

Article

Effect of Moisture Content and Wet–Dry Cycles on the Strength Properties of Unsaturated Clayey Sand

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Abstract: Based on the actual situation of the project on the Weihai–Yantai Expressway section of Rongwu Expressway, the effects of water content change and the dry–wet cycle on the mechanical behavior of unsaturated clayey sandy soil were analyzed in this study. In this study, ventilated undrained triaxial shear tests were carried out on unsaturated clayey sandy soils with different water contents (6%, 8%, 10%, 12%, 14% and 16%). Concurrently, the soil samples were subjected to three distinct wet and dry cycle pathways (2~22%, 2~12%, and 12~22%) to gain an understanding of how the mechanical features of the soil changed under the different conditions. The test findings demonstrate that when the water content increases, the unsaturated clayey sandy soil’s cohesiveness and shear strength diminish. The strength of shear decline exhibits a pattern of first being quick, followed by sluggish. The strength of shear and cohesiveness of clayey sandy soil declined under the influence of the dry and wet cycles, with the first cycle primarily affecting variations in cohesiveness and strength of shear. Furthermore, the strength of shear and cohesiveness of clayey sandy soil diminish more with increasing wet and dry cycle amplitude and upper water content limits. Lastly, the drying shrinkage and hygroscopic expansion of clay particles in clayey sandy soils during wet and dry cycles are not significant, resulting in less structural damage and deterioration of the mechanical properties of the soils. The study’s findings have a significant impact on the durability of roadbeds made of unsaturated clayey sandy soil in both wet and dry situations.

Keywords: clayey sand; wet–dry cycle; shear strength; moisture content



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1. Introduction

Clayey sand is widely distributed in regions such as Southeast China, South China, and the Middle East. It is a common roadbed filler [1]. Since the clayey sand contains a certain amount of clay particles, the soil possesses some properties of both sand and clay [2]. In actuality, clayey sandy soil subsoils found beneath roads are frequently unsaturated soils. As a result of atmospheric rainfall and fluctuations in the water table, certain clayey sandy soil subsoils undergo extended periods of wet–dry cycling. Soils tend to deteriorate when subjected to wet–dry cycles or changes in moisture content. This has a direct impact on the roadbed pavement structure’s strength, stiffness, and stability, which lowers the road’s quality and lifespan [3]. The engineering properties of significant variations existed between the sand soil and clay and clayey sand [4]. However, according to the current engineering design standards, clayey sand is often regarded as sand for design, and some characteristics of the clay particles in the clayey sand are ignored, which will have a certain impact on the rationality, safety, and economy of road design [3].

Scholars have conducted numerous investigations to comprehend the impact of wet and dry cycles and moisture content on the engineering qualities of soils. And as the

amount of moisture content changes, the mechanical properties such as shear strength, constitutive relation, cohesiveness, and the soil's frictional angle will alter [5–9]. For clayey sandy soils, Naser A et al. [4] investigated the impact of clay content as well as water percentage on soil cohesion through experiments and found that the cohesion of clayey sand increases and then decreases with the increase of water content. Tang et al. [10] carried out plate loading tests on sand–kaolinite mixtures with different water tables and found that the bearing capacity of clay containing sand increased with decreasing water content. Soils with a high content of clay-grained minerals are usually degraded to varying degrees under the action of wet and dry cycles [11–14]. In recent years, academics have conducted a number of studies on how wet–dry processes and the amount of moisture affect the soil's engineering qualities. Factors affected during the wet–dry cycle include soil shear strength, expansion and contraction deformation, microstructure, and the changing pattern of soil–water characteristic curves [15–17]. Studies such as those carried out by Hu et al. [18] and Ye et al. [19] have shown that different wet and dry cycling path parameters, such as cycling amplitude and upper limit moisture content, affect the degree of deterioration. The above research results have clarified the impact of wet and dry cycles and water content on the mechanical characteristics of soils, which are of great theoretical and engineering significance for the deformation and stability of roadbeds. However, most of the research objects are clay, sandy soil, or a mixture of clay and sand as clayey sand samples, and there are fewer studies on natural clayey sand. Meanwhile, the behaviors and properties of clayey sand under the action of different paths of wet and dry cycling are not clear, so the study of this topic is of great significance to accurately analyze the stability of the road subgrade under the shift in the water content and the action of wet and dry cycles.

Remodeled clayey sand is used as the object of study, wet and dry cycles and tests for triaxial shear were conducted to investigate the stress–strain curves, shear strength, cohesion, and the internal friction angle of the clayey sandy soil under the action of different water content and the different paths of the wet and dry cycles, so as to give the engineering application a reference for unsaturated clayey sandy soil.

2. Material and Methodology

2.1. Examine the Soil

The roadbed filler of the Weihai–Yantai segment of the Rongwu Expressway provided the soil specimens used in this investigation, which possess a particular density of 2.64 g/cm^3 , an ideal level of moisture of 12.5%, and a maximum dry weight of 1.79 g/cm^3 . Its distribution of particle sizes is displayed in Table 1. From the perspective of particle composition, the content of clay particles in the soil samples used was about 14.46%, so it was classified as clayey sand [20], Figure 1 displays example photos of the dried and sieved soil samples and the untreated soil specimens.



Figure 1. Untreated soil specimens and the expansion site of the Rongwu Expressway's Weihai–Yantai section.

Table 1. Particle grading of clayey sand.

>2 mm	1 mm~2 mm	0.5 mm~1 mm	0.25 mm~0.5 mm	0.075 mm~0.25 mm	<0.075 mm
13.41	12.31	18.90	21.98	18.94	14.46

2.2. Test Program and Methodology

The following test protocol was used to determine how different wet–dry cycling pathways and the amount of moisture affected the strength properties of clayey sand:

1. Preparation of a sample

According to past tests, clay-containing sandy soil has a strong cohesive force in its unsaturated state, and after testing, the clay-containing sandy soil in this test has a cohesive force of 42.8 kPa at 12% water content, which can be used to prepare the disturbed soil specimen by the compaction method. According to the Highway Geotechnical Test Regulations (GB/T 50123-2019) [21], its specific process is as follows: (1) The clayey sandy soil should be air-dried, crushed, and sieved. Soil samples should be prepared at 12.5% amount of moisture. After a day of sealed resting, the moisture content should be measured, and any errors in moisture content should be less than 0.5%. (2) The soil was compacted in 5 layers in the sample-making mold using a static pressure device, and the dry density was controlled to be 1.71 g/cm³ (95% compaction), taking into account the compaction requirement of the highway subgrade. The soil samples measured 39.1 mm in diameter and 80 mm in height. (3) The soil specimens were removed from the sample-making mold and carefully placed on the three-flap mold to secure the two ends. The samples' initial dry density and pore space ratio were then calculated, and the height as well as the mass were measured. To ensure that we could examine the impact of moisture percentage on unsaturated clayey sandy soils, twenty-four specimens were created, and forty-five specimens underwent wet and dry cycle testing.

2. Test how the moisture amount affects the strength properties of clayey sand

Based on the results of the field tests, the moisture content of the subgrade at different positions was mostly between 6% and 14%. Therefore, six groups of tests with different moisture content were set up, which were 6%, 8%, 10%, 12%, 14%, and 16%, respectively. The initial amount of moisture and the initial specimen's drying density were 12.5% and 1.71 g/cm³, respectively. The soil samples were sealed for 24 h after slowly air-drying or adding distilled water to the permeable stone to reach the target moisture content, followed by strength testing [5].

3. Experiment on different wet and dry cycle paths, and how they affect the strength characteristics of clayey sand

To look into how wet–dry paths for cycling affect the clayey sand's strength properties, three groups of paths were set up for wet–dry cycle tests with the following design scheme: the wet–dry cycle amplitudes of paths 1 and 2 were different, with the same lower limit for the amount of moisture; the wet–dry cycle amplitudes of paths 1 and 3 were different, with the same upper limit for the amount of moisture; paths 2 and 3 have the same amplitude of wet and dry cycles and different upper and lower moisture content. Through comparing distinct routes for the wet–dry cycle, the influence of the magnitude of the wet–dry cycling and the upper as well as lower limits of moisture on wet–dry cycling could be analyzed. Generally, the number of cycles of wet and dry clay is mostly within the scope of 3~12 times [13–19] so in this test, the most wet–dry cycles possible was set at seven. The strength test was carried out after the 0th, 1st, 3rd, 5th, and 7th wet–dry cycles, respectively. As stated by the design scheme, the cycle of wet and dry test design appears in Table 2, where the 2% lower limit for the amount of moisture is the residual amount of moisture of the sandy soil dried at low temperature, and the 22% upper limit for the amount of moisture is the amount of saturating moisture of the clayey sand.

Table 2. Wet–dry cycles test design.

Path	Initial Moisture Content/%	Lower Limit Moisture Content/%	Upper Limit Moisture Content/%	Amplitude%	Number of Cycles/Times
1	12.5	2	22	20	0, 1, 3, 5, 7
2	12.5	2	12	10	0, 1, 3, 5, 7
3	12.5	12	22	10	0, 1, 3, 5, 7

There are 45 specimens in total in the wet and dry cycle test, divided into three wet and dry cycle paths, each with 15 specimens. Three specimens per group were exposed to 0, 1, 3, 5, and 7 cycles of wet and dry cycling over the corresponding pathways. The saturated humidification of the specimen adopted the immersion method. The specimen was saturated by immersing it in distilled water for 1 day. The unsaturated humidification of the specimen was carried out by adding distilled water to the permeable stone through the test tube. The soil sample's increased amount of moisture was less than 2% each time, and the soil sample was left to stand for 2 h after each humidification process. Once the soil sample's amount of moisture reached the desired level, it was sealed so that the moisture could migrate completely and disperse evenly for one day. During the procedure of drying, the oven temperature was adjusted to 40 °C, and the weight of the specimen was measured every hour until the specimen reached the predetermined moisture content.

4. Triaxial shear test

To investigate the qualities of the strength of unsaturated clayey sandy soils, unconsolidated ventilated undrained shear tests (zero air pressure throughout the test, no measurement of pore water pressure) were conducted on remolded clayey sandy soils with a constant controlled net perimeter pressure. The soil specimens' confining pressure (σ_3) for the moisture content test was 50, 100, 200, and 300 kPa, respectively. The perimeter pressures of the specimens after the wet–dry cycle tests were taken as 50, 100, and 200 kPa, and 8% was selected as the final moisture content which was based on the information from the site investigation. The specimen's level of moisture was gauged again prior to the test to ensure that the error of the amount of moisture for the sample was less than 0.3% [13]. The triaxial test was conducted in compliance with the Standard for Unsaturated Soil Testing Method (T/CECS 1337-2023) [22], accounting for the roadbed's actual working soil conditions. The test is stopped when the specimen is entirely destroyed or the axial strain reaches 15%.

3. The Results

3.1. Impact of Moisture Content on Influencing Characteristics of Clayey Sand

To investigate the impact of moisture content on the properties of the strength of unsaturated clayey sand, the stress–strain curves of unsaturated clayey sand with different moisture content were obtained by triaxial test in this paper. As shown in Figure 2, the strength of shear of clayey sand is highly dependent on the amount of moisture present, which decreases significantly as the moisture level rises. Under 50 kPa and 300 kPa confining pressure, the strength of 16% moisture content specimens decreased by 63% and 37.3%, respectively, compared with 6% moisture content. This was mainly because of the rise in the amount of moisture, and more free water on the particle surface which had a lubricating effect, so the friction was reduced, which made the strength of soil samples lower. In addition, the rise in the amount of moisture lead to the expansion of the volume of the specimen and an increase in the pore ratio, making the structure looser, which was also one of the reasons for the reduction of shear strength.

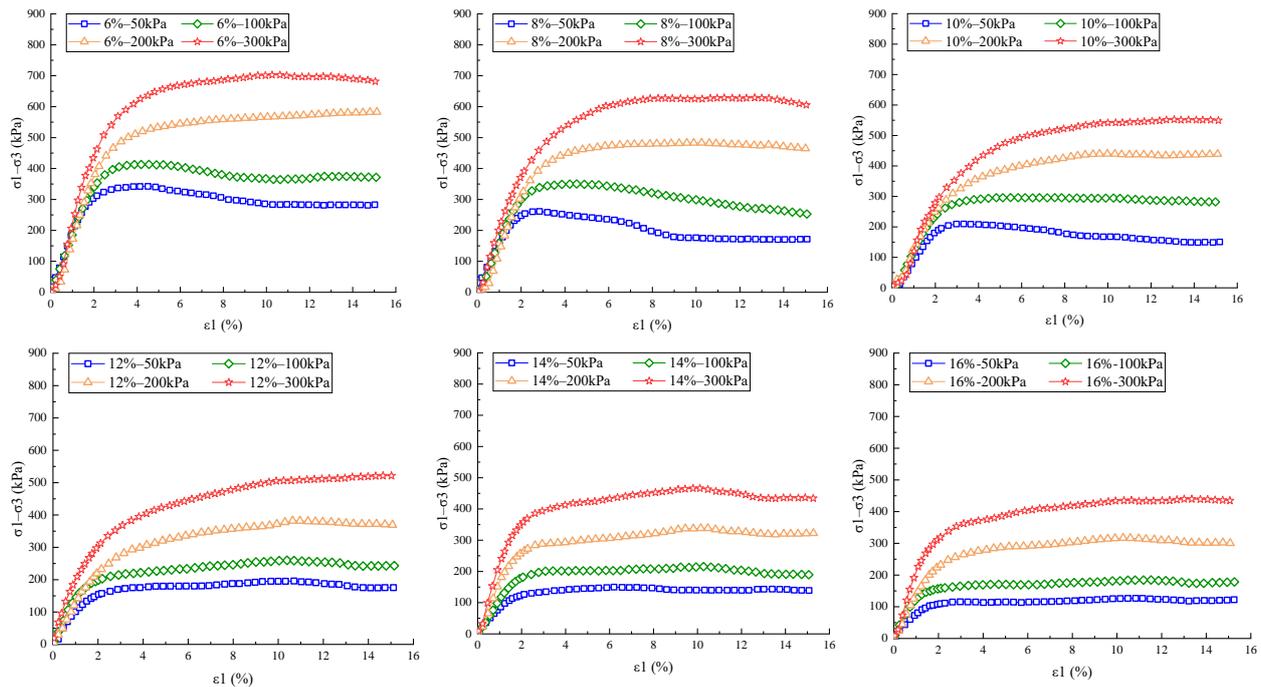


Figure 2. Curves of stress and strain for clayey sand with different moisture contents.

Meanwhile, the figure illustrates that some of the specimens of soil show brittle damage when the moisture content is small ($<12\%$), while the soil samples basically show plastic damage when there is a lot of moisture present ($\geq 12\%$). When the moisture content is less than 12% , clayey sand under low confining pressure ($50\text{--}100\text{ kPa}$) shows a pattern of stress softening. As the pressure to confine increases, the specimens of soil are transformed from stress softening to stress hardening, and the soil specimens' maximum shear strength appears at larger axial strains. When the moisture content is 12% percent or higher, the clayey sand specimens with different confining pressures all show a trend of stress hardening. From a microscopic perspective, the microstructure of the soil changes under high confining pressure, which results in increased intergranular embedding and a denser arrangement of soil particles. At the macro level, it was shown that the soil specimen's shear strength has a higher and stronger resistance to external deformation [6,23]. Whereas, when the confining pressure was identical, the rise in the amount of moisture makes the skeleton of the soil soften, and its shear strength decreases while showing stress hardening [7].

Figure 3 shows the test curves for the unsaturated clayey sandy soil's peak shear strength at various water contents. The difference in primary stress at 15% of the axial strain is used to determine the peak strength when the specimen lacks a discernible peak. Evidently, the strength of shear and confining pressure under each amount of moisture show a strong linear connection, which may be described by the Moore Coulomb strength relationship equation. At the same time, with the increase in moisture content, the strength of the shear of clayey sand declines. The strength of clayey sand with different enclosing pressures decreased by $12\text{--}23.6\%$ when the 6% to 8% amount of moisture was raised, but decreased by $6\text{--}15.3\%$ when the 14% to 16% moisture content was increased. This shows that, under similar pressure around the circumference, the peak shear strength of clayey sandy soil decreases non-linearly with a rise in the specimen's water content. In other words, the specimen's peak strength is progressively less sensitive to a rise in the amount of water, but it still decreases significantly with an up to a 16% rise in the amount of water.

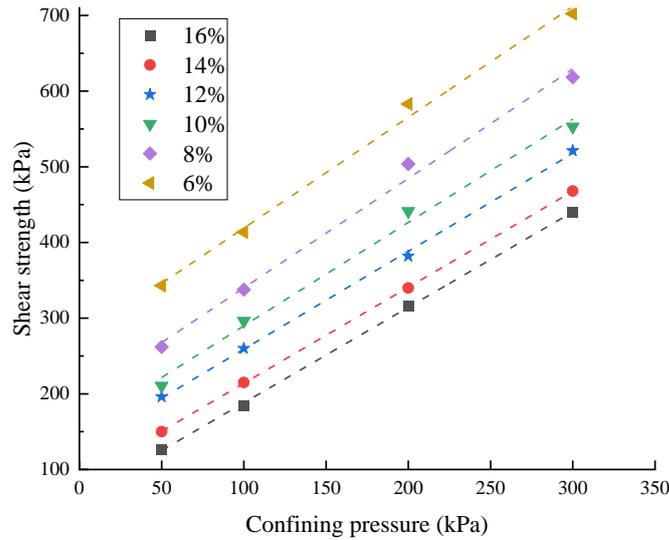


Figure 3. Shear strength of samples of soil with varying levels of moisture.

The result of the moisture percentage change on the cohesiveness and angle of internal friction of unsaturated clayey sand is shown in Figure 4. It appears that with the rise in the amount of moisture, the cohesion of clayey sandy soils shows a decreasing trend. Among them, the cohesion of 16% moisture content clayey sand decreased by 76.2% compared with that of 6% moisture content. For unsaturated clayey sand, the cohesion came from the soil's water's capillary movement [8] and the cementation body formed between clay particles and water [9]. When the amount of moisture rose, the matrix suction of soil became smaller and the water's lubricating properties reduced the soil particles' interaction with one another, both of which reduced the cohesion [6].

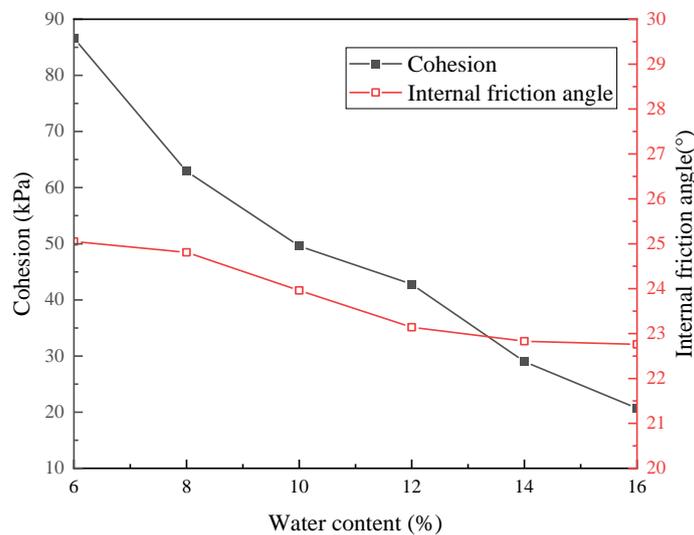


Figure 4. Impact of the amount of moisture on clayey sand's shear strength index.

Meanwhile, as the amount of moisture percentage rises, the angle of internal friction shows a decreasing trend. This is because there is more free water available between particles in the soil as the moisture percentage increases, and the free water leads to increased lubrication between the granules of soil, so the angle of internal friction decreases [9]. However, it is worth noting that the result of moisture content regarding the clayey sands' internal angle of friction is small, and the internal angle of friction of the 16% moisture percentage specimen is only reduced by 9.1% compared to that of the 6% moisture content specimen.

Through experimentation, Naser A [4] discovered that as the water content increases, the cohesiveness of clayey sandy soils first increases and subsequently declines. This could be because the unsaturated soils' shear strength increases because the matrix suction of the soil gradually increases as the amount of water drops. The presence of a peak in cohesive strength is a macroscopically manifested indicator that the area of matrix suction reduces when the water content is further reduced, and this factor has a greater influence than the increase in matrix suction. The gradation of the clayey sandy soil, however, has a significant impact on this peak; as a result, in this test, the moisture content of the clayey sandy soil varies from 6% to 16%, and the cohesiveness peak is not reached. Since this test's clayey sandy soil water content range comes from a field test, it is reasonable to infer that when the water content decreases, the roadbed's clayey sandy soil strength parameter will rise noticeably. Therefore, the water content needs to be controlled by as many anti-drainage measures as possible during the project to avoid the roadbeds being negatively affected by rainfall or rising water tables. The strength parameters of clayey sandy soils increase significantly as the water content decreases. This implies that, rather than calculating strength using the soil moisture content or optimal moisture content at the time of filling, the design strength of the roadbed should be taken into account as much as possible when it reaches equilibrium moisture content throughout the operation period.

3.2. Impact of Wet–Dry Cycling on Clayey Sand's Strength Characteristics

The strain–stress diagrams of clayey sand with distinct routes for the wet–dry cycling and different quantity of cycles between wet and dry were obtained by triaxial test, as shown in Figure 5. In the figure, 1-1-50 kPa in the legend indicates that the wet–dry cycle path is path 1, the quantity of cycles between wet and dry is 1, and the confining pressure is 50 kPa. The stress–strain curves before wet and dry cycling are shown in Figure 2 for the test results of the 8% moisture content specimens.

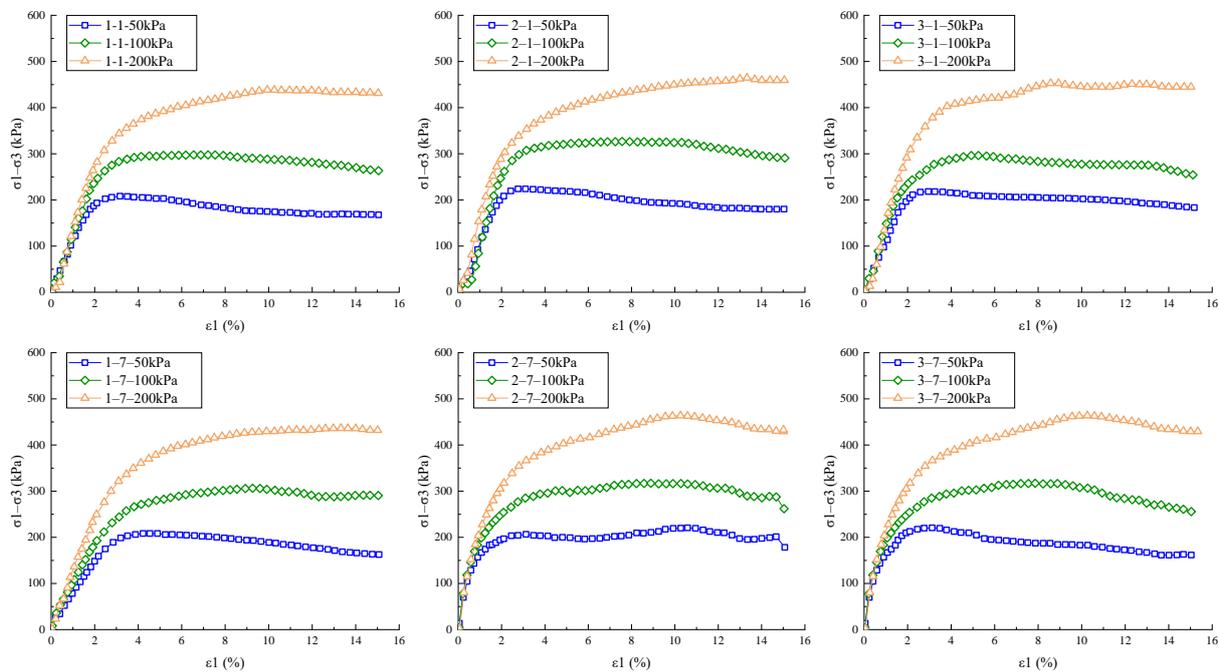


Figure 5. Soil sample stresses and strains under various conditions and the quantity of wet–dry cycles.

For wet–dry cycle action, the clayey sand had good water stability. Under different paths of wet–dry cycling, the shear strength exhibited a downward trend, and the decreasing rate ranged from 1.6% to 24.1%, which was much smaller than that of ordinary clay under wet–dry cycles. Specifically, when the confining pressure was 200 kPa, the decreasing rate was within 10%. Analyzing the reasons, it is believed that the result of wet–dry cycling on soil is represented in two aspects. First, the enlargement and reduction of clay particles

brought as a result of wet–dry cycles results in cracks in soil and an increase in the soil pore ratio. Secondly, after the repeated infiltration and dissipation of pore water, the corners of soil particles are effectively washed away and abraded, and the cementing material between aggregates is dissolved [13]. After the wet–dry cycle, no significant pore and crack development was found in the cohesive sand. Based on the decrease in the shear strength of cohesive sand, it is inferred that due to the small number of cohesive sand particles, the expansion and contraction of cohesive sand are not significant under wet–dry cycling. And the alteration of soil structure caused by the repeated infiltration and dissipation of pore water is the primary cause of the strength of shear decline in clayey sand.

Meanwhile, the decrease in shear strength for clayey sand declines noticeably when confining pressure increases. When the confining pressure is 50 kPa, the strength of shear in the soil sample decreases by 15.8~24.1% and 24.1% at most. While the confining force is 100, 200 kPa, the decreases are 6.8~18.3% and 1.6~7%, respectively.

It is important to note that where the strength qualities are impacted by wet and dry cycles of clayey sandy soil differs significantly from those of clayey soil. First off, as Figure 5 illustrates, the stress–strain relationship of clayey sandy soil is less impacted by wet and dry cycles. Low confining pressures tend to soften under wet and dry cycles, whereas high confining pressures tend to harden under such cycles. On the other hand, following wet and dry cycling, the structural characteristics of clayey soils are harmed, and their stress–strain relationship tends to change in favor of stress hardening [24]. Second, the clayey sandy soil in Figure 6a did not exhibit visible cracking during wet cycling, whereas the clayey soil in Figure 6b demonstrated visible crack development following the mixing cycle. Ultimately, as Figure 7 illustrates, although clayey sandy soil's shear strength declined as a result of wet and dry cycles, the strength of shear did not exhibit a trend of gradual decline during the increased number of wet and dry cycles, and after the first rounds of wet and dry, the strength of shear of clayey sandy soil essentially remained stable. Although clayey soil fissures continuously develop as a result of wet–dry cycle, which is the primary source of clayey soil strength decay, clayey soils often exhibit a pattern of strength stabilization after three to twelve cycles [24,25]. These phenomena demonstrate that less structural damage is caused by the expansion and contraction of clay particles in clayey sand during wet and dry cycling.



Figure 6. Pictures of soil samples with varying numbers of cycles (n). (a) sandy clay soil; (b) clay soil that is powdery.

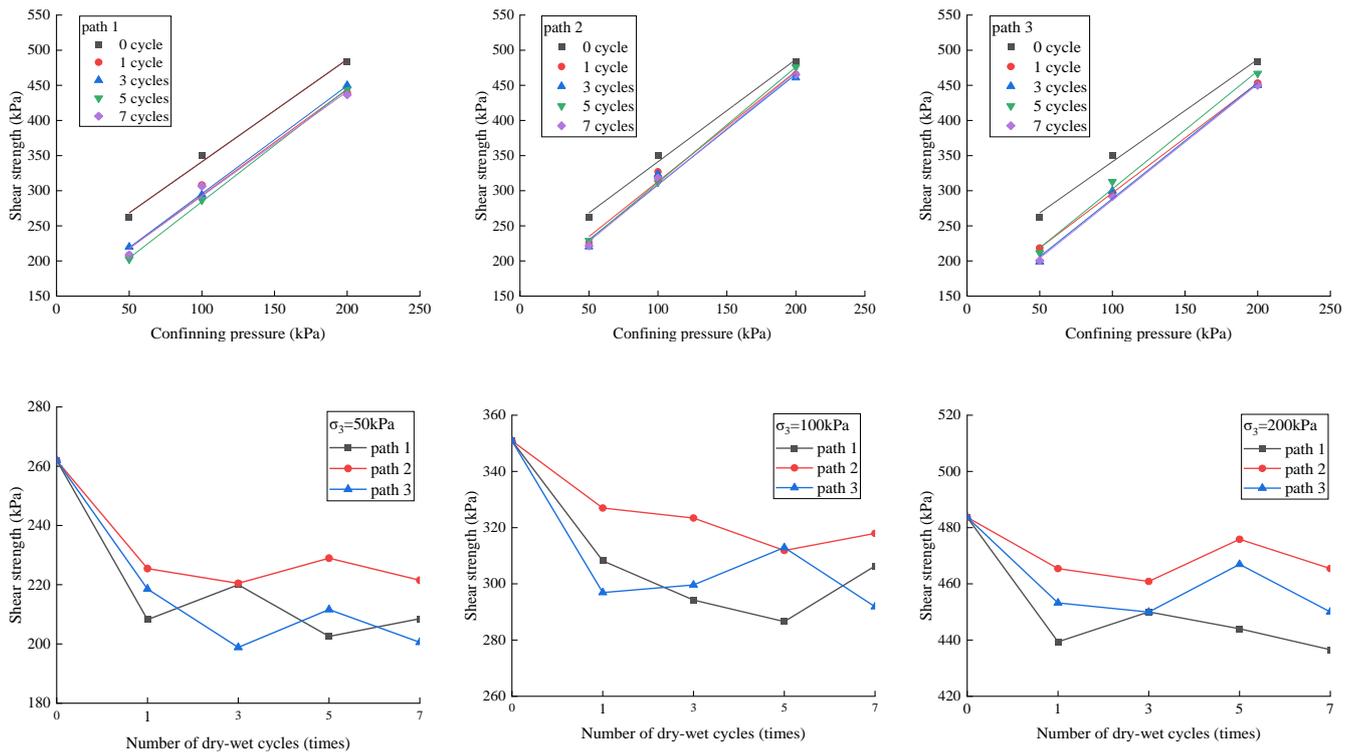


Figure 7. Peak shear strength of soil samples under different wet and dry cycle paths.

Meanwhile, the decrease of the strength of shear of clayey sand decreases significantly with the rise in confining pressure. When the stifling force is 50 kPa, the strength of shear in the soil sample decreases by 15.8~24.1% and 24.1% at most after different number of dry–wet cycles. When the confining pressures are 100 kPa and 200 kPa, the decreases are 6.8~18.3% and 1.6~7%, respectively.

According to Figure 7, compared with the soil samples without wet–dry cycling, the soil’s shear strength following the wet–dry cycling of paths 1, 2, and 3 decreased by 7~22.7%, 1.6~15.8%, and 3.5~24.1%, respectively. Among them, the decrease in shear strength of soil samples under path 2 is the lowest, while the decrease in shear strength under paths 1 and 3 is close. While paths 1 and 3 have similar magnitudes of intensity decay, paths 1 and 3 have the same upper limit moisture content, different cyclic amplitudes, and similar strength attenuation. Path 2 has a small cycling amplitude and a lower upper and lower cycling limit for water content, with the smallest shear strength decay. Therefore, comparing the different cycling paths, it can be seen that a larger upper limit water content and cycling amplitude both lead to a higher degree of strength deterioration.

The connection between the specimen’s cohesiveness and angle of internal friction under different paths and times of wet–dry cycle is displayed in Figure 8. It is evident from Figure 8a that the cohesion of clayey sand decreases after wet–dry cycling, and following the initial cycle, the cohesiveness attenuation amplitude is at its maximum, and then the attenuation amplitude decreases greatly and seems to remain steady. The deterioration of soil cohesion under paths 1, 2 and 3 is about 30%, 25% and 35%, respectively. Comparing different cyclic paths, it appears that the larger upper limit for the amount of moisture and cyclic amplitude will lead to a higher degree of deterioration of cohesion, which is consistent with the impact of wet–dry cycle paths regarding strength of shear. However, it is worth noting that under different paths the difference in the degree of deterioration of cohesion of clayey sand is small.

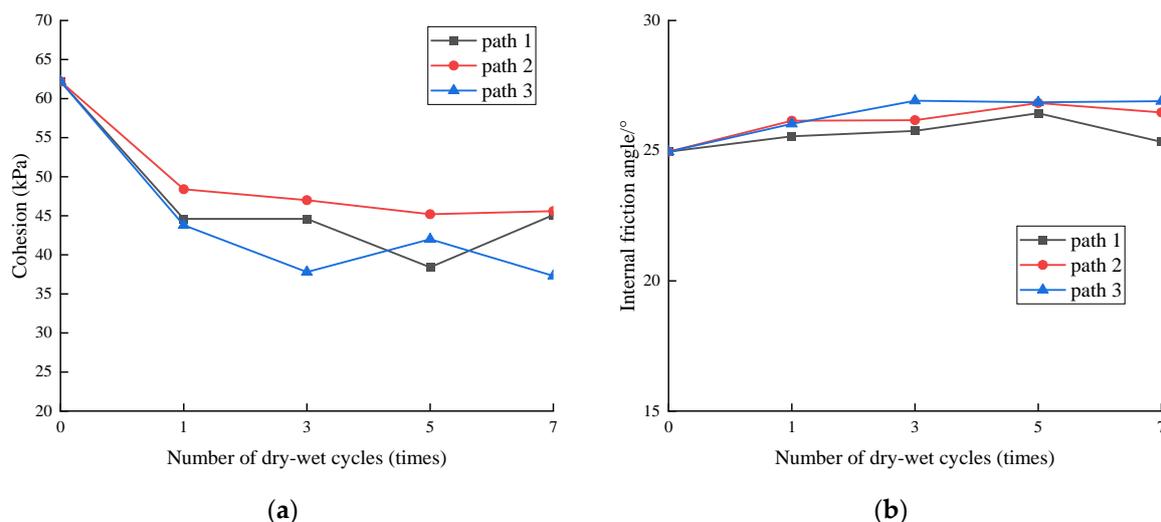


Figure 8. The impact of wet–dry cycles concerning the cohesion and angle of internal friction. (a) Cohesion; (b) Angle of internal friction.

In Figure 8b, clayey sand's angle of internal friction fluctuates within 2° following wet–dry cycling, and the spectrum of changes is small, which is much smaller than the attenuation range of cohesion. Therefore, the angle of internal friction of clayey sand is not attentive to wet–dry cycles. The analysis of the causes suggests that the angle of internal friction is relatively stable, but this does not mean that it is unaffected by wet–dry cycles, but rather that two influences lead to this phenomenon. On the one hand, the wet–dry cycles decrease the angle of internal friction and destroy the soil formation. Conversely, though the matrix suction during wet–dry cycles makes the soil compacted and increases the occlusal friction, the combined effect of these two factors causes the clayey sandy soils' internal friction angle to change somewhat, but the overall stability is maintained.

The deterioration of clayey sandy soils caused by wet and dry cycles is shown in the decrease of peak strength and cohesiveness. The project should aim to prevent wet and dry cycles from occurring or manage their amplitude in order to improve the stability of the roadbed. The more pronounced the deterioration of the soil body, the greater the amplitude of wet and dry cycles. On the other hand, clayey sandy soils degrade less under the influence of wet and dry cycles and have greater water stability than clayey soils.

4. Conclusions

In this study, the effects of moisture percentage and wet–dry cycles regarding the strength of shear characteristics of clayey sand were investigated by indoor triaxial examinations, according to which the ensuing deductions can be drawn:

1. The peak strength of unsaturated clayey sandy soil drops first swiftly and then gradually as its moisture content rises, but the strength of shear and cohesiveness of the soil decline continually. Simultaneously, the increase of water content makes the stress–strain relationship of low confining pressure clayey sandy soil change from stress softening to stress hardening. Water content has a large impact on the mechanical properties of unsaturated clayey sandy soil, and the project should try to control the increase in water content of the soil body, and in the design of the strength discount caused by the change in water content.
2. Wet and dry cycles reduced the strength of shear and cohesiveness of clayey sandy soil; the more the amplitude of wet and dry cycles and the higher the limit of moisture content, the more the soil's shear strength and cohesiveness dropped. Furthermore, the changes in shear strength and angle of internal friction were mainly concentrated in the first cycle.

3. The drying shrinkage and hygroscopic expansion of clay particles in clayey sandy soils during wet and dry cycling are not significant, resulting in less structural damage and deterioration of the mechanical properties of the soils. However, the experiments in this paper have not been carried out from a microscopic perspective to corroborate this result, and the conduct of electron microscope scanning experiments will help to further elucidate the mechanism of this phenomenon.
4. The angle of internal friction of unsaturated clayey sandy soils is increased by both decreasing the water content and wet–dry cycling. However, these effects are negligible. The variation in the angle of internal friction of soil samples under various conditions is less than 10 percent.
5. For roads that are subjected to wet and dry cycling over extended periods of time, clayey sandy soils are more suited than clayey soils with a greater clay mineral content.

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