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# Study on the Conventional Uniaxial Mechanical Properties and Micro-Mechanism of Sandstone under Dry–Wet Cycles

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**Abstract:** Dry–wet cycling has a significant impact on the mechanical properties of rocks, and a series of problems such as rock collapse can occur in rock masses under long-term dry–wet cycling. Based on this, some mechanical tests were carried out on sandstone under different dry–wet cycles to analyze the evolution law of its physical and mechanical parameters. The results show that the internal connection of the mineral becomes looser, the drying quality of the sample decreases, and the water absorption quality increases gradually under different dry–wet cycles. The peak strength of the sample decreases first and then increases with increasing dry–wet cycles. The change trend of the elastic modulus and deformation modulus with the increase in dry–wet cycles are similar to the peak strength, which is mainly related to the change in the connection between particles. Furthermore, the specimens showed axial tensile failure under uniaxial action. With the increase in dry–wet cycles, the tensile crack on the surface of the specimen increased, and the fracture of the specimen became looser. The specimen exhibited block spalling when the number of dry–wet cycles was eight times.

**Keywords:** sandstone; dry–wet cycles; uniaxial strength; deformation characteristics; failure characteristics



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## 1. Introduction

The development of underground projects is of great significance to national development. However, various environmental issues are often encountered during the process of underground project development. For instance, in certain geological and geotechnical projects, such as those in water-attached mining areas, the rock mass is influenced by the wet–dry cyclic effects due to changes in water levels [1]. The rocks undergo long-term "fatigue effects" under the influence of wet–dry cyclic conditions, which accelerate the degradation of the related mechanical properties of the rock mass, thereby affecting the stability and safety of the engineering projects [2,3]. Researchers have conducted a series of research studies on the fatigue characteristics of rocks under mechanical loading, gaining an understanding of the fatigue properties of rocks under loading conditions [4]. However, there has been relatively little research on the changes in the mechanical properties of rocks under wet–dry cyclic fatigue effects. Previous studies have already indicated that when rocks are exposed to water, complex physical, chemical, and mechanical changes occur, leading to alterations in the mechanical properties (such as strength), microstructure (such as porosity), and mineral composition (such as soluble components) of the rocks [5–7]. Therefore, it is necessary to study the mechanical properties of rocks after wet–dry cyclic effects in order to gain an in-depth understanding of the instability and failure mechanisms of underground rock engineering under the "fatigue effects" in a water environment.

Scholars have long conducted a series of studies on the effects of dry–wet cycles on the mechanical properties of rock. Li et al. [8] investigated the influence of cyclic wetting-drying weathering on the mechanical behavior of medium-grained sandstone and found that the water absorption of the rock monotonically increases with the increase in the dry–wet cycles. Moreover, the strength and deformation properties are found to decrease with increasing dry–wet cycles, and the decrease gradually diminishes as the number of dry–wet cycles becomes large. Liu et al. [9] investigated the stability of underground excavations under dry–wet cycles and found that the rock strength is affected by the dry–wet cycles and fissure angle, thereby yielding the strength expression. The sensitivity of the peak total energy and elastic strain energy of the rock samples to the fissure angle decreases as the number of dry–wet cycles increase, while the evolution characteristic gradually weakens with an increase in the number of dry–wet cycles. Huang et al. [10] conducted a series of dry–wet cycle tests to analyze the effects of dry–wet cycles and confining pressures on the mechanical properties of siltstone and found that the P-wave velocity decreases and the water content increases with increasing cycle times. Che et al. [11] studied the mechanical properties of sandstone during the acidic dry–wet cycle and found that as the number of cycles increases, the spectral area and porosity always increase, peak strain increases, and peak strength decreases. The functional relationship between the number of drying–wetting cycles and the damage magnitude is established by analyzing the quantitative relationship between porosity and rock damage. In summary, the deterioration of the physical and mechanical properties of rock after dry–wet cycling is usually due to physical or chemical action [12–15]. Zhou et al. [16] investigated the effect of dry–wet cycles on the physical and dynamic compressive properties of rocks, and some essential physical properties of sandstone specimens, including density, water absorption, porosity, P-wave velocity, and slake durability index (SDI), were measured after every 10 cycles (for a total of 50 cycles). The dynamic compressive test results showed that with increasing dry–wet cycles, the porosity and water absorption of rock increase, while the density, P-wave velocity, SDI, dynamic compressive strength, and elastic modulus decrease.

Relevant studies have shown that the deterioration of rock's physical and mechanical properties under dry and wet conditions is an accumulative process [17,18]. Underground engineering rock masses are prone to damage and failure, leading to geological hazards under the influence of dry–wet cycles. Previous research has mainly focused on the mechanical properties of rock samples after dry–wet cycles, with less consideration given to the underlying mechanisms of rock behavior during these cycles. In order to deepen our understanding of the damage process and mechanisms of rock's mechanical properties under dry–wet cycles, this study conducted uniaxial compression tests on sandstone under different dry–wet cycling conditions, and investigated the evolutionary characteristics of sandstone damage and fracturing after dry–wet cycles. Additionally, combining scanning electron microscope (SEM) tests, the microscopic structural evolution characteristics of sandstone under dry–wet cycles were analyzed, and the damage mechanisms of sandstone were explored.

### *1.1. Sample Processing*

The sandstone samples used in this study were taken from Sichuan. To ensure the homogeneity of the test samples, all test samples were taken from the same rock mass. According to ISRM, the core sample is made into a standard size of 100 mm × 50 mm. Acoustic detection was carried out on the samples before testing, and then samples with similar acoustic wave values were selected for testing, as shown in Figure 1. XRD analysis shows that the sandstone is mainly composed of quartz calcite and albite, as shown in Figure 2. To better study the mechanical properties of samples under the action of different numbers of dry–wet cycles, the sandstone samples were treated with different numbers of dry–wet cycles, and the specific flow chart is shown in Figure 3. The water absorption method of sandstone immersion is full immersion three-dimensional water absorption. The single soaking process is to put the sample into a sealed glass tank and soak it with water for 24 h. The temperature of the drying box was set at 90 °C, and the drying time was 24 h during the drying process. The samples were sealed and preserved after different numbers of drying and wetting cycles.

**Figure 1.** Samples with similar acoustic wave values.

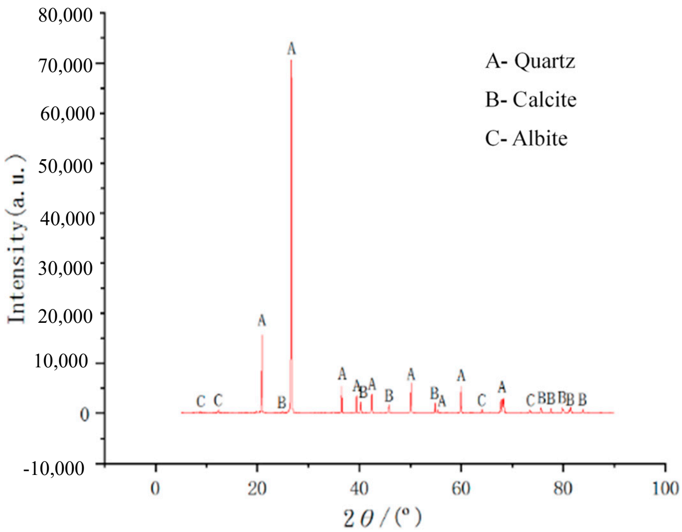


**Figure 2.** XRD test results.

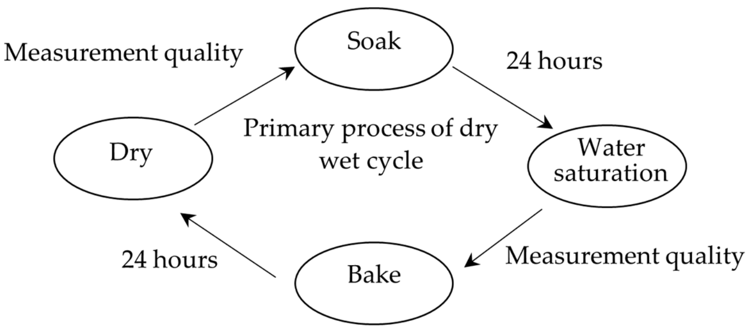


**Figure 3.** Dry–wet cycle process.

*1.2. Test Procedure*

The uniaxial mechanical properties of this paper were tested in the WAW-2000 electro-hydraulic servo pressure test system of Anhui University of Science and Technology, as shown in Figure 4a, where the maximum axial force can reach 2000 KN, the force measurement accuracy is 0.5% and the deformation measurement accuracy is 0.5%. The drying instrument used in the test is an XMA-2000 electric thermostatic drying oven, as shown in Figure 4b, in which the temperature control range is RT + 10~300.

(a) (b)

**Figure 4.** Test instruments, (**a**) WAW-2000 electro-hydraulic servo pressure testing system, (**b**) XMA-2000 Electrothermal constant temperature drying oven.

### 1.3. Experimental Plan

This experiment is used to study the uniaxial compression mechanical properties of sandstone samples under different drying and wetting cycles, and the specific test scheme is shown in Table 1. The stress control method was used in the loading process. The sample was preloaded to 500 N and then loaded at a loading rate of 1 KN/s until failure occurred.

**Table 1.** Test scheme.

| Sample Number | Number of Drying and Wetting Cycles/$n$ | Loading Method | Loading Rate |
|---|---|---|---|
| 1-1 | 1 | stress control | 1 KN/s |
| 2-1 | 8 | | |
| 3-1 | 16 | | |
| 4-1 | 24 | | |

## 2. Test Results and Analysis

### 2.1. Analysis of Microcosmic Characteristics of Samples after Drying and Wetting Cycles

To better study the microstructure changes of samples with different cycles, samples with 0, 8, 16, and 24 cycles were scanned by SEM, as shown in Figure 5. As can be seen from the figure, after the sandstone sample undergoes a dry–wet cycle, due to the erosive effect of water, the cementing material inside the sandstone sample undergoes hydrolysis, and the sandstone sample evolves from its original compact state to a dispersed state, with particles accumulating. As the number of wetting and drying cycles increases, the internal pores and voids in the sandstone sample gradually become larger, and water–rock erosion continues to occur, resulting in the development and expansion of particle gaps within the sample, and the gradual increase in microcracks. From microscopic scanning, it can be seen that the internal particles of sandstone samples are angular and the ends of the particles are relatively rough. After a certain number of dry–wet cycles, the interior of the sample gradually undergoes mudification, with the edges and corners of the particles breaking down and showing a disordered arrangement. The relationship between the particles becomes more chaotic, with a significant increase in the number and size of pores and a buildup of debris. In general, the changes in sandstone particles follow three stages of damage development with dry–wet cycles, namely, a neat and dense state, a porous and floccular state, and a cracked and turbulent state.

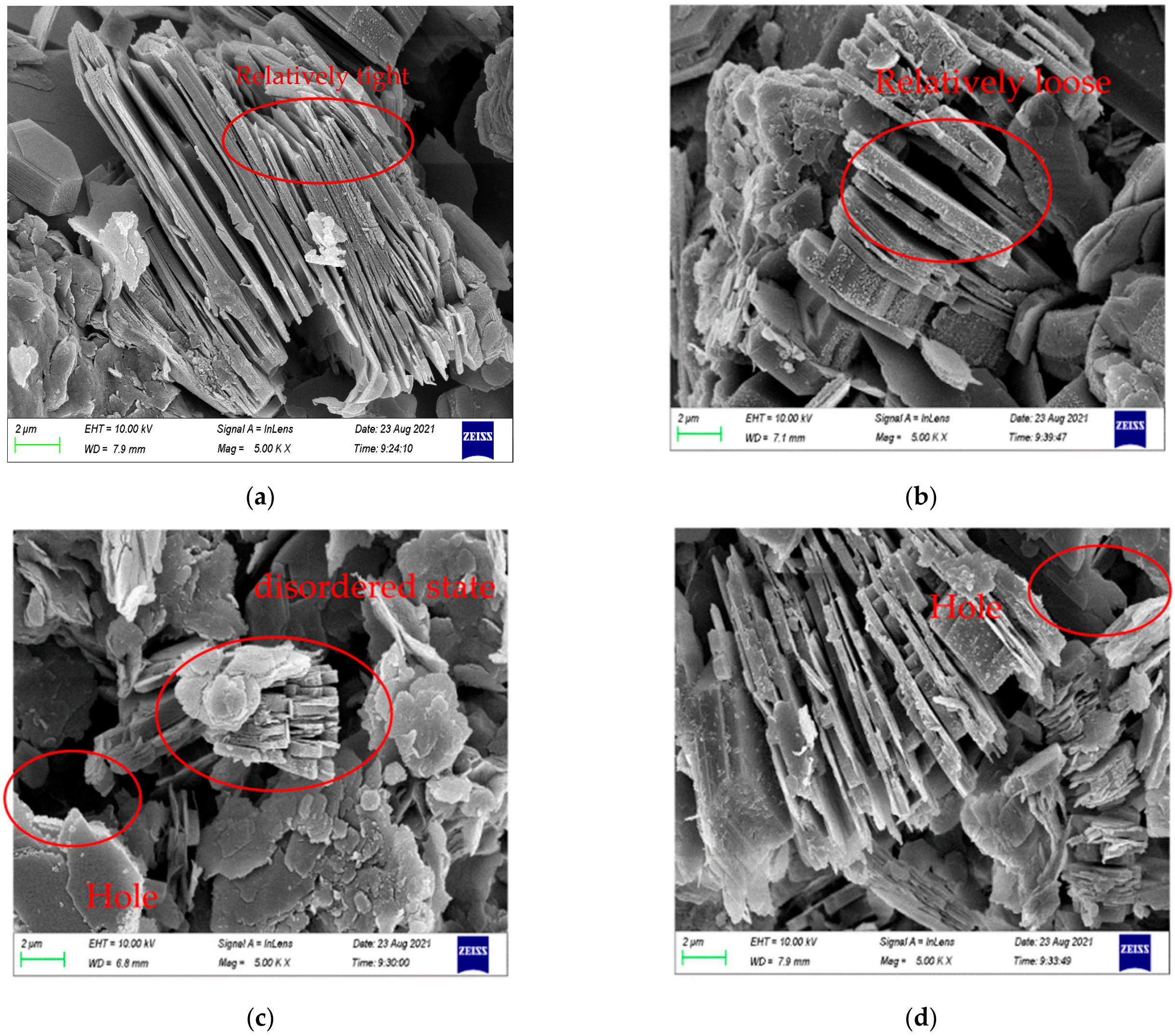


**Figure 5.** Microstructure diagram. (**a**) $n = 0$ (×5 k). (**b**) $n = 8$ (×5 k). (**c**) $n = 16$ (×5 k). (**d**) $n = 24$ (×5 k).

Furthermore, from the microscopic image in Figure 5a, it can be seen that the internal particles of the sample without the effect of drying and wetting cycles are well-defined and can be summarized as being orderly and dense. In this state, the internal particle state of the sandstone sample is characterized by uniform particle size, regular particle shape, orderly arrangement, and homogeneous particle density. The particle edges and shapes have not been eroded by water, and the particles are closely packed. Most of the sandstone particles appear as single grains, mainly in the form of flattened and granular shapes. Between the individual mitochondria, the pores exist in a state of fine micro-pores, scattered and individual, with little to no through-penetration.

From the microscopic images in Figure 5b,c, it can be seen that the internal structure of the sample after the dry–wet cycle presents a porous floccular shape. At this stage, there were significant changes in the sandstone samples compared with the samples that had not undergone dry–wet cycles. The number and size of pores and voids in the sandstone samples increased significantly, and after 16 cycles of dry–wet cycles, the particles inside the samples accumulated, and the morphology of the particles inside the samples transformed into flaky shapes and muddy appearance. The grains of sandstone in the flat state show a slight expansion, and the edges of the grains show a tendency to expand outward, resulting in a curling state. A small amount of voids in the sandstone sample have appeared to be connected, and the initial cracks have expanded, with the internal particles exhibiting a porous and flocculent state.

As shown in Figure 5d, after 24 cycles of drying and wetting, the microstructure of the sample changes into a state of cracked turbulence. The flaky particles in the sandstone have experienced swelling and shedding, and the pores and voids have developed and penetrated to form larger voids after being eroded by water, resulting in multiple secondary cracks in the particles. The morphology of the particles mostly appeared to be curling and falling off, and the particles further accumulated.

### *2.2. Change in the Physical Properties of the Sample*

The mass of sandstone samples in different stages in 2, 4, 8, 12, 16, 20, and 24 cycles of drying and wetting after water loss and water absorption of samples was obtained, as shown in Figure 6. It can be seen from the figure that with the increase in the number of cycles, the quality of the sample decreases gradually after repeated drying and increases gradually after water absorption. It is considered that some water-soluble substances in the rock are corroded under the action of water, and the quality gradually decreases after drying. The loss of internal material provides a larger space for water, so the mass gradually increases after absorption.

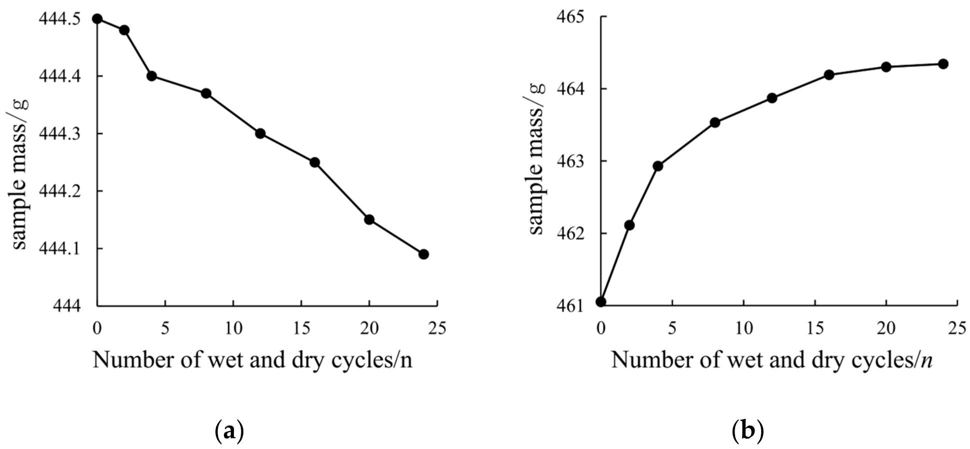


**Figure 6.** Quality change of dry wet cyclic sandstone. (**a**) Mass change after water loss. (**b**) Mass change after water absorption.

Furthermore, the mass water absorption rate is introduced to better study the quality changes of sandstone samples under different cycling effects, as shown in Equation (1). The water absorption of samples at different cycle stages was studied, and the results are shown in Figure 7.

$$\omega_{\mathrm{m}} = \frac{m_0 - m_{\mathrm{s}}}{m_{\mathrm{s}}} \times 100\% \tag{1}$$

where $\omega_{\mathrm{m}}$ is the water absorption rate of the sample, %. $m_{\mathrm{s}}$ is the dry mass of the sample, g. $m_0$ is the water absorption saturation mass, g.

It can be seen from Figure 8 that the water absorption rate of the sample increases gradually under the drying-wetting cycle, which is mainly caused by the fact that some substances in the sample dissolve in water during the drying-wet cycle and more voids are formed inside the rock.

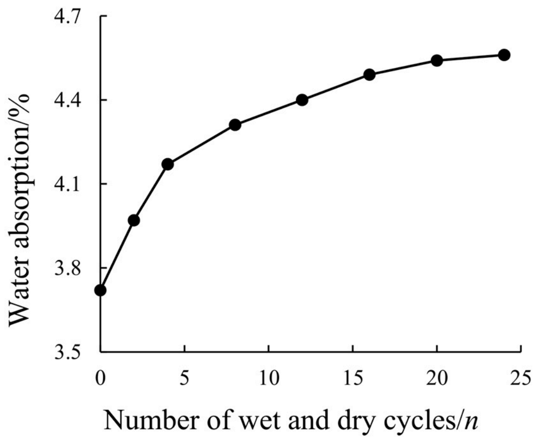


**Figure 7.** Water absorption change of sandstone.

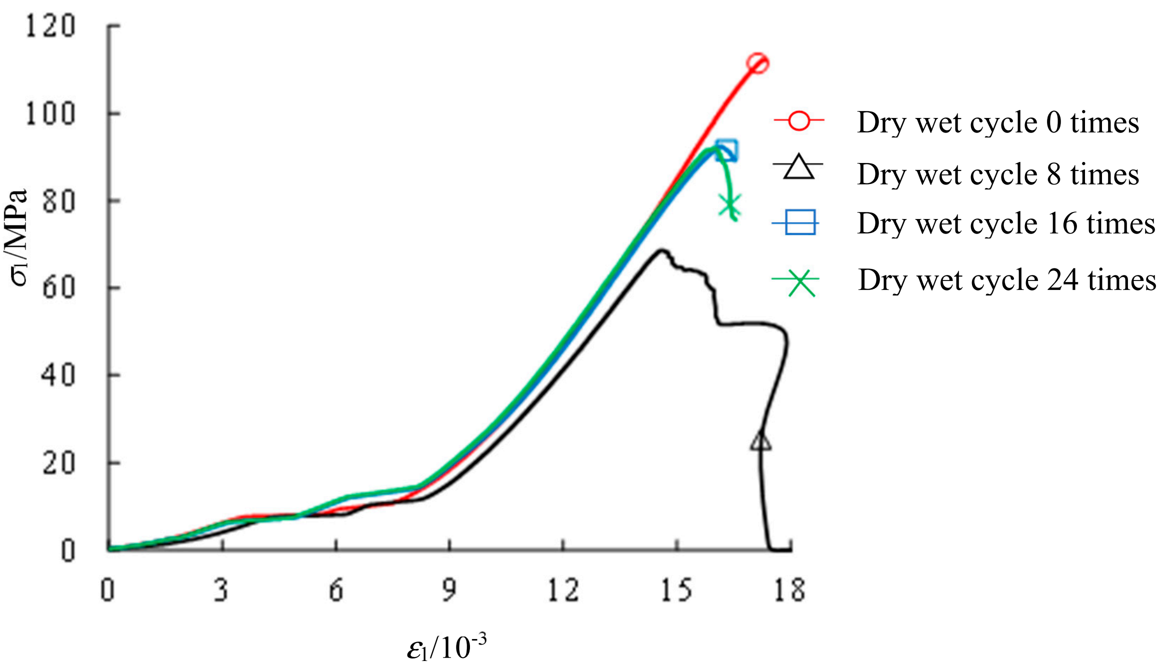


**Figure 8.** Uniaxial stress–strain curve.

### *2.3. The Stress–Strain Curves of Samples with Different Wetting and Drying Cycles*

The uniaxial stress-axial strain curves of sandstone samples after different drying and wetting cycles are studied, as shown in Figure 8. As seen from the figure, the stress–strain curves of samples under different drying and wetting cycles can be divided into four stages: ① In the pore fissure compaction stage, there are many pores and fissures in the samples. When the load is applied to the sample, the pores and fissures in the sample are gradually closed under compression. ② In the elastic deformation stage, there is a linear correlation between stress and axial strain, and the curve is approximately a straight line at this stage. ③ In the nonlinear deformation stage, the specimen gradually begins to yield, and the rate of stress increase decreases until the strength of the specimen reaches the peak. ④ For the post-peak failure strength, when the sample reaches the maximum bearing capacity, the internal cracks expand rapidly, macroscopic cracks appear on the rock surface, the sample begins to fail, and the stress–strain curve begins to show a sagging phenomenon.

### *2.4. Strength Characteristics*

The strength parameters of the sample are obtained according to the stress axial strain curves of the samples with different drying and wetting cycles. The relationship curve between the peak strength of the sample and the number of drying and wetting cycles is shown in Figure 9. As seen from the figure, the peak strength of the sample decreases first and then increases with increasing dry–wet cycles. The strength of the sample after the drying and wetting cycle is lower than that of the sample without the drying and wetting cycle. The eighth cycle is the inflection point of the peak strength of the sample, and the peak strength of the sample is the lowest at the eighth cycle.

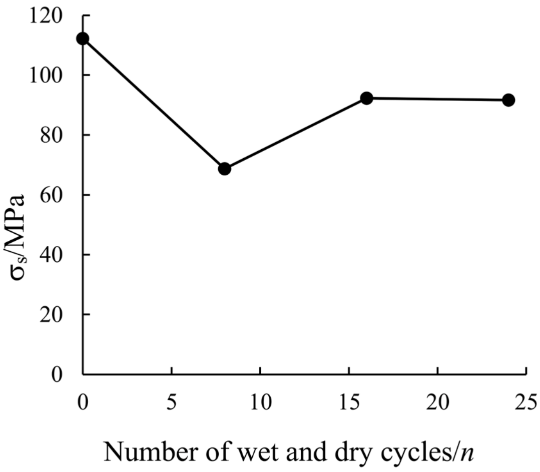


**Figure 9.** The peak intensity varies with the number of cycles.

Sandstone samples are mostly layered minerals in this test, and the gap between layered structures gradually increases under the action of dry–wet cycles, resulting in a decrease in strength. The failure occurs here first because the layered minerals are relatively weak minerals. When circulating eight times, due to the continuous expansion and contraction of layered minerals in contact with water, the interlayer spacing increases, and the strength of sandstone samples decreases. However, when the number of cycles increases (16 and 24 times), the dissolution and precipitation of water-soluble minerals lead to an increase in sediment on the surface of layered minerals, and the strength increases to a certain extent, which can also be observed by microscopic observation.

### *2.5. Deformation Feature*

The deformation parameters of sandstone samples were obtained by a stress–strain diagram. The slope of the approximate straight-line segment of the stress–strain curve was calculated as the elastic modulus of the sample, as shown in Figure 10. It can be seen from the figure that the change in the elastic modulus of samples with different cycles of drying and wetting is similar to the change in peak strength, namely, the elastic modulus decreases first and then increases with increasing cycles of drying and wetting. The cycle number increases, leading to the internal layer structure connection of the samples being looser; consequently, the specimen deformation becomes simple. Moreover, grain deposition appeared on the layered structure under the scouring action of long-term wetting and drying cycles, which increased the friction between the layered structures to a certain extent and inhibited the deformation of the samples, which was manifested as an increase in the elastic modulus of the samples. The deformation modulus of the sample changes with the number of cycles, as shown in Figure 11. The deformation modulus is the slope of the line between half of the peak strength of the sample and the origin. By comparing Figure 10, it can be found that the deformation modulus and elastic modulus of the sample change similarly with the increase in the cycle numbers. The variation in the peak strain of the sample with the cycle number was further studied, as shown in Figure 12. It can be seen from the figure that the peak strain of the sample changed slightly with increasing cycle number, indicating that the ductility characteristics of the rock did not increase after the drying and wetting cycles.

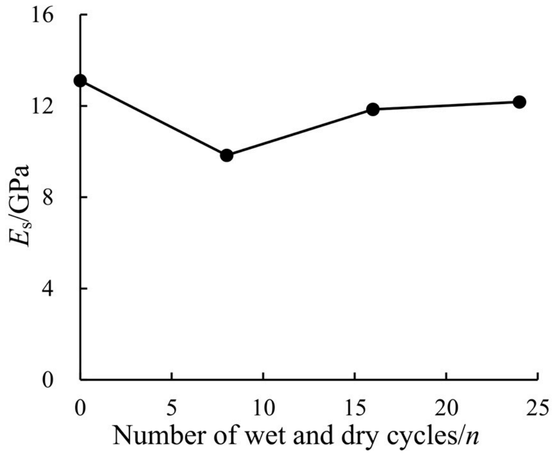


**Figure 10.** The elastic modulus varies with the number of cycles.

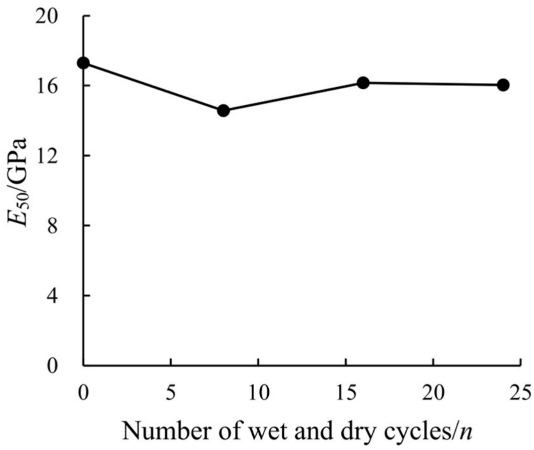


**Figure 11.** The deformation modulus varies with the number of cycles.

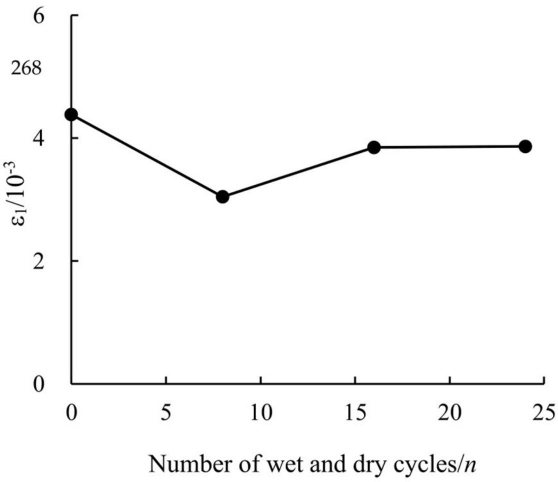


**Figure 12.** The peak strain of the specimen varies with the number of cycles.

### *2.6. Analysis of the Failure Mode*

The failure process of rock under loading can be expressed by the final failure mode of rock. The study of failure modes under different wetting and drying cycles can better explain the deformation characteristics in the process of deformation failure. The final failure mode diagram of samples under different numbers of drying and wetting cycles under uniaxial action is shown in Figure 13.

(**a**) (**b**) (**c**) (**d**)

**Figure 13.** Final fracture mode diagram of sandstone after dry wet cycle, (**a**) $n = 0$; (**b**) $n = 8$; (**c**) $n = 16$; (**d**) $n = 24$.

It can be seen from the figure that the final fracture modes of samples under different numbers of drying wetting cycles show different phenomena, and the drying wetting cycles have a great influence on the fracture modes of samples. The specimens all exhibit typical axial tensile splitting failure under uniaxial action, and there are more tensile cracks on the surface. With the increase in the cycle numbers, the tensile cracks on the surface of the sample gradually increased, and the samples with more cycles broke more loosely. For the samples with fewer cycles (8), large pieces of spalling appeared. This is because the internal structure of the sample is loosely connected after the drying and wetting cycle, and the internal crack propagation is simpler and the crack development is more abundant under the pressure. The main reason for block spalling is that there is a certain weak structural plane in the sample, which is damaged first under the action of load, leading directly to block spalling.

## 3. Discussion

The changes in rocks under the influence of wet–dry cycles are a complex process. Prolonged exposure to wet–dry cycles can have different effects on the structure of the rock mass, altering the rock structure and the state of particle cementation, thereby impacting the rock's physical and mechanical properties. Naturally, rocks are composed of different particles, with cementitious materials binding them together. Under the influence of wet–dry cycles, the cementitious materials between the particles undergo changes in their state due to the impact of water. They become more loosely bound, resulting in a loose connection between particles. After a certain number of wet–dry cycles, the cementitious materials between the rock particles become more loosely bound due to the impact of water flow, leading to changes in the mechanical properties of the rock. Additionally, in multiple wet–dry cycles, the cementitious particles within the rock experience repeated impacts and sedimentation. Certain particles that are less soluble in water become cemented together through this process, strengthening the rock's mechanical properties. This process is illustrated in Figure 14.

After treating the samples with different numbers of wet–dry cycles, the strength of the samples decreases after eight cycles. However, as the number of wet–dry cycles increases, the strength of the specimens shows an increasing trend. Overall, the strength of the samples decreases under the influence of wet–dry cycles, particularly when the number of cycles is relatively low, leading to significant degradation in strength. Therefore, considering the impact of wet–dry cycles is beneficial for the safety of engineering projects. From the failure mode of the samples, it can be observed that the damage to the rock samples is more pronounced after experiencing wet–dry cycles. Hence, it is necessary to choose appropriate construction methods in practical engineering.

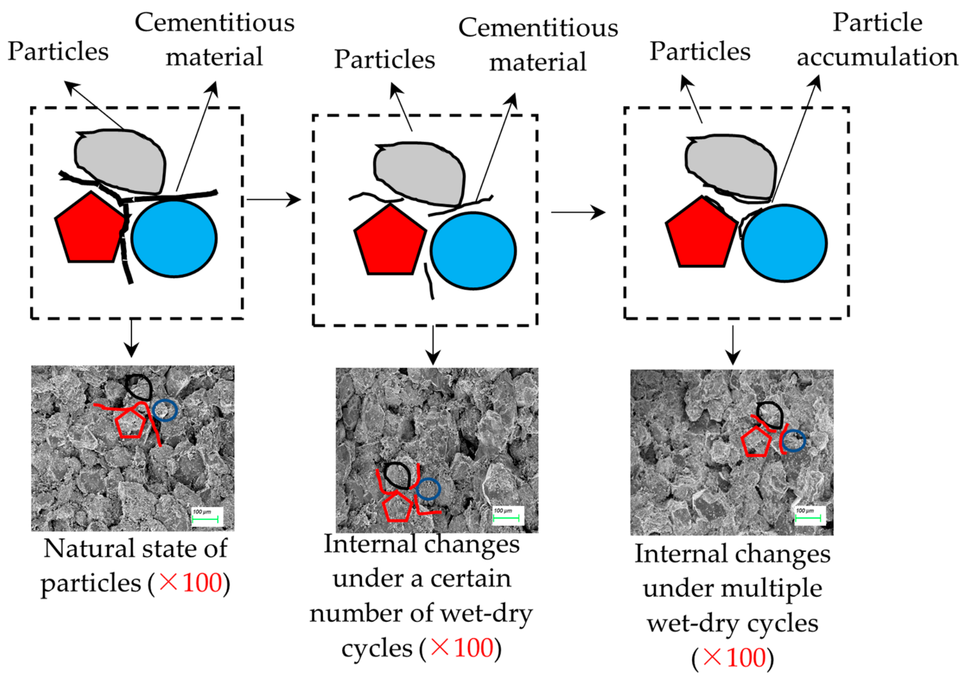


**Figure 14.** Damage process of rocks under the action of different dry–wet cycle numbers.

This study only considers the uniaxial mechanical properties and fracture characteristics of rocks under the influence of dry–wet cycling, without taking into account the triaxial mechanical properties of rocks under dry–wet cycling and the influence of actual engineering loads. Laboratory experiments have shown that the strength of this type of sandstone decreases first and then increases under a certain number of dry–wet cycles. Some researchers have found that the strength gradually deteriorates with an increasing number of dry–wet cycles, mainly due to the bonding between particles inside the rock. Therefore, there are differences in test results among different types of rocks, and the results of different rocks also exhibit variability. In the future, we will further study the changes in the mechanical characteristics of different rocks under the influence of dry–wet cycling. In addition, laboratory experiments are often conducted on intact rocks, while in actual engineering situations, rocks are often not completely intact. Factors such as temperature inconsistency and liquid environment should be considered in practical field applications. However, experimental results can provide references for actual engineering and contribute to the treatment of rock engineering under water–rock interactions. At the same time, this study provides reference value for future relevant research.

## 4. Conclusions and Suggestions

### 4.1. Conclusions

In this paper, uniaxial mechanical tests of sandstone samples after different numbers of dry–wet cycles were carried out to study the evolution law of the physical and mechanical characteristics of sandstone with drying and wetting cycling, and the mechanism of drying and wetting cycling on the physical and mechanical properties of sandstone was revealed. The following conclusions can be obtained:

(1) The intergranular connection of sandstone is a stratified structure, and the intergranular connection between the underlayer structures gradually becomes loose under the action of drying and wetting circulation. When the circulation reaches a certain extent, certain particle deposition occurs between the stratified structures inside the sample. After the drying and wetting cycle, the drying quality of the sample gradually decreases, and the water absorption quality gradually increases. The internal components of sandstone appear to dissolve under the action of water, and certain pores are formed inside.

(2) The stress–strain curves of the samples show four stages. The peak strength decreases first and then increases with the number of cycles. The change in the elastic modulus and deformation modulus is similar to the change in the peak strength with the number of cycles. This is related to the peak strain variation in the connection between the layered structures in the sandstone, and the drying and wetting cycle does not increase the ductility of the rock.
(3) The samples with different numbers of drying and wetting cycles exhibit typical axial tensile failure under uniaxial action. The tensile cracks on the surface of the samples show an increasing trend with increasing drying and wetting cycles. The sandstone surface exhibits block spalling when the number of drying and wetting cycles is less (8 times).

### *4.2. Suggestions*

(1) This article only considers the mechanical characteristics under uniaxial loading, while rocks in nature are often in a certain confining pressure environment. Therefore, experiments on rock mechanical properties under different confining pressures and dry–wet cycling can be conducted to obtain more reliable patterns.
(2) The liquid used for dry–wet cycling in this study is water, while the water encountered in actual engineering often contains acidity and alkalinity. Therefore, further research and improvement are needed to obtain research parameters that are more in line with actual conditions.

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**Data Availability Statement:** All data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors have no relevant financial or non-financial interest to disclose.

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