of the undisturbed soil constantly adjust their positions during the long-term drying–wetting cycles, such that the pore structure has a specific direction, and a specific “breathing” channel is formed. The existence of microcracks in the soil also provides a good channel for the migration of water and air. During the dehumidification of the undisturbed soil, air first enters the large crack channels and removes the pore water in them. The water in the cracked channels gradually decreases with increasing suction, whereas the water in the non-cracked channels is removed slowly, exhibiting a high water retention capacity. Consequently, the undisturbed sample exhibits characteristics of low air entry and high water retention capacity. For the remolded soil, the pores in the soil are evenly distributed with poor internal connectivity and a lack of good migration channels, making it difficult for air to enter the soil, presenting a high air-entry value on the SWCC, an indication that the influence of the soil structure on the SWCC is substantial.

The SWCC of the drying–wetting cycle sample can be compared with that of the remolded soil with a $P_c$ of 200 kPa and that of the undisturbed soil. It is evident that the initial moisture content and air-entry value of the drying–wetting cycle sample is smaller than that of the remolded soil, indicating that the changes in soil structure after the drying–wetting cycles improve the connectivity of pores in the samples, facilitating the entry of air. Consequently, the drying–wetting cycle samples also exhibit the characteristics of low air entry and high water retention capacity, which means that the water retention characteristics of the drying–wetting cycle samples are more similar to those of the undisturbed soil than those of the remolded soil.

3.6. Microstructure Analysis

The influence of the drying–wetting cycles on the compressive characteristics and lateral stress of the expansive clay mentioned above is the macroscopic expression of the effects of the drying–wetting cycle on the soil properties. A Quanta scanning electron microscope (SEM) and Poremaster high-pressure pore structure instrument were used to analyze the microstructure of the mud-remolded soil with a $P_c$ of 200 kPa, the drying–wetting cycle sample, and the undisturbed soil, and the microscopic mechanism of the effect of the drying–wetting cycle on the soil was analyzed. The specimen for the SEM
tests was a cube of 10 mm × 10 mm × 10 mm. Before SEM was performed, a fresh section of the sample was sprayed with gold to increase its electrical conductivity. Images with a representative field-of-view with magnifications of 100, 800 and 2000× were selected for each sample, as shown in Figures 10, 11, and 12, respectively.

Figure 10. Microstructure of different soils (magnifications of 100×). (a) Mud-remolded soil. (b) Drying–wetting cycle sample. (c) Undisturbed soil.

Figure 11. Microstructure of different soils (magnifications of 800×). (a) Mud-remolded soil. (b) Drying–wetting cycle sample. (c) Undisturbed soil.

Figure 12. Microstructure of different soils (magnifications of 2000×). (a) Mud-remolded soil. (b) Drying–wetting cycle sample. (c) Undisturbed soil.
The stacking structure of particles in the mud-remolded soil can be clearly identified in Figures 10a, 11a and 12a because the mud-remolded sample is slowly consolidated by mud under a certain consolidation pressure; its particles have good orientation and tend to be arranged horizontally, and there are almost no penetrating microfissures. However, the drying–wetting cycle sample shown in Figures 10b, 11b and 12b is segmented by numerous fissures with a high degree of penetration. In Figures 10c, 11c and 12c, the undisturbed soil has a small quantity of curved and crimped flaky particles with skirted edges, with the microstructure unit containing more agglomeration of particles. There are a large number of microcracks in the undisturbed soil, which are convenient for the infiltration of precipitation and can lead to the gradual failure of soil strength attenuation.

Drying shrinkage causes the agglomeration and rearrangement of clay particles, which changes the microstructure of the soil. The irreversible van der Waals force between clay particles causes the clay particles to agglomerate into large aggregates, resulting in a decrease in the content of dispersed fine particles in the soil, a decrease in the specific surface area, and deterioration of the orientation of the particles. The effect of dry shrinkage is often irreversible, and is shown as capillary hysteresis in the SWCC. Moreover, the effect of wet expansion does not restore the soil to its state before dry shrinkage but changes the structure and compressibility of the remolded soil. Consequently, the drying–wetting cycled sample achieves a lower void ratio under the same consolidation pressure, which is consistent with the effect of the drying–wetting cycles on the compression characteristics.

The pore size distribution characteristics—that is, the curve of mercury intrusion porosimetry—of the mud-remolded soil, the drying–wetting cycle sample, and the undisturbed soil are shown in Figure 13. It is evident that the total pore volume of the remolded soil is the largest (0.269 mL·g⁻¹), the total pore volume of the undisturbed soil is the smallest (0.186 mL·g⁻¹), and the total pore volume of the drying–wetting cycle sample occupies the middle region (0.215 mL·g⁻¹), which is consistent with the initial void ratio obtained from the consolidation compression curve. The mercury intrusion porosimetry curve moves upward with an increase in void ratio. The pore size distribution curve of the soil can be reorganized into a curve of \( \lg \left( \frac{V(r)}{V} \times 100 \right) - \lg(r) \) according to fractal theory, where \( V \) denotes the total pore volume of the test sample, and \( \left( \frac{V(r)}{V} \times 100 \right) \) denotes the percentage of the pore volume with a pore radius less than \( r \) in the total pore volume. The curve in Figure 14 shows that the curve of \( \lg \left( \frac{V(r)}{V} \times 100 \right) - \lg(r) \) can be divided into three straight-line segments based on fractal theory, with the pores within each line having self-similar characteristics. In other words, the pore sizes within the range of this segment have the same morphological characteristics and properties.
Consequently, the pore structure of expansive clay can be divided into three types—that is, $r$, which corresponds to the inflection point as the critical value; $r_1$, which denotes the maximum critical equivalent radius of the pores between flaky particles in particle units; and $r_2$, which denotes the maximum equivalent radius of the pores when the particle units are in close contact. Pores with pore sizes larger than $r_2$ are those with aerial characteristics between particle aggregates. Subsequently, the fractal dimension value ($D$) of the straight-line segments can be obtained from the slopes of the three straight-line segments ($b_1$, $b_2$, and $b_3$) in Figure 14 as $D = 3 - b$. The fractal dimension can reasonably describe the heterogeneity of microscopic pore distribution: the larger the difference in the fractal dimension $D$, the stronger the heterogeneity. $b$ reveals the degree of pore development. The larger $b$ is, the more pores develop.

The distribution of the three types of pore in the remolded soil is relatively uniform, with the $D_2$ value of the remolded soil being close to that of $D_3$. Meanwhile, the $D_2$ value of the drying–wetting cycle sample increases gradually ($b_2$ decreases), indicating that the
drying–wetting cycle increases the content of aerial pores between particle aggregates and decreases the content of pores between particle units. Moreover, the number of micropores in the particle unit does not change much. For the undisturbed soil, it is evident that the content of pores between particle units in the middle segment is very small \(b_2\) is close to 0, the value of \(D_2\) is the largest, and the difference between the fractal dimension of \(D_2\) and \(D_3\) is large, indicating that the pores between the particle units transition to the aerial pores between particle aggregates. The extent of aerial pores in the undisturbed soil is relatively high, with the number of large pores being relatively large. The large aerial pores between the particle aggregates play a decisive role in soil permeability.

In general, the microstructure of the mud-remolded soil undergoing drying–wetting cycles changes drastically, making the microstructure of the drying–wetting cycle sample more similar to that of the undisturbed soil. The microcosmic results are verified by the test results of the mechanical properties, indicating that the drying–wetting cycle plays an important role in the natural formation of undisturbed soil.

4. Conclusions

(1) Undisturbed expansive clay has a long and complex geological history and drying–wetting cycle, and has formed a special internal structure. In this study, remolded soil was prepared via the mud consolidation method using a saturated mud-remolded sample preparation device, simulating clay particles completing the natural consolidation sedimentation process from mud to soil under a certain consolidation pressure.

(2) The mud-remolded soil completely breaks the natural structure of the undisturbed soil, whereas the drying–wetting cycle sample restores its structure to a certain extent, not only reducing the void ratio of the sample but also changing its compressibility. The drying–wetting cycle caused by climate change is the main reason for the overconsolidation of undisturbed expansive clay, leading to the low void ratio and high strength of undisturbed expansive clay.

(3) The initial moisture content and air-entry values of the drying–wetting cycle sample are smaller than those of the remolded soil, indicating that the changes in soil structure after the drying–wetting cycles improve the connectivity of pores in the samples, facilitating the entry of air. Consequently, the drying–wetting cycle samples also exhibit the characteristics of low air entry and high water retention capacity, which means that the water retention characteristics of the drying–wetting cycle samples are more similar to those of the undisturbed soil than those of the remolded soil.

(4) The lateral stress of the expansive clay increases during the drying–wetting cycle, but the \(K_0\) of the soil decreases after the drying–wetting cycle. The change in the remolded soil fabric caused by the drying–wetting cycle does not increase the lateral stress of the soil, which decreases after the drying–wetting cycle owing to an increase in the soil density. Moreover, the \(K_0\) of the undisturbed soil is always the smallest during the loading and unloading stages.

(5) The microstructure of the mud-remolded soil undergoing drying–wetting cycles changes drastically. The drying–wetting cycle increases the content of aerial pores between particle aggregates and decreases the content of pores between particle units. The microstructure of the drying–wetting cycle sample is more similar to that of the undisturbed soil; the microcosmic results are verified by the test results of the mechanical properties, indicating that the drying–wetting cycle plays an important role in the natural formation of undisturbed soil.

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