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Effect of Drying-Wetting Cycles on Triaxial Compression Mechanical Properties of Sandstone

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Abstract

To investigate the geological hazards caused by the action of drying-wetting cycle on rocks, we conducted a conventional triaxial compression test on sandstone under a high number of repeated drying-wetting cycles. By using the TAW-2000D microcomputer-controlled electro-hydraulic servo triaxial rock testing machine, this study investigated the influences of repeated drying-wetting cycles on the deformation and strength characteristics of sandstone. At the same time, the relationships among the strength, elastic modulus, and confining pressure of sandstone were analyzed. The results show that, when the drying-wetting cycles are relatively low, both the compressive strength and elastic modulus of the sandstone increase with the increase of the confining pressure, and the more drying-wetting cycles are, the more they increase. When the confining pressure imposed on the sandstone is constant and the drying-wetting cycles amount to 10-15 times, all the compressive strength, elastic modulus, cohesion, and internal friction angle significantly decrease. When the drying-wetting cycles exceed 15 times, the internal friction angle of the sandstone increases first and then gradually decreases. The fractures of the sandstone exhibit a transformation from brittle failure to ductile failure. Under the action of drying-wetting cycles, the sandstone is greatly influenced by the softening action of water soak at the initial stage. The conclusions provide favorable evidence for the analyses of the long-term stability of rock engineering.

Keywords: Rock mechanics, Cyclic drying-wetting, Mechanical property, Triaxial compression test, Sandstone

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1. Introduction

In many special geological environments of rock mass engineering, rocks are usually subjected to dry and wet conditions because of water absorption and evaporation of rainfall caused by groundwater movements. Dry-wet alternate action of rock mass is a type of “fatigue” that causes rocks to undergo weathering and leads to the deterioration of mechanical properties, resulting in the frequent occurrence of geological disasters. The effects of repeated drying-wetting cycles on the deterioration of rocks are stronger than its impact during long-time soaking, which is critical to the stability of rock mass engineering. Previous studies less consider the slope rock mass of drying-wetting cycles and its role in the testing process. On the other hand, it does not consider the number of cycle functions and only adopt the compulsory measures of “drying-wetting cycles”. Therefore, studying sandstone in different drying-wetting cycles after triaxial compression has vital significance in mechanical properties and the long-term strength and deformation characteristics of rocks.

2. State of the art

With regard to the condition of drying-wetting cycles, domestic and foreign research on the characteristics of expansive soil has made progress. However, research on the influence of rocks is still in the preliminary exploration stage. Tang Chaosheng et al. [1] adopted two kinds of drying shrinkage paths and find that the deformation of expansive soil swell-shrink along with the increase of cycling times gradually stabilized, in which the expansion rate increased with the increase in the number of drying-wetting cycles. Yang Heping et al. [2] studied the loading condition of drying-wetting cycles on unsaturated and undisturbed expansive soil, where the swelling and shrinkage deformation of expansive soil is not fully reversible. Sun de-an et al. [3] drew a conclusion that the deformation of expansive soil and its water-holding capacity has a tendency to decline based on the different deformation rules of expansive soil on drying-wetting cycles.

As an important area in the field of water-rock interaction, changing the rule of rock mechanics and its properties caused by a dry-wet alternate function has attracted many researchers, and the research in turn produced meaningful results.

After studying repeated drying-wetting cycles, rock mechanical properties are divided into two aspects. The first one is uniaxial condition. Fu Yan et al. [4-5] conducted drying-wetting cycle tests of the slightly weathered sandstone 15 times. They concluded that tensile strength and modulus of elasticity of sandstone show a downward trend, and the drying-wetting cycles on the modulus of elasticity strength is tensile, indicating that the two have a good logarithmic relationship between the number of drying-

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wetting cycles. Li Kegang et al. [6] also conducted the drying-wetting cycles experiment 15 times and analyzed the response regularity of the physical and mechanical properties of sandstone with the change of dry-wet alternate function. Sandstone water absorption and sample rate of mass loss is positively correlated with the number of drying-wetting cycles. On the other hand, under a reduced number of drying-wetting cycles, the strength and deformation characteristics of red sandstone after 8 cycles of wetting and drying under uniaxial and triaxial compressions were studied by Yao Huayan et al. [7] They found that with the increase in the number of alternate wetting-drying cycles, the decrease in the overall change tendency of the mechanical indexes of rock is gradually reduced, and the ductility of the rock is enhanced by the alternation of wetting and drying.

Other researchers conducted more experimental studies on all kinds of rock mechanics characteristics under saturated water and different moisture content, such as compression strength and elastic modulus [8-10]. Erguler Z.A. et al. [8] For the variety of rocks under different water content on uniaxial compressive strength, elastic modulus was obtained by the mathematical expression changing with water content, Zhang Huimei et al. [9] studied under saturated conditions of the elastic modulus, the strength of sandstone and freeze-thaw cycles are positively correlated. For different drying-wetting cycles of dry and water-saturated soft sandstone under uniaxial compressive strength and tension test, Yao Huayan et al. [10] find that when the sandstone is saturated, the uniaxial compressive strength and tensile strength are decreasing, and after drying-wetting cycles, the tensile strength damage degree of sandstone is more serious than long soaking.

The reference [11-13] also discussed the related issues. Vasarhelyi B. [11] proposed to use the saturation to describe the relationship and uniaxial compressive strength. Deng Huafeng et al. [12] selected the amplitude of sandstone in the testing area and find that hydraulic lift and damage of rock by drying-wetting cycles have a cumulative effect. Zeng Sheng et al. [13] through drying-wetting cycles test, analyzed the strength variation of sandstone and discussed the red sandstone slope stability.

Obviously, the existing research achievements are mostly under the condition of uniaxial compression of the change of the physical and mechanical properties of rocks. However, since the drying-wetting cycles of rock triaxial research on the effects of mechanical properties is minimal, only Fu Yan [4] and Yao Huayan [7] related the dry and saturated water to the dry-wet alternate function of conventional triaxial compression experiments, but the number of dry-wet alternate is less (under 15). As the research object, the sandstone underwent different confining pressures, different times of drying-wetting cycles of conventional triaxial compression test, analysis of sandstone triaxial compressive strength deformation characteristics, and failure characteristics and shear parameter with the rule changes of drying-wetting cycles. The results of the study are not only a useful supplement to the rock mechanics system, but it can also be a reasonable estimation of rock mass evaluation accuracy to provide a theoretical reference basis.

The remainder of this paper is organized as follows. Section 3 describes the test sample, test equipment, and methods. Section 4 is based on test results to analyze the drying-wetting cycles influence on the mechanical properties of sandstone and further discusses the reason. Section 5 summarizes the conclusions.

3. Methodology

3.1 Test sample and equipment

The rock samples were taken from the sandstone of Yunnan pioneer open pit mine, where the integrity is better and no visible joint exists. It is mainly composed of quartz, cuttings, a small amount of feldspar composition, mud, and silica-filled cementation. To reduce the experimental results obtained from the individual differences of the rock samples and to improve the comparability of the test results, the block of rock used to prepare the samples was taken from the same parts of the same rock mass. In accordance with the specification in the study by *Ministry of Housing and Urban-Rural Development of the People's Republic of China* [14], the rock specimens processed were 50 mm in diameter and 100 mm in height like a standard cylinder specimen. As shown in Fig. 1, the loading equipment used was a TAW-2000D microcomputer to control the electro-hydraulic servo rock triaxial testing machine.

Fig. 1. TAW-2000D microcomputer-controlled electro-hydraulic servo rock triaxial testing machine

3.2 Test method

The operability of test and the test method of previous studies [4-7] synthetically consider the rock itself as a result of a natural environment process. We placed the rock sample into the stove at 50° for 12 hours until the sample cooled to room temperature. Then, we soaked it in water for 48 hours to complete one drying-wetting cycle. After the drying and processing of samples in accordance with the norms of the free immersion method for soaking, the specimen became absorbent after 48 hours in the water. The specimen stuck to the surface water was removed before weighing. To maintain the uniformity of the wet and dry operations, the oven temperature is controlled in the range of 50° plus or minus 2 degrees.

Selected drying-wetting cycle 0 (natural), 1, and 5 sandstone specimens of different confining pressure (2, 6, and 10 Mpa) under triaxial compression deformation test, a TAW-2000D microcomputer-controlled electro-hydraulic servo rock triaxial testing machine was used. The entire process was divided into six groups, each with 4 deformation control methods used in the loading process of the experiment. The axial load was applied to 0.05mm/min deformation rate until the test samples were completely destroyed.

To fully simulate the actual rock engineering in the drying-wetting cycle simulation, the high times for sandstone drying-wetting cycles test was conducted to ensure that the “natural” way was followed. To examine the instrument adequately in the triaxial compression test, we determined the applied confining pressure to keep constant pressure. We also determined the instrument tube to prevent water leakage and check if the rubber membrane was intact so that measurement accuracy could be ensured. The single uniformity of full water-to-air drying cycle effect may also have a certain influence when the air differs under varying environmental conditions. In this test on free immersion and drying method, the final test result would have a certain regularity and would show an easy grasp of actual engineering rock mass stability. On the other hand, the physical properties of the rock and mechanical test results were greatly influenced by the moisture content. Therefore, to better grasp the trial rules in the test process, all of the physical and mechanical parameters were determined in a saturation of the sample.

4. Result Analysis and Discussion

According to the results of the triaxial test, the times of drying-wetting cycles are significant for sandstone. When the number of drying-wetting cycles increased, the tendency to confine the pressure effects of the sandstone sample decreased. Table 1 shows the results of the sandstone triaxial compression test under different confining pressures.

Table 1. Triaxial compression experimental results of sandstones under the different times of drying-wetting cycle

Drying- wetting cycle number /*n*	Confining pressure/MPa	Compressive strength/MPa	Elasticity modulus /GPa	*C*/MPa	*φ*/(°)
0	2	110.02	26.71	13.86	56.29
	6	174.54	24.78		
	10	185.97	30.97		
1	2	96.81	18.38	12.75	54.66
	6	147.38	8.99		
	10	173.21	28.06		
5	2	95.50	23.79	13.44	52.57
	6	133.66	24.94		
	10	165.11	28.95		
15	2	71.39	9.11	7.89	56.24
	6	122.87	31.51		
	10	157.22	11.34		
30	2	75.67	13.86	6.75	55.29
	6	89.28	9.25		
	10	148.88	20.88		
50	2	59.80	5.81	6.21	54.06
	6	90.87	9.88		
	10	135.12	15.48		

4.1 Effect of drying-wetting cycles on triaxial compressive strength of sandstone

The relationship between the compressive strength of sandstone under different confining pressures and the times of drying-wetting cycles are shown in Fig. 2. The figure shows the following:

1) The effect of drying-wetting cycles significantly reduces the triaxial compressive strength of sandstone, and a large degree of weakening occurs in the early stage of drying-wetting. With the increase in the number of cycles, the tendency of deterioration gradually weakens.

2) Under the same number of drying-wetting cycles, the compressive strength of sandstone increases with the increase of confining pressure, but the rate of increase is not the same. Overall, the number of times of drying-wetting cycles is greater with a greater value of increased ranges of triaxial compressive strength. The increased ranges of triaxial compressive strength are greater, whereas the influence on the rock strength increases.

3) If the confining pressure is constant, the sandstone samples of triaxial compressive strength gradually decrease with the increase in number of drying-wetting cycles and the decreased amplitude also showed a decreasing tendency. Respectively, when the confining pressure is 2, 6, and 10 MPa, after 50 drying-wetting cycles, the rates of sandstone triaxial compressive strength are 45.64%, 47.94%, and 27.34%,is less than by 0 times (natural).

4) From the variation curve, the triaxial compressive strength eventually and gradually becomes parallel to the horizontal axis, that is, the intensity is not reduced to zero indefinitely. However, it becomes a value under drying-wetting cycles as the final state.

5) Fitting analysis shows a clear logarithmic function relationship between the triaxial compressive strength of sandstone and the number of drying-wetting cycles. It is expressed in the following formula:

$$\sigma_c(n) = ALn(n+1) + B\ (n \leqslant 50) \tag{1}$$

In this formula, n is the number of drying–wetting cycles, whereas A, B are constants.

For different confining pressures, constants A and B are not the same. According to the experimental results of triaxial tests, A and B under different confining pressures are shown in Table 2.

Table 2. The regression equation coefficient under different confining pressure

Confining pressure/MPa	A	B	R^2
2	-11.61	109.28	0.896
6	-20.70	169.97	0.993
10	-11.35	184.77	0.949

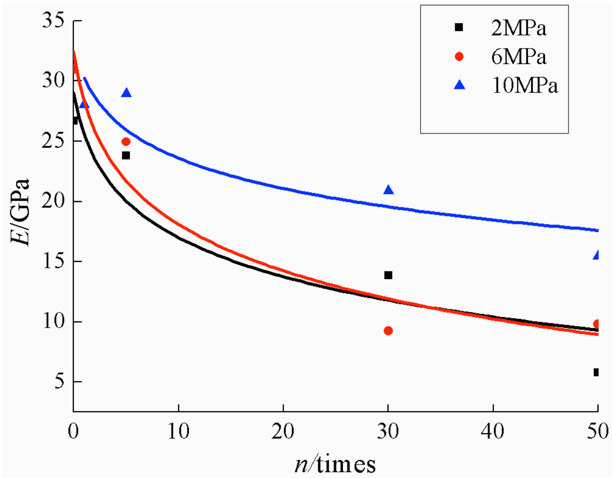


Fig. 2. Relationship curves between σ_c and n

4.2 Influence of drying-wetting cycles on deformation characteristics of sandstone

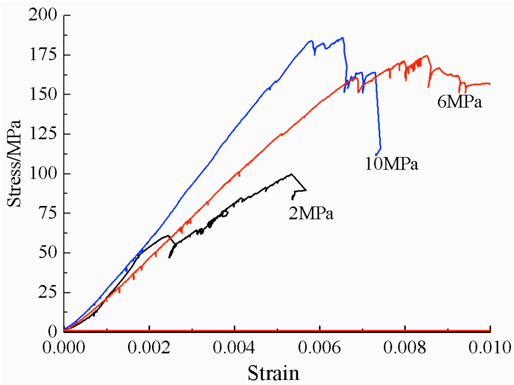
Figure 3 shows the triaxial compressive stress-strain curve of the sample under different numbers of drying-wetting cycles. Owing to space limitations, this article provides only a part of the cycle times (0, 5, 30, and 50 times). The figure shows the following:

1) Rock samples under different confining pressures and cycles as well as the stress-strain curves of the morphology are basically the same. The characteristics of specimen can be roughly summed up into three stages: rock fracture compaction, elastic deformation, and post rock-fracture stage.

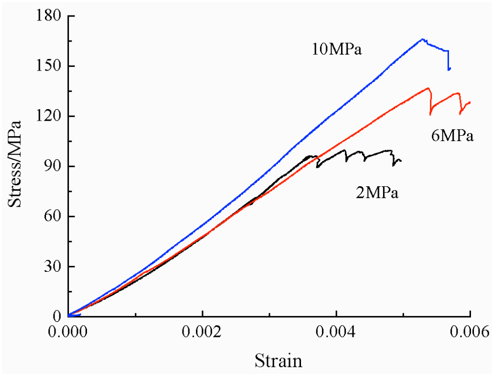
2) With the increase in the number of drying-wetting cycles, the compaction segment of curve grows significantly. Mainly because the sample grain skeleton structure under the action of a cycle is changing, micro cracks and micro cracks evolve, which constantly increase the porosity results.

3) When the number of drying-wetting cycles is less (such as 0 and 5 times), the curves before the peak of rock samples under different confining pressures are substantially coincident and elastic modulus does not change obviously. However, with the increase of cycling times under different confining pressures before the peak curve discrete degree increases, the elastic modulus scale clearly shows the “confining pressure” effect.

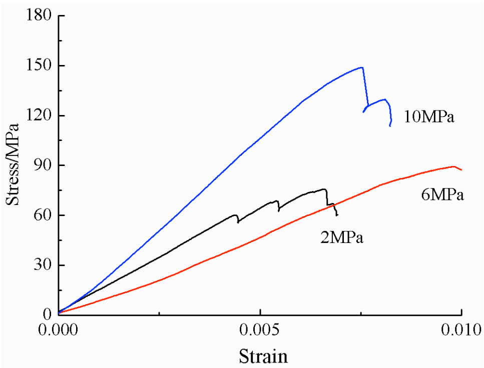
4) The enhancement of drying-wetting cycles greatly weakens the ability of the rock to resist deformation. The elastic modulus decreases obviously, and the “soft” tendency of rock is significant. This finding is consistent with previous results [15-16].



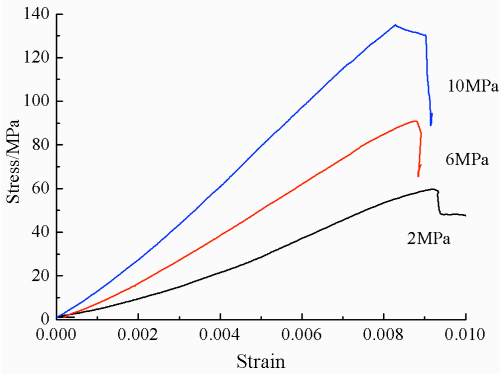
(a) Cycle 0 times



(b) Cycle 5 times



(c) Cycle 30 times



(d) Cycle 50 times

Fig. 3. Typical stress-strain curves of sandstone under different drying-wetting cycles

Figs. 4 and 5 show the elastic modulus of sandstone with the number of drying-wetting cycles and the graphs showing the elastic modulus of sandstone with the confining pressure respectively. We can see from the figure that

1) Under the same confining pressure, the elastic modulus negatively correlated with the number of drying-wetting cycles. That is, with the increase of wetting and drying effects, the elastic modulus of sandstone is decreased and the variation of lower range will appear smaller after the first larger. Both expressed by logarithmic function relationship as follows:

$$E(n)=CLn(n+1)+D\,(n\leqslant 50) \tag{2}$$

Formula: n is the number of drying-wetting cycles, C and D is constant

In this triaxial test, C and D values under different confining pressures are shown in Table 3.

Table 3. The regression equation coefficient under different confining pressure

Confining pressure/MPa	C	D	R^2
2	-5.01	29.01	0.803
6	-5.96	32.39	0.915
10	-3.90	32.94	0.753

2) In the same number of wet and dry effects, the elastic modulus and confining pressures are positively correlated. That is, as confining pressure increases, the modulus of elasticity of rock is growing, both showing a good exponential relationship. In cycle number n = 50 case (Fig. 4.), its function can be expressed as follow:

$$E_e = 4.61 e^{0.122\sigma_3} \left(R^2 = 0.997\right). \tag{3}$$

Although there have been individual fluctuating abnormal points in the test, such as the elastic modulus under confining pressure of 2 MPa and 6 MPa when cycle number n = 30 in Fig. 3. However, this does not affect the overall grasp in the rules.

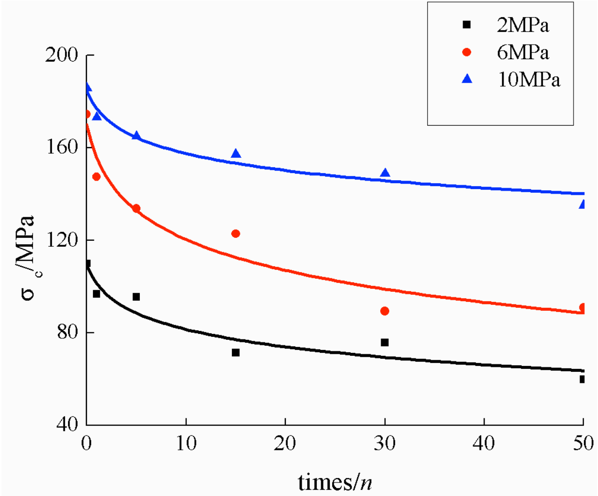


Fig. 4. Relationship curves between E and n

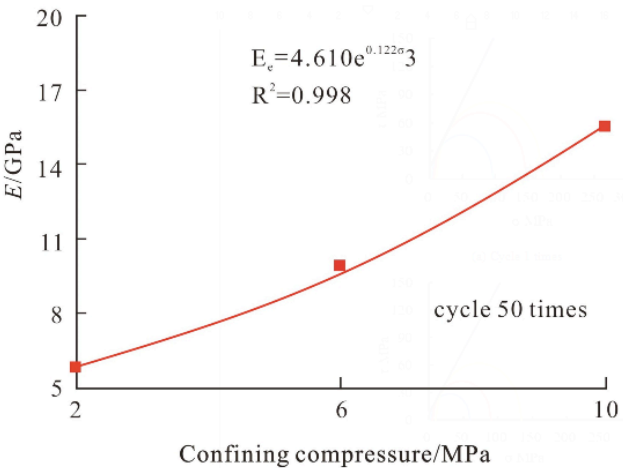


Fig. 5. Relationship curve between E and confining pressure

4.3 Influence of drying-wetting cycles on shear parameters of sandstone

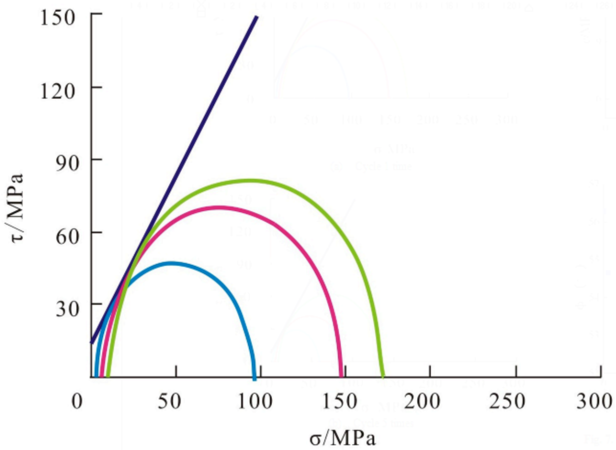
Due to limited space, Fig. 6 shows Mohr stress circle and intensity envelope drawn based on the test result of drying-wetting cycles of 1, 5, and 50 times, respectively. Sandstone cohesive force and internal friction angle of relation curve, along with the change of drying-wetting cycles is shown in Fig. 7. The results showed the following:

1) With the increase of drying-wetting cycles, the cohesive force of c significantly reduced. When drying-wetting cycles n = 50, the cohesive force is reduced to a minimum 6.21 MPa. Compared with 13.86 MPa when n = 0, the extent of reduction is 55.19%. Analysis can be obtained by the following conclusions: Owing to the reaction of the cohesive force in its bite between rock particles, under repeated dry-wet weathering, rock particles indicate the physical, chemical, and mechanical damage, the degree of internal bonding between the particles continues to decline, which leads to the shrinkage of cohesive force. By regression, the logarithmic function expressed between them is as follow:

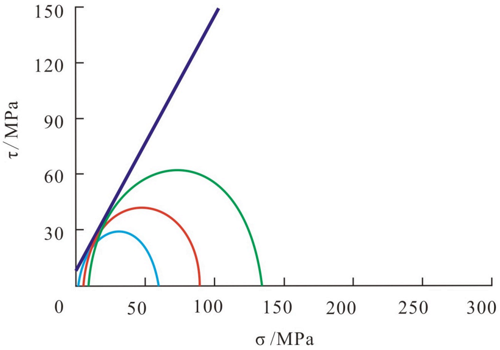
$$c = 2.14 Ln(n+1) + 14.43 \left(n \leqslant 50, R^2 = 0.833\right) \tag{4}$$

2) The internal friction angle does not exhibit similar variation to the cohesive force, however, fluctuations present a sharp decrease where the increase comes first, then they slowly decrease. An inflection point occurred when a number of wet and dry, this is inconsistent with what has been achieved [5-7]. From the analysis, we can obtain the following conclusions: Owing to the internal friction angle φ reflected in the friction between the particles at the beginning of the dry-wet alternate action, water lubrication is dominant, which do not make an arrangement between the particles to produce a significant change. Therefore, the friction between the particles decreased, specifically, φ become smaller. However, with the enhancement of the role of wetness and dryness, the arrangement between the particles can produce a series of changes, which can increase the sliding friction between the particles, there by reducing the friction force that reflects the inner friction angle. As presented in the literature [5-7], the φ values continued a decreasing trend in which a sudden increase and decrease may also occur (e.g., this study).

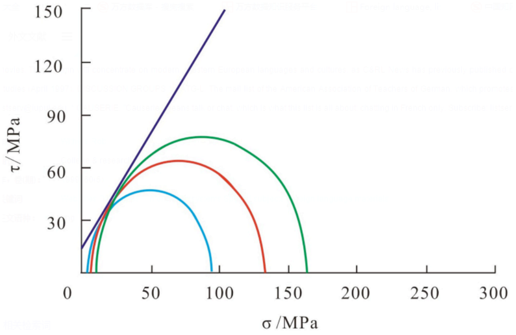
3) Overall, the influence of drying-wetting cycles on the cohesive force is larger than that of the internal friction angle, the cohesive force of the wet effect on the reaction is more sensitive than the internal friction angle. This finding coincides with the law presented in the study by Deng Huafeng [17].



(a) Cycle 1 time

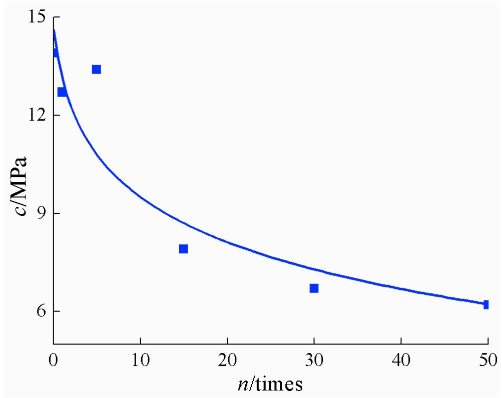


(b) Cycle 5 times

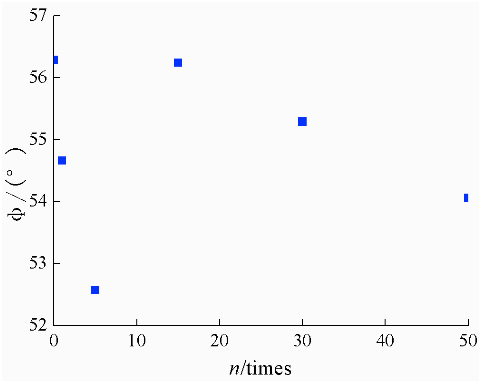


(c) Cycle 50 times

Fig. 6. Shear stress curves under different drying-wetting cycles



(a) Cohesion



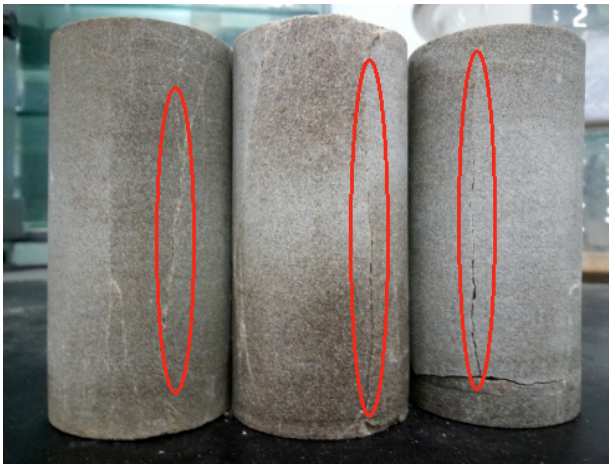
(b) Internal friction angle

Fig. 7. Relationship curve between shear parameters and *n*

4.4 Influence of drying-wetting cycles on failure characteristics of sandstone

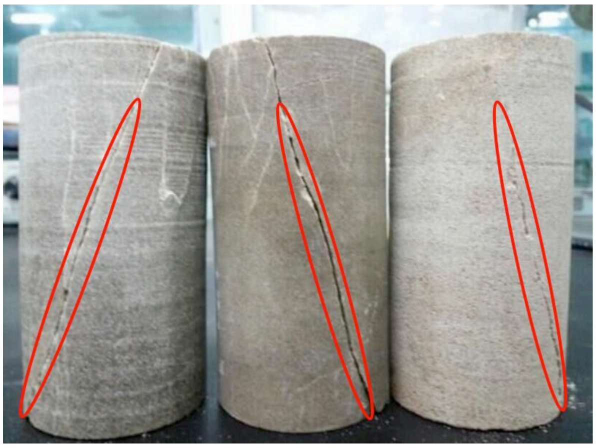
Failure modes of rock can be divided into ductile and brittle failure. A part of the macroscopic damage forms of sandstone under different cycles is shown in Fig. 8. The failure characteristics of rock samples before and after the test showed that the degree of fragmentation of the sample is relatively high in the low-level dry-wet effect. A crisper cracking sound would be issued when the material is damaged and most of the surface would exhibit one or several vertical fractures (Fig. 8a). At this time, a more brittle fracture is observed. With the increase in the number of drying-wetting cycles, the fracture surface of the rock sample slants in a certain angle with the axial direction of the force formed (Fig. 8b). The sample begins to show shear failure characteristics, which shows that brittle failure characteristics are beginning to weaken. When the wetting and drying effect continues to strengthen, a more pronounced rupture through the surface appears after rock failure. The fracture surface width becomes wider and exhibits a trace of friction with powder particles falling off (Fig. 8c). Then, ductile characteristics become apparent. This condition suggests that the early stage of the water-rock interaction and the dynamic character of rock cracking significantly stabilizes late in this stage [18-20].

The preceding results show that the wetting and drying effect causes the destruction of sandstone to present brittle-ductile transition [21]. Undergoing this test as an example before drying-wetting cycles for 10-15 times, the specimen is given priority with brittle failure. After 15 times, ductile fracture is dominant, which shows that the bite and arrangement structures of rock particles begin to change, leading to the destruction of rock shape. This conclusion is also consistent with Section 4.3, which shows that the friction angle mutations occur within drying-wetting cycles for 10-15 times.



(a) Drying-wetting cycle 5 times

(b) Drying-wetting cycle 15 times



(c) Drying-wetting cycle 50 times

Fig. 8. Typical failure modes of sandstone under different drying-wetting cycle

4.5 Discussion

As the rock samples are taken from natural rock with its own non-uniformity coupled with processing accuracy, the impact of end effects and other factors on the specimens inevitably lead to deviation and discrete test data, thereby affecting the test results. Nevertheless, the test results of this study on the mechanical properties of sandstone under triaxial effect of drying-wetting cycles still exhibit a certain regularity.

Sandstone has varying degrees of internal joints and cracks, and the composition of the particle-bound sandstone is not very tight. Confining pressure makes the rocks within the voids and cracks by the compaction and decreased inter-particle contacts improved. The friction characteristics and macroscopic mechanical properties of the resulting optimization are enhanced. However, in the drying-wetting cycles effect, the sandstone inside these larger pore structures become negative factors that affect its mechanical properties. On the one hand, water constantly flows through the flow channel between the interior of the particle; thus, the binding force between rock particles weakens and decreases the friction. On the other hand, after repeated heating, the rock sample cooled and suffered thermal expansion through the water shrinkage test. Owing to the different thermal expansion and shrinkage rates of sandstone mineral particles, this condition resulted in different particles and particle perimeter expansion, uncoordinated contraction effects, and mutual restraint among the various mineral particles. As a result, interparticle and particle internal tension-compression stress formation occurred within the weathered structure. When this kind of stress exceeds rock strength limit, new fissures produce original crack propagation with alternating wet and dry continuous action, thus, additional cracks in the rock are generated internally. More crack of inside the rock generate constantly, and the crack also continues to widen through the original fracture, where the mechanical properties of the rock specimen are declining. The macro performance also deteriorated the mechanical properties of the rock. Even if the confining pressure can improve the mechanical properties of the sandstone, the role of alternating wetness and dryness imposes greater damage on the sand mechanical properties, thus, the overall trend showed a deterioration of the macroscopic mechanical properties.

5. Conclusions

To avoid the unknown hidden danger of dry-wet alternate condition of the rock mass for practical engineering stability, this study investigated the mechanical properties of dry-wet effect rule of sandstone by conducting repeated drying-wetting cycles under a triaxial mechanical experiment. The following conclusions were obtained:

1) The triaxial compressive strength and elastic modulus of sandstone affected the confining pressure and drying-wetting cycles significantly. This condition is positively correlated with the confining pressure and negatively correlated with drying-wetting cycles.

2) Drying-wetting cycles has varying degrees of influence on the shear parameters of sandstone. Cohesion with enhanced drying-wetting cycles effect decreases, whereas the internal friction angle changes. However, sandstone does not exhibit regularity and its variation width is small, indicating that the cohesion reaction to drying-wetting cycles effects is more sensitive than the angle of internal friction.

3) Drying-wetting cycles damage showed obvious features such as brittle and ductile sandstone transformation rule, where the number is less brittle mainly because of wet destruction. However, with the increase in the number of wet and dry cycles, ductile failure characteristics are obvious. Throughout this trial, drying-wetting cycles of 10-15 times for the mechanical properties of sandstone shift nodes.

This experiment investigated the effects of repeated drying-wetting cycles on the mechanical properties of sandstone under triaxial compression, thereby providing a theoretical reference to evaluate rock mass stability. However, in practical engineering, rock mass is subjected to external loads while also being subjected to alternating wet and dry conditions. Therefore, subsequent studies still require further solutions under certain load conditions that repeatedly undergo drying-wetting cycles on triaxial compression of rock mass mechanical properties.

Acknowledgements

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