Journal of Civil Engineering and Urban Planning (2025)
Clausius Scientific Press, Canada
DOI: 10.23977/jceup.2025.070302
ISSN 2616-3969 Vol. 7 Num. 3

Experimental Investigation on the Expansive Characteristics of Clay-Sulfate Rocks Subjected to Confined Compression and Cyclic Drying Wetting

Cheng Shufan[1,2,a,*]

[1]*Hubei Province Road and Bridge Co., Ltd., Wuhan, China*
[2]*School of Civil Engineering, Wuhan University, Wuhan, China*
[a]*chengshufan@whu.edu.cn*
[*]*Corresponding author*

Keywords: Expansive Rock, Coupling Effect, Meso-Structure

Abstract: Gansu clay-sulfate rock is a special red-bed rock that formed in an evaporation environment with strong oxidation. In this study, a loadable cyclic drying-wetting instrument was designed to simulate the occurrence of the surrounding rock mass of a tunnel experiencing a periodic change in groundwater level. Firstly, a series of drying-wetting cycle tests with different normal pressure were carried on to obtain the expansion regulation of clay-sulfate rock. Then, computed tomography (CT) and scanning electron microscope (SEM) tests were carried on to explain the corresponding mechanism in mesoscopic. The test results show that large expansive deformation was generated in the first water immersion and only part of the deformation can be recovered during the later drying process. Meanwhile, the degeneration of the clay-sulfate rock was observed in the first cycle by the CT and SEM test. It indicates the clay rock, in large part, degenerated to clay soil during the first drying-wetting cycle. Structural degradation and hydration of anhydrite is the main source of irreversible expansive deformation. Moreover, normal stress and confined restraint can reduce or even eliminate the expansive deformation, however, cannot avoid the degeneration of mesostructure.

1. Introduction

In tunnel construction or mineral excavation, the cyclic changes in hydrogeological conditions may cause engineering hazards, especially in the regions of sulfate-bearing rock[1,2]. However, the mechanism of the water-rock effect remains poorly understood because the expansion of clay-sulfate rocks is controlled by coupled hydraulic, chemical, and mechanical processes.

Over the past decades, researchers conducted numerous laboratory tests to investigate water-rock interaction, including water-softening, expansive (or swelling), slaking (or disintegration) and etc. In most of the tests, clay-bearing rocks were regarded as water-sensitive[3]. Some clay-bearing rock even exhibits behavior intermediate between sedimentary rock and clay. This kind of semi-rock tends to fully disintegrate when exposed to water directly[4]. The clay-sulfate rock collected in

Gansu is a typical red-bed semi-rock that belongs to both clay-bearing rock and sulfate-bearing rock. The sulfate in the rocks is partly hydrated and the cementation of the mineral is weak, which is different from the clay-sulfate rocks with high content of anhydrite in Germany and Switzerland[2]. Meanwhile, its hydraulic properties are more complex, because the content of carbonate minerals is high. In sum, Gansu clay-sulfate rock is an expansive semi-rock with a special composition.

In underground engineering, confined expansive deformation is more common than slaking of unconstrained rock due to the restraint of supporting structures or surrounding rocks[5], and drying-wetting cycles caused by the change in water level are more common than long-term soaking. A better understanding of the physical and mechanical properties of constrained rock subjected to periodic water erosion remains an ongoing research issue. Some novel instruments and test methods were proposed[6,7] in recent years. The mineral arrangement and mesostructure are the internal factors that lead to the expansion of rock samples and CT and SEM tests can identify mesoscopic and internal damage in rock materials[8,9]. Considering the sample is special and the lack of systematic investigation, the meso-mechanism of the confined expansive phenomenon and its main impact factor (maybe expansive mineral content, cementation structure, or others) is not understood clearly. The experimental and theoretical investigation of expansive mechanisms needs to be supplemented.

The main objective of this research is to understand the water-induced degeneration of clay-sulfate rock after cyclic drying-wetting treatments. In the section "Materials and test methodology", the physical and hydraulic properties of the rock sample and the theory of the loadable cyclic drying-wetting tests were introduced. Then, the drying-wetting cycle tests were carried on and expansive (swelling) characteristics of clay-sulfate rocks were analyzed in the section "Test results". In the section "Mesoscopic expansive mechanism", the influence of structural degeneration on the expansion regulation of the clay rock was analyzed based on CT and SEM tests.

2. Materials and Test Methodology

2.1 Material Properties

The rock sample, which is a Neogene red-bed argillaceous rock, was collected from a tunnel under construction of the G8513 expressway, Gansu, China. The basic physical properties test shows that the rock sample has low moisture content and high expansive pressure, as indicated in Table 1. To understand the source of expansion pressure and the mineral composition of the rock, the result of X-ray diffraction (XRD) tests were performed (Table 2).

Table 1 Physical properties of rock samples

Porosity (%)	Dry density (g/cm3)	Natural density (g/cm3)	Moisture content (%)	Free expansion ratio	Expansive Pressure (kPa)
11.2~14.6	2.07~2.24	2.05~2.46	5.80~7.66	2.28	525

Table 2 Mineral composition of rock samples (%)

sulfate		clay mineral		carbonate		silicate (non-clay)			others
gypsum	anhydrite	illite	chlorite	dolomite	calcite	quartz	muscovite	feldspar	
17	6	19	7	4	9	18	3	15	2

As shown in Table 2, the sample consists of 36% non-clay silicate, 26% clay mineral, 23%sulfate and 13% carbonate. It is notable that 18% of the content is gypsum. It means 30% of sulfate is still not hydrated and the rock belongs to the clay-sulfate rock[2]. The expansive potential of anhydrite (about 61%) and clay mineral is the main cause of the disintegrating (slaking) behavior of clay-sulfate rocks.

2.2 Instrument and method of the drying-wetting cycle test

Stress state and drying-wetting transmission are the two key variables studied in this paper. A cyclic drying-wetting instrument was designed and created to simulate the occurrence of in-situ rocks, which are subject to a confined compression state. The sketch and photo of the instrument are shown in Fig. 1.

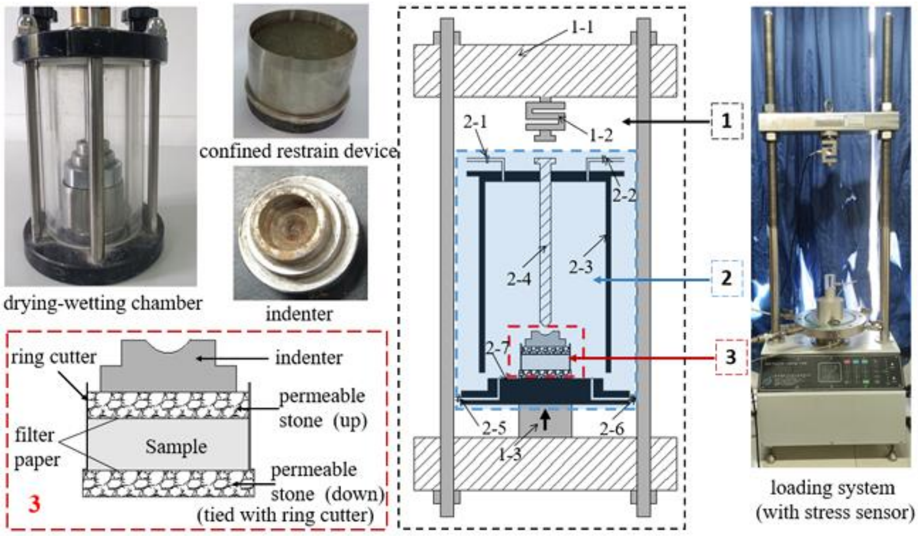

Fig.1 Sketch and photo of the instrument

The function of the instrument extended beyond the cyclic drying-wetting cycle coupled with normal compression and confined restrict. The expansive potential and expansive pressure could be measured without removing the sample from the instrument. In terms of the expansive stress test, by limiting the normal displacement, the history of expansive force would be recorded by the stress sensor. The expansive pressure can be calculated by Eq. (1)

$$p_n=(F_n-G_0)/A_0 \tag{1}$$

Where, p_n is the expansive pressure of the sample after n times drying-wetting cycle, and G_0 is the gravity of the indenter and permeable stone above the sample. A_0 is the cross-section area of the sample, and F_0 is the normal force recorded by the stress sensor of the instrument.

In terms of the confined expansive ratio test, the history of expansive strain would be calculated by the data of normal displacement of the indenter. Due to the confined function of the instrument, the sectional area of the specimen does not change, the expansion strain can be calculated from Eq. (2) by the height of specimens:

$$\varepsilon_n=\Delta h/h_0 \tag{2}$$

Where Δh is the increment of specimen height; h_0 is the initial height of the specimen.

To study the coupling effect of the confined compression and cyclic drying-wetting transmission on the clay-sulfate rock, five groups of tests were conducted under the normal pressure of 0, 100, 200, 400, and 600kPa, respectively. The maximum normal stress 600kPa was greater than expansive stress.

Considering the environment of underground rock, the drainage consolidation method was used instead of the oven evaporation method in drying-wetting cycles. In the tests, the preset normal pressure was applied and maintained until the test over. When the normal stress had been stable, the samples were soaked for 12h and then consolidated for another 36 h as a drying-wetting cycle. In total, 5 cycles were repeated.

3. Test Results

3.1 Expansive characteristics in the drying-wetting cycle

The history curve of expansive volume strain during the first cycle is presented in Fig. 2.

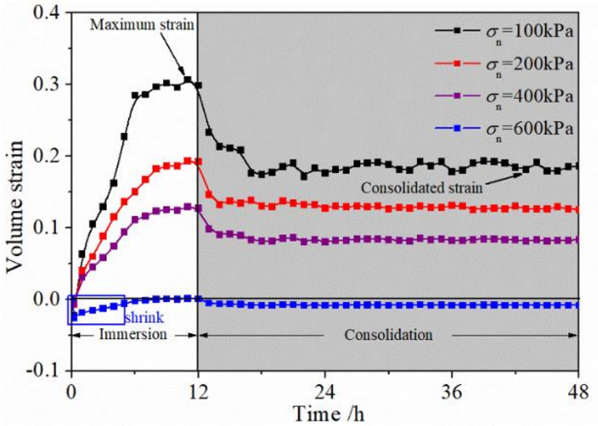

Fig.2 The expansive volume strain during the first drying-wetting cycle

When the normal stress is below the expansive pressure, the undisturbed samples experienced a short decrease in volume and then started to expand during the immersion process. The compression deformation indicates that the soft phenomena were represented early than expansion. In the consolidation process, some of the expansive deformations recovered, however, a large amount of deformation was irrecoverable. This phenomenon is due to the irreversible hydration of anhydrite and the consolidated pressure is limited. The maximum strain and consolidated strain (minimum strain in the consolidation process) during the first drying-wetting cycle move down when the normal stress increases. When the normal stress reached 600kPa, which is larger than expansive pressure, the expansive behavior disappeared in the immersion process. This observation shows that the normal stress could suppress or even eliminate the expansion of clay-sulfate rock in macroscopic.

The maximum and consolidated volume strain of the clay-sulfate rock during the five drying-wetting cycles under different normal pressure is present in Fig. 3.

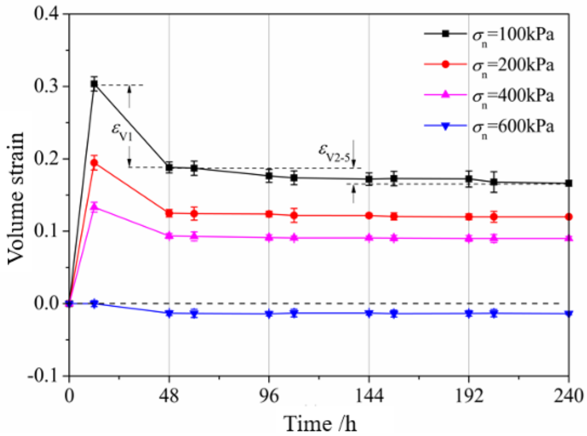

Fig.3 Maximum and consolidated volume strain during the drying-wetting cycles

It is observed that variation of both maximum and consolidated volume is less than 5% during the second to the fifth cycle. When the cycles are the same, the bigger the normal stress is, the smaller the consolidated volume strain is. The recoverable expansion is positively related to normal stress.

3.2 Mesoscopic Expansive Mechanism

The expansion of clay-sulfate rocks involves both "clay expansion" and "sulfate expansion". In terms of clay expansion, the osmotic water inflow between the surfaces of clay may be the major resource. In addition, sulfate expansion may belong to inner crystalline expansion, which is caused by sulfate hydration (from anhydrite to gypsum). The osmotic water can be dried out by pressure and clay expansion may be recoverable. However, the combined water cannot be dehydrated spontaneously by pressure. To accurately analyze the irreversible expansive strain, the undisturbed sample, and sample after one drying-wetting cycle were scanned by scanning electron microscope (SEM) and computer tomography (CT) machine. The mesoscopic structure are shown in Fig. 4.

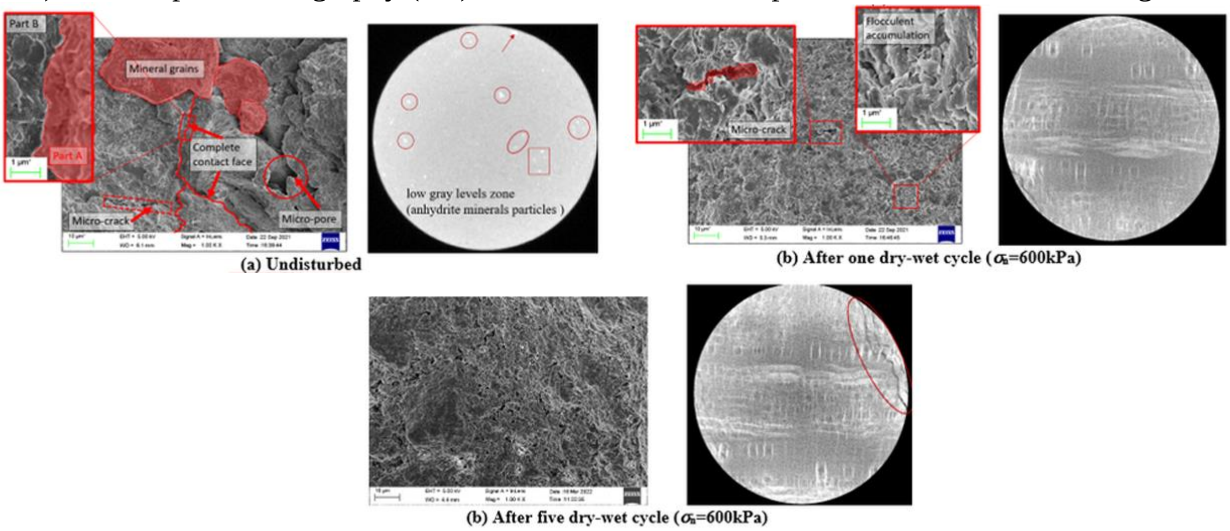

Fig.4 The typical SEM and CT picture of sample

According to Fig. 4(a), based on the right CT picture, some high-density anhydrite minerals particles with low gray levels distributed in clay minerals can be observed. Meanwhile, micro-crack and micro-pore can be observed in the scanning face of the left SEM picture. The bonded structure of the mineral skeleton and its boundary (contact face) can be identified clearly. Therefore, undisturbed clay-sulfate rock may belong to the weak cementation rock, namely semi-rock. The CT and SEM picture of the 600kPa normal stress group is shown in Fig. 4(b). In the right CT picture, the non-uniformity of gray distribution is strong and some macroscopic fractures appear on the outside boundary of the sample. The mesostructure in the left SEM picture has also changed significantly, and scale-like clay minerals are flocculent accumulated. We also observed the skeleton of the larger mineral particles is not clear. It was attributed that they may be covered by clay minerals. The micro-crack in the sample after a drying-wetting cycle is smaller and denser than the undisturbed sample. Finally, the CT and SEM picture of clay rock that experienced one and five drying-wetting cycles have the same mesostructure. The micro-crack in the SEM picture and macro-crack in the CT picture seems generated and propagated in this process.

Compared with the initial cement structure, the flocculent structure is more common in compacted clay. Therefore, the intrinsic of the sample after the first drying-wetting cycle may be clay (soil) rather than clay rock. Once, the normal stress is up to the sample's expansive pressure, the expansive deformation was eliminated. However, the degeneration process of rock still occurred.

The influence of the drying-wetting cycle on the expansive properties of samples can be divided into two stages. The first stage only corresponds to the first drying-wetting cycle, which is mainly manifested in the structural change in mesoscopic. In this process, the clay-sulfate rock degenerated from semi-rock to clay with the increase in volume. Due to the changes in mesostructure and unrecoverable expansive deformation, the expansive potential and expansive pressure are decreased significantly. The next stage corresponds to the second to fifth drying-wetting cycles, which are characterized by a gradual decrease in both volume expansive potential and expansive pressure.

4. Conclusions

A self-designed instrument was created and used to conduct the drying-wetting cycle experiments on confined compression rock. The coupled effect of stress state and cyclic drying-wetting transmission on the expansive properties of soft rock was studied. The following conclusions can be drawn from the experimental results.

(1) Gansu clay-sulfate rock is a special red-bed argillaceous rock that is sedimented in a drying and strong oxidizing environment. Its sulfate content is 23%, and the hydration ratio of sulfate is 70%. Due to the high content of clay minerals and sulfate, the rock samples are water-sensitive. The samples show accelerated slake tendency in freely drying-wetting cycles, and the 2nd and 5th cycle slakes durability index is 0.798 and 0.206.

(2) With a confined restrain device and controllable normal force, the self-designed instrument achieves the coupling between the cyclic drying-wetting transmission and a constant stress state in the experiment. When the normal stress is below the expansive stress, the volume increased significantly in the first wetting process, and only a part of the deformation can be recovered in the first drying process. Later, in the 2nd to 5th drying-wetting cycles, the expansive-shrinking deformation of rock is little and the volume of specimen tends to be constant.

(3) In the first drying-wetting cycle, the mesostructure of the test sample changes from particle cementation to flocculent accumulation, which indicated the clay-sulfate rock, in a large part, degenerated from semi-rock to clay. During the 2nd to 5th drying-wetting cycles, there is no essential structural change. Moreover, the normal pressure may decrease and even eliminate the expansive deformation of clay-sulfate rock, however, which cannot avoid the degeneration process.

References

[1] Kwon S, Lee C S, Cho S J, Jeon S W, Cho W J (2009). An investigation of the excavation damaged zone at the KAERI underground research tunnel. Tunn. Undergr. Sp. Tech. 24(1):1-13.

[2] Butscher C, Huggenberger P, Zechner E, Einstein HH (2011). Relation between hydrogeological setting and swelling potential of clay-sulfate rocks in tunneling. Eng. Geol. 122(3):204-214.

[3] Liu D, Wang Z, Zhang X, Wang Y, Zhang X, Li D (2018). "Experimental investigation on the mechanical and acoustic emission characteristics of shale softened by water absorption." J. Nat. Gas. Sci. Eng. 50(Feb):301-308.

[4] Alonso E, Pineda J, Cardoso R (2010). Degradation of marls; two case studies from the Iberian Peninsula Geological Society, Engineering Geology Special Publications, London, U. K.

[5] Li Q, Shi W, Yang R (2016). Deformation mechanisms in a coal mine roadway in extremely swelling soft rock. SpringerPlus. 5(1):1310.

[6] Hu M, Liu Y, Ren J, Wu R, Zhang Y (2019). laboratory test on crack development in mudstone under the action of dry-wet cycles. B. Eng. Geol. Environ, 78(1):543-556.

[7] Zeng L, Luo J, Liu J, Gao Q (2021). Disintegration characteristics and mechanisms of carbonaceous mudstone subjected to load and cyclic drying-wetting. J. Mater. Civil Eng. 33(8):04021195.

[8] Jia L, Chen M, Jin Y (2014). 3D imaging of fractures in carbonate rocks using X-ray computed tomography technology. Carbonate Evaporites 29, 147–153.

[9] Kuang H, Wang P, Ai X, et al. (2022). Study of the karst development rate of the Jinping porous carbonate rock formation based on porosity analysis of rock images. Carbonates Evaporites 37: 55.