

Review Article

Deterioration of Physical and Mechanical Properties of Rocks by Cyclic Drying and Wetting

Zhizhen Zhang ^{1,2}, Yixin Niu ¹, Xiaoji Shang ¹, Peng Ye,¹ Rui Zhou,² and Feng Gao¹

¹State Key Laboratory for Geomechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China

²State Key Laboratory of Coal Mine Safety Technology, China Coal Technology & Engineering Group Shenyang Research Institute, Shenyang Demonstration Zone, 113122, China

Correspondence should be addressed to Zhizhen Zhang; zzzhang@cumt.edu.cn and Xiaoji Shang; shangxj2016@cumt.edu.cn

Received 25 February 2021; Accepted 3 May 2021; Published 28 May 2021

Academic Editor: Guanglei Zhang

Copyright © 2021 Zhizhen Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Both surface and underground rocks in nature often undergo repeated drying and wetting. The dry-wet cycle is a weathering effect that includes physical and chemical processes, which has varying degrees of degradation effects on the physical and mechanical properties of rocks. This paper analyzes and discusses this kind of rock degradation based on the existing literature data. First, the deterioration degree of various physical and mechanical properties (including density, P-wave velocity, porosity, static and dynamic compressive/tensile strength, and fracture toughness) is summarized as the number of dry-wet cycles increases. Secondly, the possible degradation mechanism of the dry-wet cycle is explained in terms of clay mineral swelling, solute migration, and microcrack evolution. Then, the damage constitutive model of the rock after cyclic dry-wet treatment is introduced. Finally, the issues that need to be studied in the future are put forward.

1. Introduction

Rock is the most common geological material in projects such as oil and gas development, coal mining, and hydroelectric power generation. In engineering practice, rocks are commonly affected by dry and wet cycles, for example, the surrounding rock of reservoir bank slope engineering by the influence of daily and seasonal changes of water level (see Figure 1) [1–4]; the thin granite veneer cladding panels installed on the exterior of buildings subjected to environmental weathering [5]; tunnel excavation under the influence of groundwater level fluctuation [6]; the slope stability of open-pit coal mine affected by rainfall (see Figure 2) [7]; the tailings pond by the impact of abandoned tailings discharge and pumping [8]; the swelling rock of the base and slope of the water conveyance channel (see Figure 3) [9–11]; the coastal rock masses affected by tides [12–15]; the stone monuments, sculptures, and historical sites affected by acid rain erosion [16, 17]; the subgrade and surrounding rock of railway tunnel [18]; the retaining dam of an under-

ground reservoir [19]. After the dry-wet cycle, the physical and mechanical properties of the rock will change to varying degrees, and the changes are very important to the design, construction, and operation of rock projects.

In recent years, with the continuous progress of research on water-rock interactions, the effects of dry-wet cycles on the degradation of rock properties have gradually attracted wide attention from scholars. The dry-wet cycle test was first used as an experimental method to study the durability of rocks after weathering, and it was often used as a comparison with freeze-thaw cycles and cold-heat cycles [18, 20–26]. Ito et al. [27] carried out the freeze-thaw cycle and dry-wet cycle test of rocks in cold regions and found that the influence of the dry-wet cycle on the rock sample is almost equal to or even more serious than the freeze-thaw cycle. The experiment of Loubser [28] found that water saturation does not seem to be the main factor affecting the degree of rock deterioration, and the influence of the number of wet and dry cycles is more significant. At present, most experiments have found that the rock samples deteriorate



FIGURE 1: The famous scenic spot at the Three Gorges Reservoir, Baidicheng, whose reinforcement slope is designed to resist periodic reservoir fluctuations [1].



(a) Local landslide

(b) Overall collapse

FIGURE 2: Landslides and collapses caused by rainfall [7].



FIGURE 3: The bedrock of Saranbe River, experiencing seasonal cycles of dry and wet [9].

significantly after the cyclic dry-wet treatment. However, there are still experiments found that the discrete difference of the dry-wet cycle test samples masks the degradation effect on the rock samples [20].

The dry-wet cycle itself is a weathering mechanism, and the properties of weathered substances are affected by the way of wetting [29]. In response to this problem, different scholars have adopted different cyclic dry-wet treatment methods (see Table 1). The cyclic dry-wet treatment methods are roughly divided into three types: the real wet-dry cycle of natural soaking and room temperature drying, the accelerated dry-wet cycle of vacuum pressure saturation and high temperature drying, and the mixed cycle treatment of the two (as seen in Figure 4). In the drying process, the rock deterioration is the greatest when the drying temperature is 60°C, that is, the porosity increases rapidly and the water absorption is the most [30].

Table 2 details the changes in the physical and mechanical properties of the rock samples with different lithologies in different tests after a certain number of dry and wet cycles. It was found that the physical and mechanical properties of the rock samples were degraded to varying degrees in most of the tests, but even the same type of rock differed significantly in different tests due to its different composition. In Chen et al.'s [6] test on altered granite, the reduction in internal friction angle reached an astonishing 93.76%, while Hale et al. [20] considered that the dry-wet cycle had no obvious deterioration effect on the rock sample when compared with the freeze-thaw cycle test. From Liu et al. [31] and Zhao et al.'s [32] separate experiments on sandstones with different clay content, it can be seen that the level of clay content is an important factor in the degree of rock degradation caused by the dry-wet cycle.

From the above, it is necessary to summarize the influence of dry and wet cycles on the physical and mechanical properties of rocks. In this article, we mainly reviewed the rock degradation after cyclic dry-wet treatment from three aspects, namely, quantitative characterization of degradation degree, degradation mechanism, and degradation constitutive model.

2. Rock Deterioration Degree after Dry-Wet Cycle

Due to the huge differences in the mineral composition of different types of rock samples, their physical and mechanical properties are very different, resulting in different sensitivity of rocks to water. Therefore, the effects of wet and dry cycles on rock degradation are different. This paper selected published test results from different researchers and normalizes them to make them comparable. The degradation degree of a certain physical and mechanical parameter is characterized by its relative change, that is, the ratio of the difference between the parameter value of the rock sample after the dry-wet cycle and the initial value to the initial value.

$$R_n = \frac{V_n - V_0}{V_0} \times 100\%, \quad (1)$$

where R_n is the degradation degree, V_n is the parameter value of the rock sample after the dry-wet cycle, and V_0 is the initial value.

2.1. Physical Properties. The physical properties of rock mainly include density, elastic wave velocity, porosity, water absorption, magnetic susceptibility, resistivity, thermal conductivity, radioactivity, and durability, which are the basis for the formation of various geophysical fields. The infiltration of water on the rock causes the salt inside the rock to dissolve, and the water reacts with the rock minerals chemically, which changes the internal composition and microstructure of the rock, which in turn leads to the deterioration of its physical properties. Take Zhou et al.'s test results as a representative [33], during the dry-wet cycle; this infiltration occurs repeatedly, and various physical properties of the rock change to varying degrees (as shown in Figure 5). It can be

TABLE 1: Different cyclic dry-wet treatment methods.

Rock type	Reference	Sample size	Wetting-drying cycle method	
			Wetting	Drying
Mudstone	Y. Zhao et al. [39]	Cylinder 25 * 50 mm	Vacuum-saturated 24 h	Oven dried at 60°C for 24 h
Red-Bed sandstone	Z. Zhang et al. [36]	Cylinder 50 * 100 mm	Vacuum-saturated 4 h and pure water saturated at room temperature for 44 h	Oven dried at 45°C for 20 h and drying in vacuum pump for 4 h
Sandstone	P. Yuan et al. [30]	Cylinder 50 * 25 mm	Pure water saturated for 24 h	Oven dried at 60°C for 24 h
Chlorite	X. Yang et al. [7]	Cylinder 50 * 100 mm	1/4 L, 1/2 L, 3/4 L of sample L each for 2 h and 1 L for 48 h	Room temperature dried for 7 d
Sandstone	K. Xie et al. [1]	Cylinder 50 * 100 mm	Vacuum-saturated 4 h and pure water saturated for 44 h	Oven dried at 50°C for 24 h and room temperature vacuum-dried 4 h
Altered rock	Z. Qin et al. [8]	Cylinder 50 * 100 mm	Water saturated for 24 h	Oven dried at 105°C for 12 h
Argillaceous limestone	B. Meng et al. [35]	Cylinder 50 * 100 mm	Vacuum-saturated 3 d	Room temperature dried for 3 d
Red sandstone	G. Khanlari et al. [22]	Cylinder 50 * 100 mm	Water saturated for 24 h	Oven dried at 110°C for 24 h

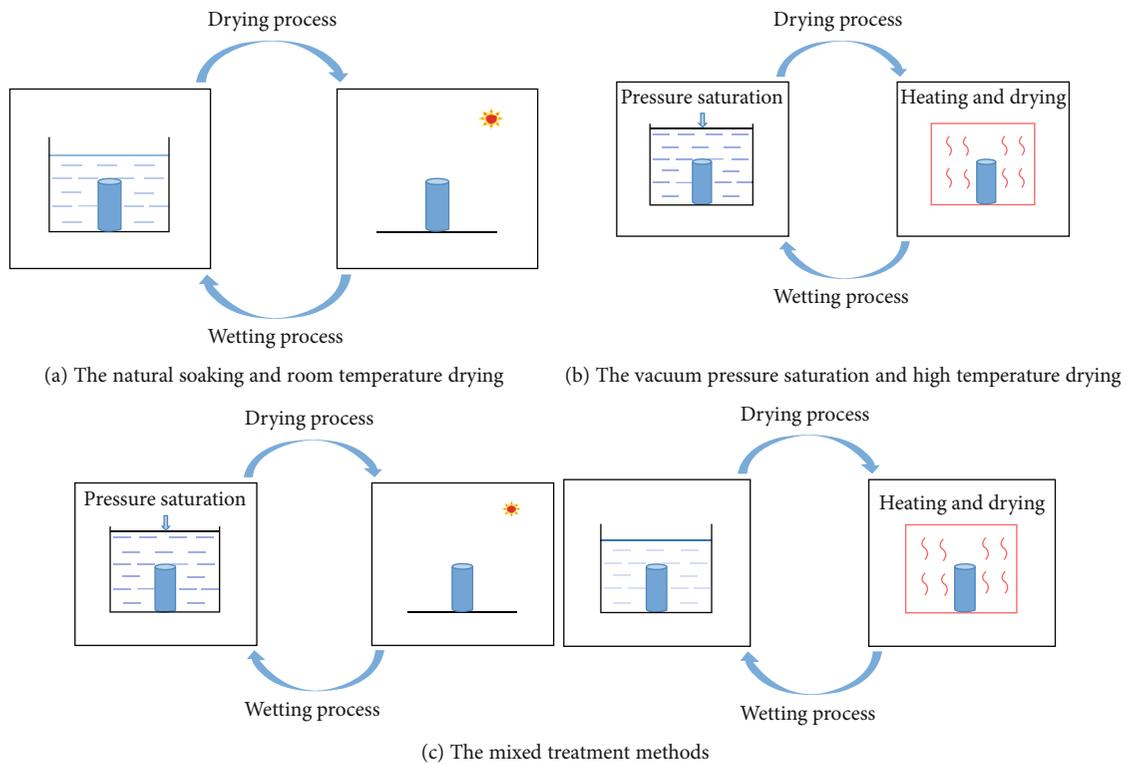


FIGURE 4: Three types of cyclic dry and wet treatment methods.

seen that with the increase in the number of dry and wet cycles, the dry weight, P-wave velocity, and slake durability index of the rock sample gradually decrease, while the porosity and water absorption gradually increase. It is worth noting that the decrease in dry weight and slake durability index is relatively small. Since the ability of rock materials to hold water depends to a large extent on their porosity, the water absorption and porosity of the rock sample will change simultaneously, which has a good linear relationship [34]. From the perspective of the change trend, the deterioration rate is faster before the 20th-30th cycle and then tends to

be stable. As the number of cycles increases, the damage effect caused by the water-rock interaction on the rock is reduced. The relationship between these physical parameters and the number of dry-wet cycles can usually be described by an exponential equation [34, 35].

Among the various physical properties of rocks, the P-wave velocity is affected by the characteristics of the internal pores and water content of the rock, and its monitoring methods are relatively simple and widely used. In addition, it is also related to mechanical parameters such as elastic modulus and strength, so it is a very important petrophysical

TABLE 2: Deterioration of different rocks after cyclic dry-wet treatment.

Rock type	Reference	Max n	Max variation			
			Physical properties		Mechanical properties	
Sandstone	Z. Zhou et al. [33]	50	ρ	-5.69%		
			W_a	+16.91%		
			P	+12.48%		—
			v_p	-24.64%		
			SDI	-3.07%		
Sandstone joint	J. Fang et al. [43]	20	S_p	-8.98%		
			S_v	-8.62%	JRC	-6.47%
			S_z	-8.75%	JCS	-44.21%
Red-sandstone	B. Du et al. [37]	20	S_{dr}	-4.96%	φ	-8.93%
			ρ	-3.62%	UCS	-18.28%
			v_p	-24.93%		
Shaly sandstone	X. Liu et al. [31]	20	—	—	UCS	-68.69%
					E	-70.02%
Low clay sandstone	Z. Zhao et al. [32]	15	—	—	TS	-5%
					E	-14.17%
					K	-15%
Mudstone	M. Hu et al. [90]	15	Weight loss	-60.7%	G	-15.22%
					φ	-19.31%
					c	-55.31%
					UCS	-50.22%
					E	-63.84%
Altered granite	X. Chen et al. [6]	60	P	+33.86%	φ	-93.76%
					c	-53.90%
			v_p	-8.33%		
Black ignimbrites	A. Özbek [21]	50	ρ	-6.1%	UCS	-16.08%
			P	+13.99%		
			W_a	+12.18%		

n is the number of dry-wet cycles, ρ is the density, W_a is the water content, P is the porosity, v_p is the P-wave velocity, S_p is the largest bulge on the joint surface, S_v is the largest valley on the joint surface, S_z is the largest drop on the joint surface, and S_{dr} is the expansion area ratio of the joint surface (indicating the complexity of the joint surface); JRC is the roughness coefficient of the joint, JCS is the compressive strength of the joint surface, SDI is the slake durability index, φ is the internal friction angle, c is the cohesive force, UCS is the uniaxial compressive strength, TS is the tensile strength, E is the elastic modulus, G is the shear modulus, and K is the bulk modulus.

parameter. In laboratory tests, P-wave velocity is often used in the selection of rock samples to reduce the dispersion of rock samples as much as possible [31]. A large number of test results show that with the increase of the number of dry-wet cycles, the P-wave velocity of rock samples decreases to varying degrees. Figure 6 shows the changes of P-wave velocity in different experiments based on previous literature, and Figure 7 shows the degradation degree of P-wave velocity. It can be seen that even if it is all sandstone, the P-wave velocity variation law is very different due to the different producing areas and the subtle differences in the test methods. The difference between different types of rocks is even greater. For example, for ignimbrite rocks with different colors [21], although the initial wave velocity is different, the degradation degree of the P-wave velocity is within 10% as the number of

wet and dry cycles increases. However, for the sandstone samples in different tests, not only the initial wave velocity is greater than that of the ignimbrite rock, but the degradation degree can reach nearly 20% [34] or even more than 20% [36, 37] after a small number of wet and dry cycles. In addition, the water temperature will also accelerate the deterioration of the P-wave velocity [30]. To put it simply, the velocity of P-wave propagation in the air is much smaller than that in the solid, and it is equivalent to increasing the probability of P-wave propagation in the air due to the increasing rock porosity after dry-wet cycles, so the P-wave velocity is decreasing [38]. And if these pores are filled with water, the P-wave velocity in the water is much greater than that in the air, and the water completely replaces the air in the pores and microcracks in the saturated state, so the

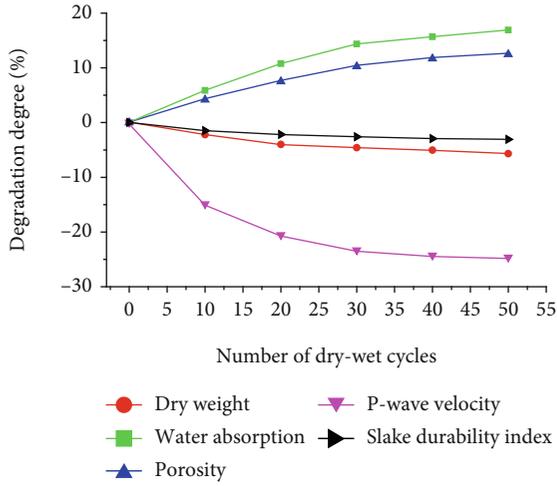


FIGURE 5: Degradation degree of physical properties of sandstone after dry-wet cycles [33].

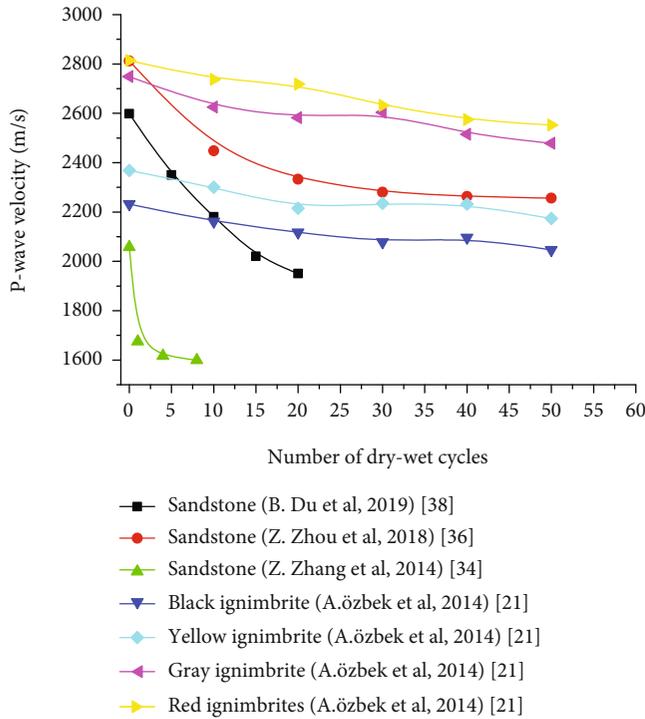


FIGURE 6: Variation of P-wave velocity after different dry-wet cycles.

deterioration rate of the sample in the dry state is much greater than that in the saturated state [34, 38]. But in general, as the number of wet and dry cycles increases, the P-wave velocity across the sample would decrease under both dry and saturated conditions. This can be explained by increased porosity and density loss [38].

Rock porosity and pore size distribution are the macroscopic manifestations of the initiation, development, and expansion of internal microscopic cracks, which can be measured by nuclear magnetic resonance (NMR), mercury intrusion porosimetry (MIP), scanning electron microscopy

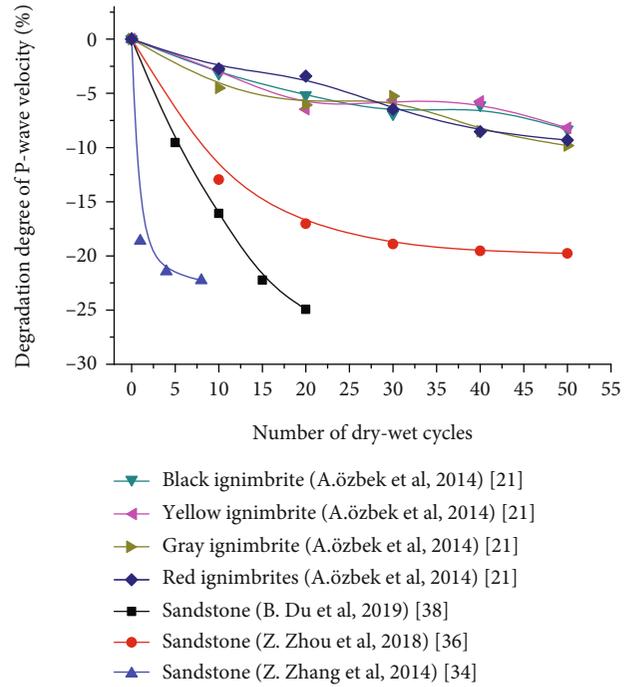


FIGURE 7: Degradation degree of P-wave velocity after different dry-wet cycles.

(SEM) and other test methods. Figure 8 shows the porosity of the rock samples in different tests with the number of dry-wet cycles. It is found that the porosity of the rock shows a differential increase with the increase of the number of dry-wet cycles, which roughly obeys the linear relationship with different slopes [39]. Regardless of whether it is ignimbrite rock or sandstone, the porosity increases by about 20% after 50 dry-wet cycles, while it can exceed 40%, up to 44.4% for mudstone samples drilled from Simianshan [39]. The increase in porosity will cause the deterioration of the mechanical properties such as uniaxial compressive strength (UCS) and elastic modulus of the rock sample. The relationship between UCS and porosity can be quantitatively described by an exponential function [39]. The dry-wet cycle not only increases the porosity of the rock but also changes its pore structure, causing the pores to change from small pores (0.01~0.1 μm) to larger pores (0.1~1.0 μm) [35]. The pore size distribution is concentrated in two intervals and has an optimal value. As the number of cycles increased, the optimal pore size increases, and the corresponding component decreases. This variation may be related to the periodic water-rock interaction [39].

2.2. Mechanical Properties. The influence of dry-wet cycles on the physical properties of rocks eventually leads to the deterioration of mechanical properties, which is manifested in the static compressive and tensile strength, dynamic compressive and tensile strength, fracture toughness, elastic modulus, friction angle, cohesion, etc. decrease to varying degrees, which can usually be described by an exponential function [35].

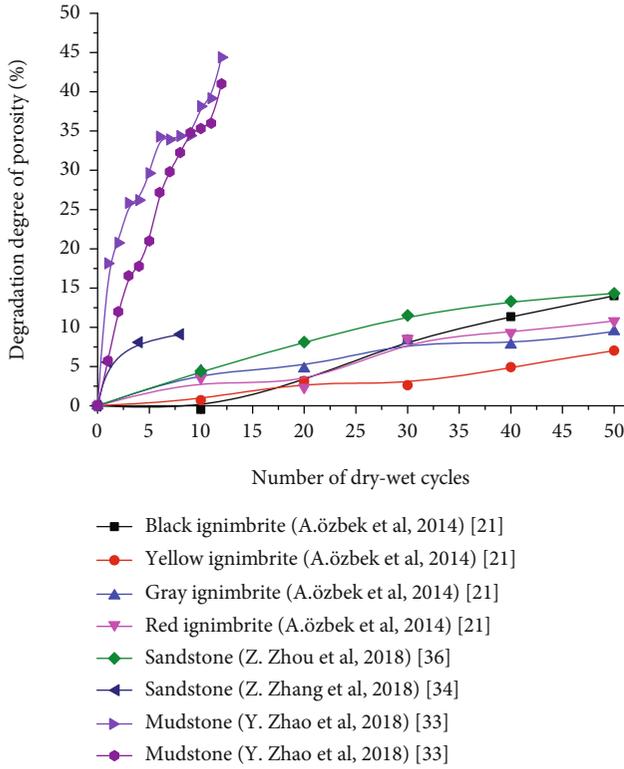


FIGURE 8: Degradation degree of porosity after different dry-wet cycles.

The strength properties of rocks would be significantly deteriorated after the cyclic dry-wet treatment. Khanlari et al. [22], Özbek [21], Zhao et al. [32], Huang et al. [40], and Chen et al. [41] performed static compression tests after dry and wet cycles on sandstone, melted limestone, mudstone, and coalstone, respectively. All of the results shown that with the increase of the number of dry and wet cycles, the uniaxial compressive strength and triaxial compressive strength of the rock sample decreased to varying degrees. There are relatively few studies on the static tensile strength of rocks after wet and dry cycles. Zhao et al. [32] conducted a Brazilian split test on a sandstone with low clay content and found that the deteriorating effect of dry and wet cycles on static tensile strength is not significant. In the rock dynamic compression test, Du et al. [37] found that the dynamic compressive strength of the sample is related to the number of wet and dry cycles and the loading rate. Taking the influence of the loading rate into account, he proposed a decay function to predict the long-term dynamic compressive strength of sandstone considering the number of wet and dry cycles. Zhou et al. [34] established an empirical equation based on experimental results, describing the influence of strain rate and the number of wet-dry cycles on the dynamic compressive strength of rock materials. Because the stress path involving surrounding rock in tunneling is an unloading process, that is, it can be regarded as a dynamic tensile process, Zhou et al. [33] and Li et al. [42] and others conducted related experiments and found that the cyclic dry-wet treatment increases the density, complexity, and connectivity of microcracks, which also significantly

degrades the dynamic compressive strength of the rock. The shear strength of jointed rock mass would also deteriorate after drying and wet cycles, which is caused by the changes in the micromorphology and joint wall strength of the joint surface [43].

According to the total number of wet and dry cycles in the test and the interval between monitoring points, the number of dry and wet cycles below 20 is considered a short-term test, and more than 20 times is considered a long-term test. Figures 9 and 10 show the changes of the uniaxial compression strength degradation in different tests under short-term and long-term wet and dry cycles. In the long-term dry-wet cycle test, since the monitoring point interval is at least 10 dry-wet cycles, the nonlinear changes within the 10 dry-wet cycles are ignored, and there is no obvious regularity on the whole, and the uniaxial compressive strength is even enhanced to some extent. In the short-term test, the uniaxial compressive strength of the rock changes drastically when the number of dry-wet cycles is less than 5, and changes more steadily when it is greater than 5.

The dry-wet cycle also has a certain degradation effect on the fracture toughness of the rock. Hua et al. [44–46] pointed out that the tensile strength of sandstone and the fracture toughness of type I and type II cracks all decrease with the increase of the number of dry-wet cycles, and there is a good linear relationship between the fracture toughness of type I crack and tensile strength. Cyclic wet and dry treatments can also degrade cohesion and friction angle. Figure 11 shows that uniaxial tensile strength, elastic modulus, cohesion, and internal friction angle all decrease to varying degrees with the increase in the number of wet and dry cycles. However, some studies have shown that the influence of dry-wet cycles on sandstone cohesion is different from the influence on friction angle. The change in cohesion in the wet-dry cycle is similar to the change in the peak strength, while the friction angle seems to have nothing to do with the wet-dry cycles [36].

2.3. Chemical Corrosion. Water has dissolution, erosion, and softening effects on rocks [47–52]. However, in many cases, rocks are affected by the coupling of chemical corrosion and dry-wet cycles. Therefore, many scholars have also done related research about the deterioration of rocks under non-neutral dry-wet cycles. Smith [53] systematically studied the weathering of desert rocks due to temperature, moisture, and salt and chemical reactions. Yuan et al. [54, 55] studied the mechanical properties and ion change characteristics of sandstone under pH = 4, 7, and 9, respectively. Feng et al. [56] lists the chemical reaction equations of various materials in sandstone under acid-base and neutral conditions. Sun et al. [16] used MgSO₄ solutions of different concentrations (4%, 6%, 8%) to saturate sandstone and found that compared with pure water wet and dry cycles, the threshold was reached at 30 times of dry and wet cycles, and the P-wave velocity began to rise in the reverse direction, and the tensile strength suddenly dropped sharply. It was found that the color brightness and thermal conductivity of the rock sample showed a good linear relationship with the tensile strength.

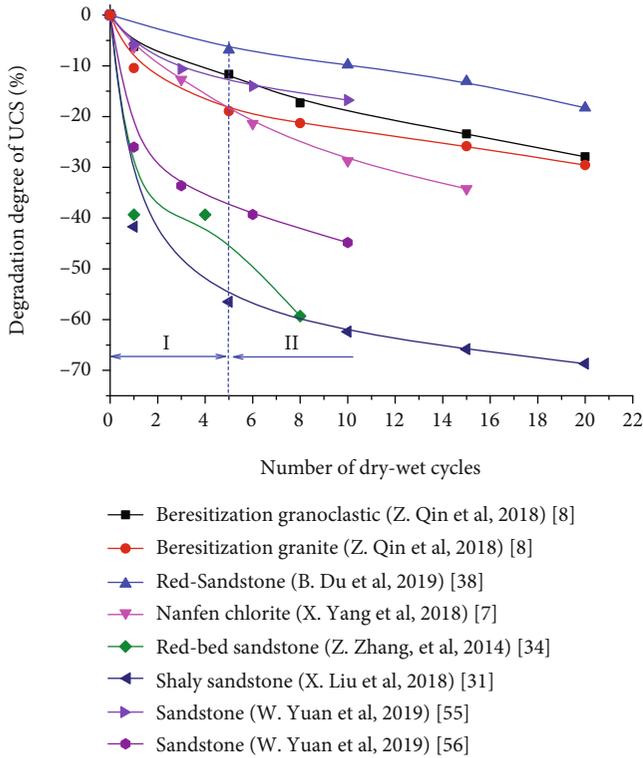


FIGURE 9: Degradation degree of UCS after short-term dry-wet cycles.

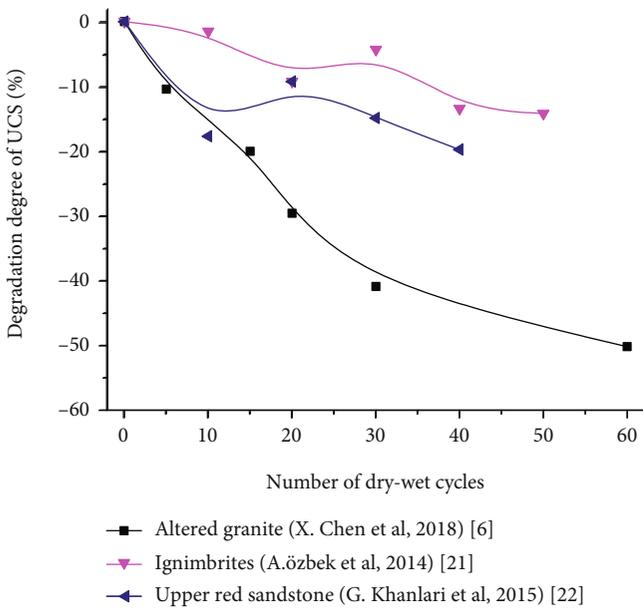


FIGURE 10: Degradation degree of UCS after long-term dry-wet cycles.

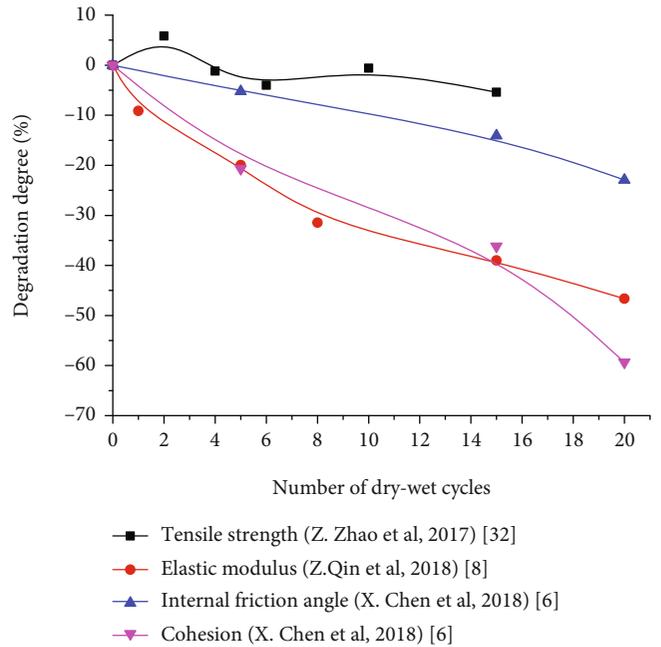


FIGURE 11: Degradation degree of several mechanical properties after different dry-wet cycles.

3. Rock Deterioration Mechanism after Dry-Wet Cycle

3.1. Soaking and Drying-Soaking Cycle. During the dry-wet cycle, there is a compound effect of soaking and drying-soaking alternately. It can also be considered as a fatigue damage process of water to rocks. Van Eeckhout [47] summarized five possible mechanisms for the impact of water soaking on the strength degradation of rocks, that is, reduction in fracture energy, reduction in capillary tension, increase in pore pressure, reduction in friction coefficient, and degradation due to chemical corrosion. In order to distinguish the effects of soaking and drying-soaking cycles, Zhao et al. [32] conducted a comparison test of pure soaking (16 days) and dry-wet cycles (soaking lasting 15 days) on low clay sandstone. The test results show that the rock strength decreased by 59% after 16 days of pure water immersion, while it decreased by only 5% after 15 wet and dry cycles. However, this test has a relatively big problem: the test state of the rock samples is different, that is, the pure water immersion test inevitably requires the rock sample to be tested in a saturated state, while the dry-wet cycle rock sample strength test is in a dry state. In terms of fracture behavior, the dynamic fracture initiation, propagation toughness, and crack propagation velocity of saturated specimen were apparently lower than that of dry ones at the same loading rate [57]. Although there is a strong correlation between the moisture content of rock samples and the deterioration of various physical properties [58–64], there is no obvious difference in the degradation of rocks with different moisture content after wet and dry cycles [65].

Whether the rock sample is in a saturated state or a dry state after the dry-wet cycle, its strength is very different.

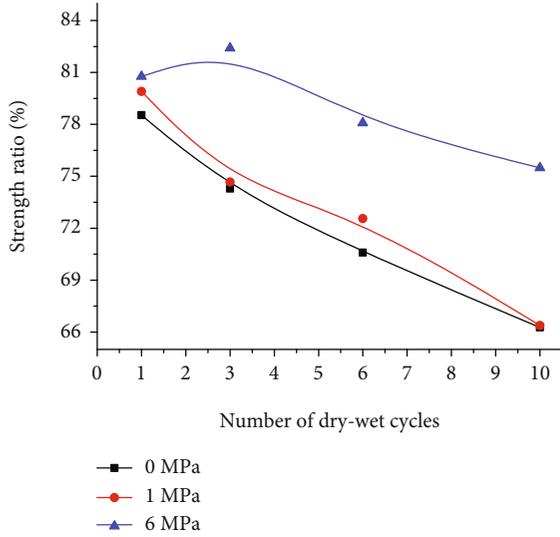


FIGURE 12: Strength ratio of saturated rock samples to dry rock samples after the same number of dry-wet cycles (after [54]).

Yuan et al. [54, 55] conducted strength tests on sandstones in different states. Figure 12 shows the strength ratio of saturated rock samples to dry rock samples after the same number of dry-wet cycles. It can be seen that as the number of dry-wet cycles increases, the saturation-dry strength ratio decreases significantly, which means that the difference between the strength of saturated rock samples and dry rock samples is getting larger and larger. This downward trend contains information about dry-wet cycle damage. Furthermore, the greater the confining pressure, the smaller the decrease, and the saturation-dry strength ratio under high confining pressure (6 MPa) is significantly greater than that under low confining pressure (0 MPa). Figure 13 shows the difference in strength degradation between the saturated state and the dry state under different wet and dry cycles and confining pressure. The strength degradation difference is defined as the ratio of the strength difference after n wet and dry cycles to the initial strength. It is found that the strength deterioration difference under low confining pressure gradually increases with the increase of the number of dry and wet cycles, while the trend is not obvious under high confining pressure. The enhancement effect of the confining pressure partially covers the deterioration caused by the dry and wet cycle.

3.2. Clay Content and Swelling Behavior. The swelling behavior of rock is often related to its clay composition. Clay minerals mainly include montmorillonite, illite, chlorite, kaolinite, and serpentine. These minerals would swell after absorbing water and eventually lead to rock damage and destruction [66–70]. The cyclic dry-wet treatment process would cause repeated expansion and contraction of clay components, and moisture fluctuation is the main reason [71–74]. The volume of expanded clay changes with the fluctuation of water, which causes the air pressure in the pores to rise sharply, and finally ruptures to form cracks. This irreversible phenomenon is called “air breakage” [75]. On the other hand, there would be obvious argillization phenomena

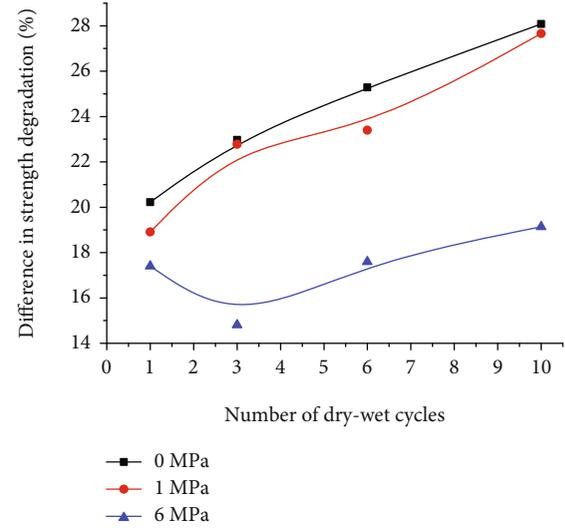


FIGURE 13: Difference in strength degradation between the saturated state and the dry state under different wet and dry cycles and confining pressure (after [54]).

after undergoing wetting-drying cycles, which weakens the cementation between mineral grains in the rock and smooths the shape of the grains themselves [36]. The increase in saturation will also increase the dissolution of clay minerals and the lubricity between mineral particles. Therefore, these effects significantly reduce the strength and deformation properties of the rock [35] and also reduce its brittleness, resulting in the failure mode of the specimen from extension failure to shear failure [36]. It should also be noted that the dissolution and precipitation of soluble substances are accompanied by substance migration. Beck et al. [76] observed the surface of limestone samples after 50 dry-wet cycles and found that the appearance of the limestone changed in color, becoming slightly brown, and a hard thin layer appeared in about 20% of the place, similar to the oxide layer on the metal, and the surface roughness of the rock sample decreased. The reason is that during the saturation process, the soluble matter dissolves, and during the subsequent drying process, the soluble matter migrates to the surface of the rock sample along with the water vapor, where it crystallizes out again. This phenomenon is macroscopically manifested as the reversibility of rock properties to a certain extent, that is, the strength recovery occurs in the dry state [77, 78] (as shown in Figures 12 and 13).

The internal microscopic damage caused by the dry-wet cycle would vary depending on the amount of clay content. Lin et al. [79] found that the fracture mechanism of all dry sandstones is mainly intracrystalline fracture, while saturated sandstones with high chlorite content mainly intracrystalline fracture and saturated sandstones with low chlorite content intercrystalline fracture. Wang et al. [80] observed that argillaceous rocks have a certain irreversible deformation regardless of whether they are wet or dry. The form is a typical $1 \mu\text{m}$ open-pore microcrack network: the former is located in the block and/or inclusion-matrix interface of the clay matrix; the latter mainly exists in the block of clay matrix. For rocks with low clay mineral content, the main degradation

mechanism is to reduce the fracture energy and friction coefficient, while the possible softening, expansion, and dissolution behavior of clay minerals can only play a small role [32]. In short, the content of clay components is a key component factor that affects the effect of dry-wet cycles on rock degradation.

3.3. Microstructure Evolution. By means of scanning electron microscopy (SEM) observation, image analysis, and discrete element simulation, the microscopic morphology and structure of the rock surface, including the particles contact network, particles force chains distribution, microcrack diameter, length, and area, can be obtained. After cyclic drying and wetting treatment, the microstructure of rocks changes from a well-organized dense structure stage to a porous stage and then to a cracking stage [1, 6, 7, 30, 31, 34–37, 45, 80–82]. Microcracks in the rock grow and expand, and their density, length, complexity, and interconnectivity increase. At the same time, the size, shape, and distribution of pores also undergo significant changes, and the grains are also degraded. These changes are the main reason for the degradation of mechanical properties [33, 34]. The initiation and propagation of microcracks are mainly the result of cyclic loading and unloading of tensile stress caused by water absorption and desorption of rocks in the cyclic wetting and drying process [30].

Figure 14 shows the SEM images of the rock surfaces after different wet-dry cycles. When the rock sample does not absorb water, the microstructure of the particles shows a clear outline without obvious overlap. After the water-rock interaction, the microstructure of the rock sample surface is no longer compact and uniform, and the particle shape gradually changes from blocky and flat to flocculent and disordered [83]. When the number of wetting and drying cycles reaches more than 10 times, the microstructure of the rock changes greatly compared with the natural state [6, 82]. The original small pores gradually infiltrated and merged into large pores, and the phenomenon of stacking and overlapping and massive precipitation appeared, and the shape of the grains changed from a clear, neat, and dense edge to a mud layer. When the number of wetting and drying cycles reaches more than 30 times, the pores further expand and become larger, and obvious microcracks appear.

The dry-wet cycle has a great deteriorating effect on the dynamic energy absorption of the rock. Yuan et al. [84] found that the fracture surface energy of the sandstone sample decreases due to the stress transformation between sandstone mineral particles during the dry-wet cycle. Hu et al. [85] analyzed the degradation mechanism of the rock during the dry-wet cycle by considering the temperature-induced stress, load, and fluid effect, that is, temperature-induced stress and applied load cause tensile stress inside the rock sample and compressive stress on the surface; when the stress generated by the temperature and the overburden load is greater than the tensile strength of the rock sample, the internal cracks begin to expand, providing a channel for the action of water, and the contact area between water and rock is increasing; under the action of hydraulic fracturing and

weakening, the fractures are connected and the width of the fractures increases, which eventually leads to failure.

In summary, the development process of rock microstructure after cyclic drying and wet treatment is roughly shown in Figure 15. Without wet and dry treatment, the mineral particles are tightly connected by cement, and the shape of the particles is clear and sharp. After 1 to 10 cycles of dry and wet treatment, the soluble matter dissolves and migrates, resulting in small erosion pores between the particles, but the morphology of the particles does not change much. After 10 to 30 wet and dry cycles, the pores gradually become larger, the dissolved substances fall off and settle on the edges of the pores, and the mineral particles become apparently smooth. After more than 30 wet and dry cycles, microcracks appear between the particles, the surface roundness of the mineral particles is larger, the cohesive force is greatly reduced, and secondary cracks also appear in the particles, which tend to be looser and disintegration breakage. It should be noted that the number of dry and wet cycles mentioned above is only an approximate number. For different rocks, these specific times are different, but the whole process of change is roughly the same.

4. Rock Deterioration Constitutive Model after Dry-Wet Cycle

Macroscopically, the mass loss of rock samples, P-wave velocity attenuation, relative changes in water content, elastic modulus, friction angle, and cohesion; microscopically, the CT number of CT scanning, and the characteristic parameters of microscopic cracks obtained by SEM image processing include quantity, size and surface area; in addition, statistical parameters, fractal dimensions, etc. can all be used as damage variables. The constitutive model of rock damage is difficult to be unified due to the complexity of damage variables [86–89]. Based on different damage variables, the constitutive equations describing the deterioration of rocks after drying and wet cycles are also different. Hu et al. [90] established the damage constitutive equation under the coupling action of the dry-wet cycle and the load based on the influence of temperature and the number of dry-wet cycles on the attenuation rate, combined with the damage evolution equation based on the energy principle. Du et al. [91] separated macroscopic damage variables and microscopic damage variables and constructed the constitutive equation of sandstone after impact load and dry-wet cycle coupling. Wang et al. [92] proposed an improved *D-C* equation to describe the initial compression stage and the residual stage after the peak during rock deformation. Wang et al. [93] proposed a damage nonlinear Burgers viscoelastic-plastic (DNBVP) model considering the effect of saturation-dehydration cycles by introducing a nonlinear viscoplastic body and a damage variable describing dry-wet cycles and then derived the three-dimensional creep equations of the new model and identified its creep parameters. Furthermore, Wang et al. [94] proposed four kinds of functions including an exponentially decreasing function, a linearly decreasing function, a linearly increasing function, and an exponentially increasing function to express the relationships between the shear modulus, viscoelastic

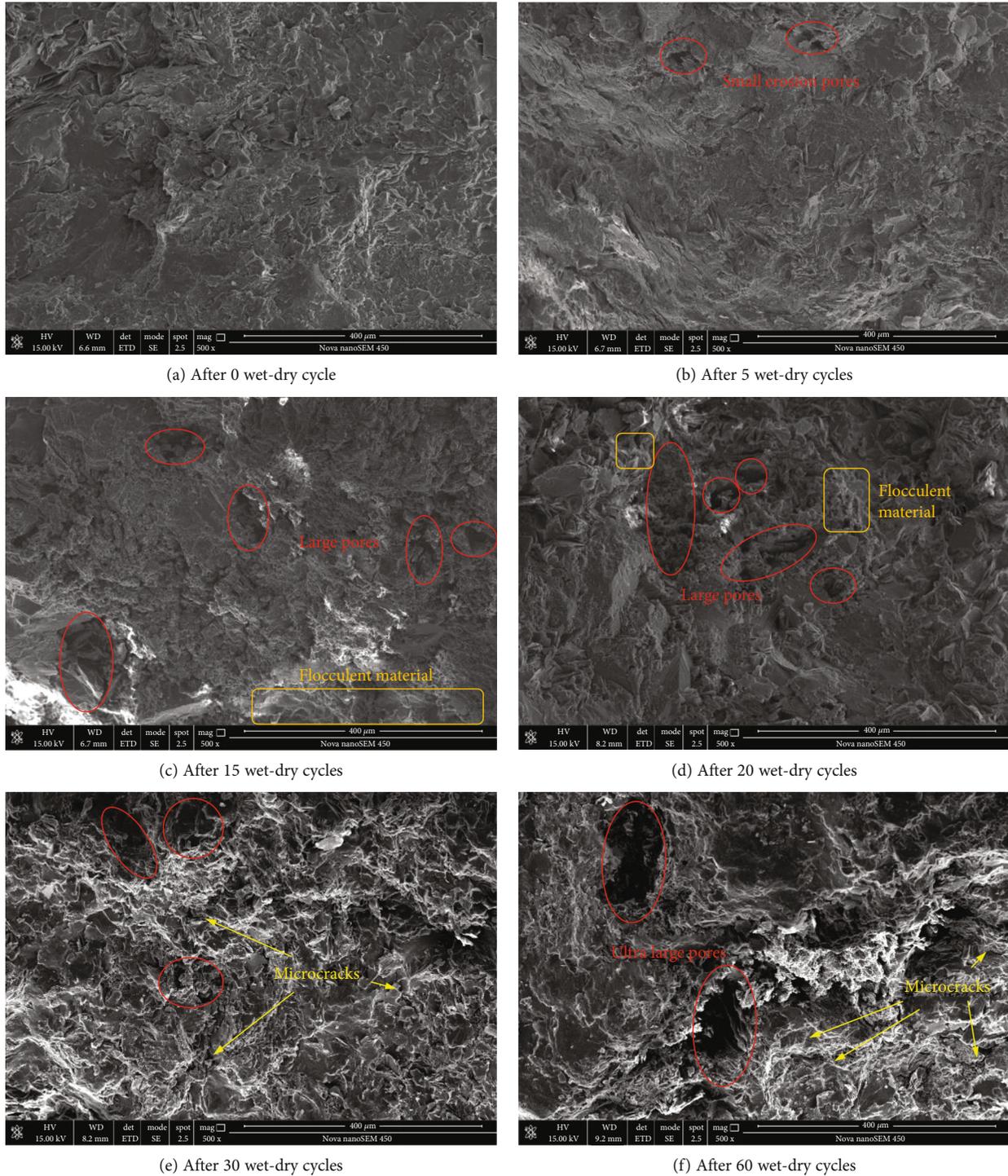


FIGURE 14: SEM images of rock surfaces after different wet-dry cycles (after [6]).

parameters of the Burgers model, and the deviatoric stress under different dry-wet cycles. Through comparative analysis, it is found that the theoretical curves generated using proposed four kinds of functions are in good agreement with the experimental data. Liu et al. [95] proposed a damage variable considering the combined influence of cyclic wetting-drying and loading and further established an improved damage model which considers the effect of cyclic wetting-drying on internal friction angle and the nonlinear deformation

characteristics in the fissure closure stage with statistical damage mechanics. The determination method for the parameters in the proposed damage model was also introduced. He et al. [96] explored the deterioration features and acoustic wave parameters and resistivity (AWPR) of the sandstone in cyclic wetting and drying experiments and proposed a cumulative damage model in the light of the AWPR through the instantaneous damage analysis. Huang et al. [97] investigated the physical and mechanical properties under

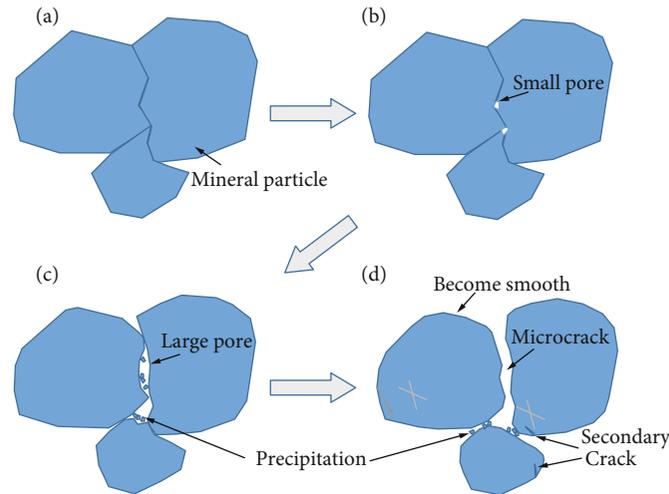


FIGURE 15: Diagrams of the microstructure development process after different wet-dry cycles. (a) 0 times; (b) 1-10 times; (c) 10-30 times; (d) >30 times.

acid dry-wet cycles and established a constitutive model of uniaxial compression based on Weibull damage variable, which has the best effect in acid solution with less cycle times or pH value of solution greater than 6. Zhang et al. [98] derived an evolution model of the disintegration breakage of red-bed soft rock using the Morgan-Mercer-Florin (MMF) model, measured the disintegration behaviours of red-bed soft rock by the disintegration ratio, and derived a new formula to calculate the disintegration ratio based on the concept of the traditional disintegration ratio using the established model. Xu et al. [99] established a traditional strength prediction model based on P-wave velocity combined with the damage theory and Lemaitre strain equivalence hypothesis and then proposed a modified model considering both the drying-wetting cycle number and confining pressures.

In shale gas development and other engineering practices, the study of rock mass diffusion and seepage equations is very important [100–102]. There are few studies on the influence of the dry-wet cycle on the law of water migration. Van der Hoven [103] conducted a detailed analysis of the unsaturated flow and solute transport of the high-porosity matrix rock during the dry-wet cycle, and the modeling results indicated that the advective flux of solutes from the fractures into the matrix during wetting was greater than from the matrix back into the fractures during drying, resulting in a net storage of solutes in the matrix, and the rock system behaved more like a fully saturated system where diffusion is the dominant transport process between fractures and matrix with the increase of number of dry-wet cycles.

5. Conclusions and Prospects

This article summarizes the geological and engineering scenarios of the dry-wet cycle and the research results of the rock degradation effect. Through the collection and normalization of the dry-wet cycle test data in the existing literature, the degradation degree and mechanism of the

physical and mechanical properties of rocks are analyzed. The main conclusions are as follows.

- (1) As the number of wet and dry cycles increases, the physical properties (including dry weight, P-wave velocity, porosity, water absorption, and durability index) and mechanical properties of rocks (including static compressive/tensile strength, elastic modulus, dynamic compressive/tensile strength, shear strength, fracture toughness, cohesion, and internal friction angle) would all experience different degrees of deterioration
- (2) The possible mechanisms of the influence of dry-wet cycles on rock degradation include reduction of fracture energy, reduction of capillary tension, increase of pore pressure, reduction of friction coefficient, chemical corrosion, mineral dissolution, expansion and softening, and solute migration
- (3) The content of clay components is a key factor that affects the effect of dry-wet cycles on rock degradation. The degradation mechanism of rocks with different clay content is also different
- (4) The evolution of rock microstructures, especially microcracks, after dry-wet cycles is closely related to changes in the physical and mechanical properties

Based on these conclusions, we need to focus on the following aspects in the future. First, what is the actual dry and wet cycle process (frequency and mode) in nature? Second, what is the mineral composition and structure of the rock? What are the components of the solution? What kind of chemical, biological, physical, and mechanical interactions occur between the solution and the rock? Third, what kind of theoretical model is used or established to describe the dry-wet cycle process so as to predict the degradation behavior of the physical and mechanical properties of rocks?

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

The authors are supported by the National Natural Science Foundation of China (Grant nos. 42030810 and 51934007) and the Fundamental Research Funds for the Central Universities (Grant no. 2017QNA31).

References

- [1] K. Xie, D. Jiang, Z. Sun, J. Chen, W. Zhang, and X. Jiang, "NMR, MRI and AE statistical study of damage due to a low number of wetting-drying cycles in sandstone from the three gorges reservoir area," *Rock Mechanics and Rock Engineering*, vol. 51, no. 11, pp. 3625–3634, 2018.
- [2] X. Liu, Z. Wang, Y. Fu, W. Yuan, and L. Miao, "Macro/micro-testing and damage and degradation of sandstones under dry-wet cycles," *Advances in Materials Science and Engineering*, vol. 2016, Article ID 7013032, 2016.
- [3] X. Min, G. M. Ren, and X. Lei, "Deformation and mechanism of landslide influenced by the effects of reservoir water and rainfall, Three Gorges, China," *Natural Hazards*, vol. 68, no. 2, pp. 467–482, 2013.
- [4] T. Zhang, E. Yan, J. Cheng, and Y. Zheng, "Mechanism of reservoir water in the deformation of Hefeng landslide," *Journal of Earth Science*, vol. 21, no. 6, pp. 870–875, 2010.
- [5] S. Noor-E-Khuda and F. Albermani, "Flexural strength of weathered granites under wetting-drying cycles: implications to steel structures," *Advanced Steel Construction*, vol. 15, no. 3, pp. 225–231, 2019.
- [6] X. Chen, P. He, and Z. Qin, "Damage to the microstructure and strength of altered granite under wet-dry cycles," *Symmetry*, vol. 10, no. 12, p. 716, 2018.
- [7] X. Yang, J. Wang, D. Hou, C. Zhu, and M. He, "Effect of dry-wet cycling on the mechanical properties of rocks: a laboratory-scale experimental study," *Processes*, vol. 6, no. 10, p. 199, 2018.
- [8] Z. Qin, X. Chen, and H. Fu, "Damage features of altered rock subjected to drying-wetting cycles," *Advances in Civil Engineering*, vol. 2018, Article ID 5170832, 2018.
- [9] T. Inoue, S. Yamaguchi, and J. M. Nelson, "The effect of wet-dry weathering on the rate of bedrock river channel erosion by saltating gravel," *Geomorphology*, vol. 285, pp. 152–161, 2017.
- [10] C. Zhang, Z. Cai, Y. Huang, and H. Chen, "Laboratory and centrifuge model tests on influence of swelling rock with drying-wetting cycles on stability of canal slope," *Advances in Civil Engineering*, vol. 2018, Article ID 4785960, 2018.
- [11] X. Gong, L. Xiao, Z. Zhao et al., "Spatial variation of polycyclic aromatic hydrocarbons (PAHs) in surface sediments from rivers in hilly regions of Southern China in the wet and dry seasons," *Ecotoxicology Environmental Safety*, vol. 156, pp. 322–329, 2018.
- [12] A. S. Trenhaile, "Modelling tidal notch formation by wetting and drying and salt weathering," *Geomorphology*, vol. 224, pp. 139–151, 2014.
- [13] A. Trenhaile, "Tidal wetting and drying on shore platforms: an experimental study of surface expansion and contraction," *Geomorphology*, vol. 76, no. 3-4, pp. 316–331, 2006.
- [14] J. I. Kanyaya and A. S. Trenhaile, "Tidal wetting and drying on shore platforms: an experimental assessment," *Geomorphology*, vol. 70, no. 1-2, pp. 129–146, 2005.
- [15] E. F. McBride and M. D. Picard, "Origin of honeycombs and related weathering forms in Oligocene Macigno Sandstone, Tuscan coast near Livorno, Italy," *Earth Surface Processes and Landforms*, vol. 29, no. 6, pp. 713–735, 2004.
- [16] Q. Sun and Y. Zhang, "Combined effects of salt, cyclic wetting and drying cycles on the physical and mechanical properties of sandstone," *Engineering Geology*, vol. 248, pp. 70–79, 2019.
- [17] M. Akin and A. Ozsan, "Evaluation of the long-term durability of yellow travertine using accelerated weathering tests," *Bulletin of Engineering Geology and the Environment*, vol. 70, no. 1, pp. 101–114, 2011.
- [18] Z. Zeng and L. Kong, "Effect of wetting-drying-freezing-thawing cycles on the swelling behaviour of the Yanji mudstone," *Environmental Earth Sciences*, vol. 78, no. 15, p. 435, 2019.
- [19] F. T. Wang, N. N. Liang, and G. Li, "Damage and failure evolution mechanism for coal pillar dams affected by water immersion in underground reservoirs," *Geofluids*, vol. 2019, 2019.
- [20] P. A. Hale and A. Shakoor, "A laboratory investigation of the effects of cyclic heating and cooling, wetting and drying, and freezing and thawing on the compressive strength of selected sandstones," *Environmental & Engineering Geoscience*, vol. 9, no. 2, pp. 117–130, 2003.
- [21] A. Ozbek, "Investigation of the effects of wetting-drying and freezing-thawing cycles on some physical and mechanical properties of selected ignimbrites," *Bulletin of Engineering Geology and the Environment*, vol. 73, no. 2, pp. 595–609, 2014.
- [22] G. Khanlari and Y. Abdilor, "Influence of wet-dry, freeze-thaw, and heat-cool cycles on the physical and mechanical properties of Upper Red sandstones in central Iran," *Bulletin of Engineering Geology and the Environment*, vol. 74, no. 4, pp. 1287–1300, 2015.
- [23] K. Cui, G. Wu, X. Wang, and W. Chen, "Behaviour of slate following freeze-thaw and dry-wet weathering processes," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 50, no. 2, pp. 117–125, 2017.
- [24] K. Hall, E. KOSTER, and H. FRENCH, "The interconnection of wetting and drying with freeze-thaw: some new data in periglacial processes and landforms," *Zeitschrift für Geomorphologie. Supplementband*, vol. 71, no. 1, pp. 1–11, 1988.
- [25] A. Prick, "Dilatometrical behaviour of porous calcareous rock samples subjected to freeze-thaw cycles," *Catena*, vol. 25, no. 1-4, pp. 7–20, 1995.
- [26] D. T. Nicholson and F. H. Nicholson, "Physical deterioration of sedimentary rocks subjected to experimental freeze-thaw weathering," *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, vol. 25, no. 12, pp. 1295–1307, 2000.

- [27] Y. Ito, Y. Kusakabe, and S. Anan, "Experimental study on rock deterioration by repetition of freezing and thawing, and by repetition of dry and wet in cold region," in *Engineering Geology for Society and Territory*, vol. 5, pp. 1293–1297, Urban Geology, Sustainable Planning and Landscape Exploitation, 2015.
- [28] M. J. Loubser, "Weathering of basalt and sandstone by wetting and drying: a process isolation study," *Geografiska Annaler Series a-Physical Geography*, vol. 95, no. 4, pp. 295–304, 2013.
- [29] K. Hall and A. Hall, "Weathering by wetting and drying: some experimental results," *Earth Surface Processes and Landforms*, vol. 21, no. 4, pp. 365–376, 1996.
- [30] P. Yuan, N.-N. Wei, Q.-Y. Ma, and J.-C. Chang, "Coupled effect of water temperature and cyclic wetting and drying on dynamic mechanical characteristics of sandstone," *Advances in Civil Engineering*, vol. 2019, Article ID 8167651, 2019.
- [31] X. Liu, M. Jin, D. Li, and L. Zhang, "Strength deterioration of a Shaly sandstone under dry-wet cycles: a case study from the Three Gorges Reservoir in China," *Bulletin of Engineering Geology and the Environment*, vol. 77, no. 4, pp. 1607–1621, 2018.
- [32] Z. Zhao, J. Yang, D. Zhang, and H. Peng, "Effects of wetting and cyclic wetting-drying on tensile strength of sandstone with a low clay mineral content," *Rock Mechanics and Rock Engineering*, vol. 50, no. 2, pp. 485–491, 2017.
- [33] Z. Zhou, X. Cai, D. Ma, L. Chen, S. Wang, and L. Tan, "Dynamic tensile properties of sandstone subjected to wetting and drying cycles," *Construction and Building Materials*, vol. 182, pp. 215–232, 2018.
- [34] Z. Zhou, X. Cai, L. Chen, W. Cao, Y. Zhao, and C. Xiong, "Influence of cyclic wetting and drying on physical and dynamic compressive properties of sandstone," *Engineering Geology*, vol. 220, pp. 1–12, 2017.
- [35] B. Meng, H. Jing, W. Zhu, and H. Su, "Influences of saturation and wetting-drying cycle on mechanical performances of argillaceous limestones from Liupanshan tunnel, China," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 9236172, 2019.
- [36] Z. Zhang, Q. Jiang, C. Zhou, and X. Liu, "Strength and failure characteristics of Jurassic Red-Bed sandstone under cyclic wetting-drying conditions," *Geophysical Journal International*, vol. 198, no. 2, pp. 1034–1044, 2014.
- [37] B. Du, H. Bai, and G. Wu, "Dynamic compression properties and deterioration of red-sandstone subject to cyclic wet-dry treatment," *Advances in Civil Engineering*, vol. 2019, Article ID 1487156, 2019.
- [38] C. Liu, Y. Wu, X. F. Zhang et al., "Propagation of shock waves in dry and wet sandstone: experimental observations, theoretical analysis and meso-scale modeling," *Defence Technology*, vol. 14, no. 5, pp. 513–521, 2018.
- [39] Y. Zhao, S. Ren, D. Jiang, R. Liu, J. Wu, and X. Jiang, "Influence of wetting-drying cycles on the pore structure and mechanical properties of mudstone from Simian Mountain," *Construction and Building Materials*, vol. 191, pp. 923–931, 2018.
- [40] S. Huang, J. Wang, Z. Qiu, and K. Kang, "Effects of cyclic wetting-drying conditions on elastic modulus and compressive strength of sandstone and mudstone," *Processes*, vol. 6, no. 12, 2018.
- [41] S. Chen, T. Jiang, H. Wang, F. Feng, D. Yin, and X. Li, "Influence of cyclic wetting-drying on the mechanical strength characteristics of coal samples: a laboratory-scale study," *Energy Science & Engineering*, vol. 7, no. 6, pp. 3020–3037, 2019.
- [42] S. Li, C. Li, W. Yao, R. Zhang, and Z. Zhang, "Impact of wetting-drying cycles on dynamic tensile strength of rock," *Thermal Science*, vol. 23, pp. 115–115, 2019.
- [43] J. Fang, H. Deng, Y. Qi, Y. Xiao, H. Zhang, and J. Li, "Analysis of changes in the micromorphology of sandstone joint surface under dry-wet C strength and failure characteristics of Jurassic Red-Bed sandstone under cyclic wetting-drying conditions cycling," *Advances in Materials Science and Engineering*, vol. 2019, Article ID 8758203, 2019.
- [44] W. Hua, S. Dong, Y. Li, and Q. Wang, "Effect of cyclic wetting and drying on the pure mode II fracture toughness of sandstone," *Engineering Fracture Mechanics*, vol. 153, pp. 143–150, 2016.
- [45] W. Hua, S. Dong, F. Peng, K. Li, and Q. Wang, "Experimental investigation on the effect of wetting-drying cycles on mixed mode fracture toughness of sandstone," *International Journal of Rock Mechanics and Mining Sciences*, vol. 93, pp. 242–249, 2017.
- [46] W. Hua, S. Dong, Y. Li, J. Xu, and Q. Wang, "The influence of cyclic wetting and drying on the fracture toughness of sandstone," *International Journal of Rock Mechanics and Mining Sciences*, vol. 78, pp. 331–335, 2015.
- [47] E. M. Van Eeckhout, "The mechanisms of strength reduction due to moisture in coal mine shales," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 13, no. 2, pp. 61–67, 1976.
- [48] A. Hawkins and B. McConnell, "Sensitivity of sandstone strength and deformability to changes in moisture content," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 25, no. 2, pp. 115–130, 1992.
- [49] E. Verstrynge, R. Adriaens, J. Elsen, and K. Van Balen, "Multi-scale analysis on the influence of moisture on the mechanical behavior of ferruginous sandstone," *Construction and Building Materials*, vol. 54, pp. 78–90, 2014.
- [50] Z. Zhou, X. Cai, Y. Zhao, L. Chen, C. Xiong, and X.-b. Li, "Strength characteristics of dry and saturated rock at different strain rates," *Transactions of Nonferrous Metals Society of China*, vol. 26, no. 7, pp. 1919–1925, 2016.
- [51] Z. Zhou, X. Cai, D. Ma, W. Cao, L. Chen, and J. Zhou, "Effects of water content on fracture and mechanical behavior of sandstone with a low clay mineral content," *Engineering Fracture Mechanics*, vol. 193, pp. 47–65, 2018.
- [52] T. S. Rötting, L. Luquot, J. Carrera, and D. J. Casalinuovo, "Changes in porosity, permeability, water retention curve and reactive surface area during carbonate rock dissolution," *Chemical Geology*, vol. 403, pp. 86–98, 2015.
- [53] B. Smith, "Weathering processes and forms," in *Geomorphology of Desert Environments*, pp. 69–100, Springer, 2009.
- [54] W. Yuan, X. Liu, and Y. Fu, "Chemical thermodynamics and chemical kinetics analysis of sandstone dissolution under the action of dry-wet cycles in acid and alkaline environments," *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 2, pp. 793–801, 2019.
- [55] W. Yuan, X. Liu, and Y. Fu, "Study on deterioration of strength parameters of sandstone under the action of dry-wet cycles in acid and alkaline environment," *Arabian*

- Journal for Science and Engineering*, vol. 43, no. 1, pp. 335–348, 2018.
- [56] X. Feng, W.-x. Ding, H. Yao, Q. Cui, and S. Chen, *Coupled Chemical-Stress Effect on Rock Fracturing Process*, Science Press, Beijing, 2010.
- [57] Z. Zhou, X. Cai, D. Ma et al., “Water saturation effects on dynamic fracture behavior of sandstone,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 114, pp. 46–61, 2019.
- [58] N. Price, “The compressive strength of coal measure rocks,” *Colliery Engineering*, vol. 37, no. 437, pp. 283–292, 1960.
- [59] N. J. Price, “The influence of geological factors on the strength of coal measure rocks,” *Geological Magazine*, vol. 100, no. 5, pp. 428–443, 1963.
- [60] P. Colback and B. Wiid, “The influence of moisture content on the compressive strength of rocks,” *Geophysics*, 1965.
- [61] J. Fedá, “The influence of water content on the behaviour of subsoil, formed by highly weathered rocks,” in *1st ISRM Congress*, pp. 283–288, International Society for Rock Mechanics and Rock Engineering, 1966.
- [62] M. Ruiz, “Some technological characteristics of twenty six Brazilian rock types,” in *Proc. 1st Cong. Int. Soc. Rock Mech*, pp. 115–119, 1966.
- [63] L. Burshtein, “Effect of moisture on the strength and deformability of sandstone,” *Soviet Mining*, vol. 5, no. 5, pp. 573–576, 1969.
- [64] B. Vásárhelyi, “Some observations regarding the strength and deformability of sandstones in dry and saturated conditions,” *Bulletin of Engineering Geology and the Environment*, vol. 62, no. 3, pp. 245–249, 2003.
- [65] P. D. Sumner and M. J. Loubser, “Experimental sandstone weathering using different wetting and drying moisture amplitudes,” *Earth Surface Processes and Landforms*, vol. 33, no. 6, pp. 985–990, 2008.
- [66] M. Gysel, “Design of tunnels in swelling rock,” *Rock Mechanics and Rock Engineering*, vol. 20, no. 4, pp. 219–242, 1987.
- [67] H. Einstein, “Tunnelling in difficult ground—swelling behaviour and identification of swelling rocks,” *Rock Mechanics and Rock Engineering*, vol. 29, no. 3, pp. 113–124, 1996.
- [68] M. Barla, *Tunnels in Swelling Ground—Simulation of 3D Stress Paths by Triaxial Laboratory Testing*, Unpublished Doctoral Dissertation, Politecnico di Torino, 1999.
- [69] B. Hawlader, Y. Lee, and K. Lo, “Three-dimensional stress effects on time-dependent swelling behaviour of shaly rocks,” *Canadian Geotechnical Journal*, vol. 40, no. 3, pp. 501–511, 2003.
- [70] B. Hawlader, K. Lo, and I. Moore, “Analysis of tunnels in shaly rock considering three-dimensional stress effects on swelling,” *Canadian Geotechnical Journal*, vol. 42, no. 1, pp. 1–12, 2005.
- [71] S. Huang, R. Speck, and Z. Wang, “The temperature effect on swelling of shales under cyclic wetting and drying,” in *International journal of rock mechanics and mining sciences & geomechanics abstracts*, vol. 32, no. 3, pp. 227–236, 1995.
- [72] O. J. Pejón and L. V. Zuquette, “Analysis of cyclic swelling of mudrocks,” *Engineering Geology*, vol. 67, no. 1-2, pp. 97–108, 2002.
- [73] R. Doostmohammadi, M. Moosavi, T. Mutschler, and C. Osan, “Influence of cyclic wetting and drying on swelling behavior of mudstone in south west of Iran,” *Environmental Geology*, vol. 58, no. 5, pp. 999–1009, 2009.
- [74] M. R. Vergara and T. Triantafyllidis, “Swelling behavior of volcanic rocks under cyclic wetting and drying,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 80, pp. 231–240, 2015.
- [75] R. Taylor and D. Spears, “The breakdown of British coal measure rocks,” *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 7, no. 5, pp. 481–501, 1970.
- [76] K. Beck and M. Al-Mukhtar, “Cyclic wetting-drying ageing test and patina formation on tuffeau limestone,” *Environmental Earth Sciences*, vol. 71, no. 5, pp. 2361–2372, 2014.
- [77] Q. Pham, F. Vales, L. Malinsky, D. N. Minh, and H. Gharbi, “Effects of desaturation-resaturation on mudstone,” *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 32, no. 8-14, pp. 646–655, 2007.
- [78] D. Yang, M. Bornert, S. Chanchole, H. Gharbi, P. Valli, and B. Gatmiri, “Dependence of elastic properties of argillaceous rocks on moisture content investigated with optical full-field strain measurement techniques,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 53, pp. 45–55, 2012.
- [79] M. L. Lin, F. Jeng, L. Tsai, and T. Huang, “Wetting weakening of tertiary sandstones—microscopic mechanism,” *Environmental Geology*, vol. 48, no. 2, pp. 265–275, 2005.
- [80] L. L. Wang, M. Bornert, E. Heripre, D. S. Yang, and S. Chanchole, “Irreversible deformation and damage in argillaceous rocks induced by wetting/drying,” *Journal of Applied Geophysics*, vol. 107, pp. 108–118, 2014.
- [81] L. Zeng, J. Liu, Q. F. Gao, and H. Bian, “Evolution characteristics of the cracks in the completely disintegrated carbonaceous mudstone subjected to cyclic wetting and drying,” *Advances in Civil Engineering*, vol. 2019, Article ID 1279695, 2019.
- [82] X. Yang, J. Wang, C. Zhu, M. He, and Y. Gao, “Effect of wetting and drying cycles on microstructure of rock based on SEM,” *Environmental Earth Sciences*, vol. 78, no. 6, 2019.
- [83] F.-S. Jeng, M.-L. Lin, and T.-H. Huang, “Wetting deterioration of soft sandstone—microscopic insights,” in *ISRM International Symposium*, International Society for Rock Mechanics and Rock Engineering, 2000.
- [84] P. Yuan and Q. Y. Ma, *Energy Analyses of Uniaxial Impact Compressive Tests for Coalmine Sandstone After Cyclic Wetting and Drying*, Rock Engineering and Rock Mechanics: Structures in and on Rock Masses, 2014.
- [85] M. Hu, Y. Liu, J. Ren, R. Wu, and Y. Zhang, “Laboratory test on crack development in mudstone under the action of dry-wet cycles,” *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 1, pp. 543–556, 2019.
- [86] A. Minardi, A. Ferrari, R. Ewy, and L. Laloui, “Nonlinear elastic response of partially saturated gas shales in uniaxial compression,” *Rock Mechanics and Rock Engineering*, vol. 51, no. 7, pp. 1967–1978, 2018.
- [87] Z. Wang, H. Shi, and J. Wang, “Mechanical behavior and damage constitutive model of granite under coupling of temperature and dynamic loading,” *Rock Mechanics and Rock Engineering*, vol. 51, no. 10, pp. 3045–3059, 2018.
- [88] L. Liu, W. Xu, L. Zhao, Q. Zhu, and R. Wang, “An experimental and numerical investigation of the mechanical behavior of granite gneiss under compression,” *Rock Mechanics and Rock Engineering*, vol. 50, no. 2, pp. 499–506, 2017.

- [89] L. Berto, A. Sietta, and D. Talledo, "Constitutive model of concrete damaged by freeze-thaw action for evaluation of structural performance of RC elements," *Construction and Building Materials*, vol. 98, pp. 559–569, 2015.
- [90] M. Hu, Y. Liu, L. Song, and Y. Zhang, "Constitutive model and damage evolution of mudstone under the action of dry-wet cycles," *Advances in Civil Engineering*, vol. 2018, Article ID 9787429, 2018.
- [91] B. Du and H. Bai, "A damage constitutive model of red sandstone under coupling of wet-dry cycles and impact load," *Shock and Vibration*, vol. 2019, Article ID 7692424, 2019.
- [92] Z. Wang, X. Liu, X. Yang, and Y. Fu, "An improved Duncan-Chang constitutive model for sandstone subjected to drying-wetting cycles and secondary development of the model in FLAC(3D)," *Arabian Journal for Science and Engineering*, vol. 42, no. 3, pp. 1265–1282, 2017.
- [93] X. Wang, B. Lian, and W. Feng, "A nonlinear creep damage model considering the effect of dry-wet cycles of rocks on reservoir bank slopes," *Water*, vol. 12, no. 9, 2020.
- [94] X. Wang, B. Lian, J. Wang, W. Feng, and T. Gu, "Creep damage properties of sandstone under dry-wet cycles," *Journal of Mountain Science*, vol. 17, no. 12, pp. 3112–3122, 2020.
- [95] X. Liu, Q. Liu, S. Huang, B. Liu, and J. Liu, "Effects of cyclic wetting-drying on the mechanical behavior and improved damage model for sandstone," *Marine Georesources & Geotechnology*, pp. 1–11, 2020.
- [96] Y. He, K. Wang, Y. Ji, G. Wu, and M. Zhao, "Evaluation of cumulative damage of sandstone under cyclic wetting and drying through acoustic wave parameters and resistivity testing," *Journal of New Materials for Electrochemical Systems*, vol. 23, no. 4, pp. 256–261, 2020.
- [97] X. Huang, J. Pang, G. Liu, and Y. Chen, "Experimental study on physicochemical properties of deep sandstone by coupling of dry-wet cycles and acidic environment," *Advances in Civil Engineering*, vol. 2020, Article ID 2760952, 2020.
- [98] Z. T. Zhang and W. H. Gao, "Effect of different test methods on the disintegration behaviour of soft rock and the evolution model of disintegration breakage under cyclic wetting and drying," *Engineering Geology*, vol. 279, p. 105888, 2020.
- [99] Z. H. Xu, G. L. Feng, Q. C. Sun, G. D. Zhang, and Y. M. He, "A modified model for predicting the strength of drying-wetting cycled sandstone based on the P-wave velocity," *Sustainability*, vol. 12, no. 14, 2020.
- [100] J. Deng, W. Zhu, and Q. Ma, "A new seepage model for shale gas reservoir and productivity analysis of fractured well," *Fuel*, vol. 124, pp. 232–240, 2014.
- [101] C. Freeman, "A numerical study of microscale flow behavior in tight gas and shale gas," in *SPE Annual Technical Conference and Exhibition* Society of Petroleum Engineers.
- [102] A. Beskok and G. E. Karniadakis, "Report: a model for flows in channels, pipes, and ducts at micro and nano scales," *Microscale Thermophysical Engineering*, vol. 3, no. 1, pp. 43–77, 1999.
- [103] S. J. Van der Hoven, D. K. Solomon, and G. R. Moline, "Modeling unsaturated flow and transport in the saprolite of fractured sedimentary rocks: effects of periodic wetting and drying," *Water Resources Research*, vol. 39, no. 7, 2003.