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Research Article

Degradation of Strength and Stiffness of Sandstones Caused by Wetting-Drying Cycles: The Role of Mineral Composition

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Rock mechanical parameters are of great importance for the construction and design of rock engineering. Rocks are usually subjected to the deteriorating effect of cyclic wetting-drying because of the change in moisture content. The main objective of this study is to reveal the degradation effects of wetting-drying cycles on strength and modulus on varying rocks. Three kinds of sandstones with different mineral constituents are selected for testing. Artificial treatments of cyclic wetting-drying are conducted on respective specimens of the three sandstones (0, 10, 20, 30, and 40 cycles) to simulate the damage of rocks exposed to natural weathering. Uniaxial compressive tests are carried out on sandstone specimens to obtain their strength and modulus. Test results show that, for the tested sandstones, both of the uniaxial compressive strength (UCS) and modulus are reduced as the cyclic number rises. In the first ten cycles, the losses of UCS and modulus are very significant. Subsequently the changes of UCS and modulus become much more placid against cyclic number. When the cyclic number is the same, the loss percentages of rock mechanical properties of the three sandstones are very different which mainly depends on the contents of expandable and soluble minerals.

1. Introduction

In the pluvial region, rock masses are commonly exposed to cyclic wetting-drying (WD) interactions in many rock engineering applications, such as slope, mining, tunnelling, and underground storage [1–3]. The periodic cyclic WD can deteriorate the mechanical characteristics of rocks, which would cause some engineering geological hazards, e.g., ground subsidence, landslide, and mine collapse [4–7]. Thus, on account of the stability and safety of rock engineering, a deep understanding the deformation and mechanical behavior of rocks exposed to WD cycles is of great significance.

So far, the impact of WD weathering on rock mechanical properties has been widely explored. For instance, Hale and Shakoor [8] performed uniaxial compressive tests on six kinds of sandstones after 50 WD cycles. They reported that no remarkable correlation between uniaxial compressive strength (UCS) and WD cycles can be found. Similar tests have been widely carried out under quasistatic and dynamic conditions. More researchers however hold the opinion that as the number of WD cycles increases, the UCS of rocks is decreased [9–20]. Except for uniaxial compressive tests, many other types of experimental tests were also performed on rock specimens exposed to cyclic WD treatments, such as triaxial compressive test [13, 21, 22], Brazilian disc test [17, 23, 24], bending test [25–27], and shear test [28, 29]. For example, Zhang et al. [29] found that under the same vertical stress, the shear strength of siltstone declines after cyclic WD treatments. Hua et al. [26, 27] measured mode I and mode II fracture toughness of a Chongqing sandstone of sandstone and found that the two modes of fracture toughness are decreased by 52.4% and 56.2% when the sandstone specimen is endured seven WD cycles. Zhou et al. [24] first investigated the dynamic tensile properties of sandstone

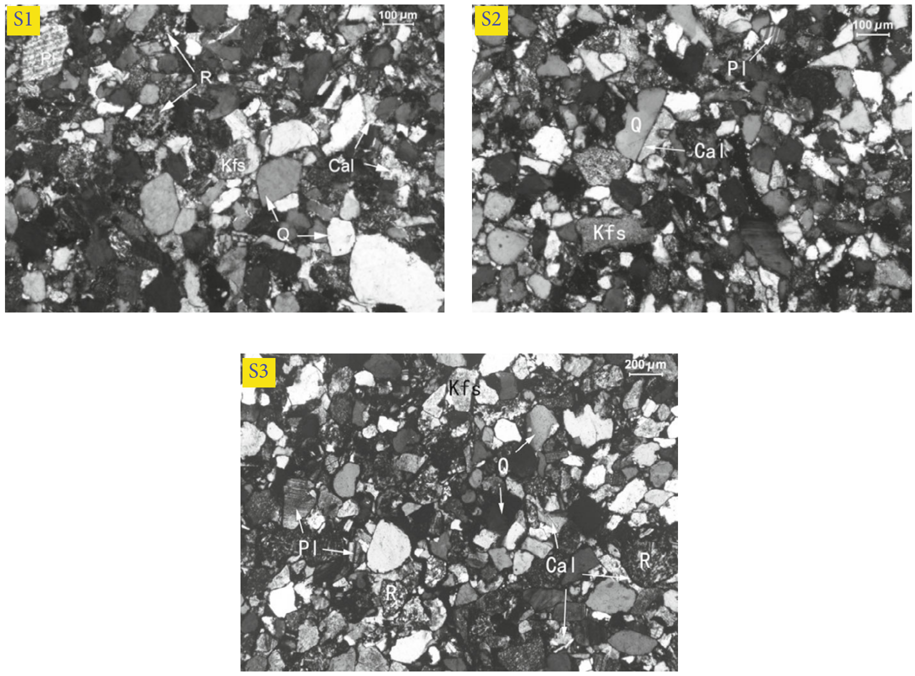

Figure 1: Optical microscope images of the three tested sandstones.

subjected to cyclic WD treatments by means of a split Hopkinson pressure bar. They discovered that as the WD cycles rises, the dynamic tensile strength of sandstone declines significantly at given loading rates. Also, they established a strength prediction model considering rate effect and WD deterioration. Overall, the strength, stiffness, and fracture toughness of different rocks experience varying deterioration levels after cyclic WD. However, the underlying mechanism is not understood. Technically speaking, the test data in different publications are not comparable due to the differences in lab weathering methods and testing conditions, such as wetting or drying method, testing machine, and loading speed.

This research is aimed at understanding the deterioration of mechanical behavior of rock caused by cyclic WD; a series of uniaxial compressive tests are conducted on three kinds of sandstone specimens. The strength and elastic modulus of sandstone specimens after different WD cycles are obtained. The sensitivity of mechanical behavior for the three sandstones to cyclic WD deterioration is revealed. The weakening mechanisms induced by cyclic WD are elucidated.

2. Experimental Method

2.1. Testing Materials and Specimen Preparation. Three kinds of sandstones with different engineering properties are selected for test materials, which are labelled as S1, S2, and S3, respectively. The optical image of thin sections for the three sandstones is shown in Figure 1. Their mineralogical constituents are measured via X-ray diffraction (XRD) technique, as listed in Table 1. As seen in Table 1, mineral contents of the three sandstones are very different. S1 holds abundant content of clay minerals (about 13.77%), while S3 has few clay minerals (less than 1%). S2 has a moderate clay content of 2.03%.

Table 1: Mineral constituents of the three sandstones.

Mineral		Mass percentage (%) S1	S2	S3
Quartz		57.20	44.94	63.39
Feldspar		13.48	28.71	29.09
Calcite		5.26	17.36	1.79
Hematite		6.45	5.35	1.07
Mica		3.84	1.61	2.21
Clay	Smectite	9.72	0	0
	Chlorite	4.05	2.03	0
	Clinochlore	0	0	<1

50 mm rock cores are first drilled from one single slate without visible discontinuities. Then, the cores are sliced into cylindrical specimens with the length slightly greater than 100 mm. Subsequently, all ends of each specimen are polished by a grinding machine to the top and bottom surfaces planar to each other and perpendicular to the long axis of this specimen. After specimen manufacturing, the internal moisture of all specimens is removed via the oven-dried method under a constant temperature of 50°C for more than 48 hours. These specimens are considered the specimens free from cyclic WD treatments for comparison.

The whole artificial WD treatment includes a free-soaking period and oven-drying period, as depicted in Figure 2. In the former period, the specimens are submerged a tank full of distilled water at 25°C for 48 hours to get a nominal complete water-saturated state. In the later period, the water-saturated specimens are put into the oven at 50°C for 48 hours for drying. Then, the specimens are cooled in the oven at 25°C for 2

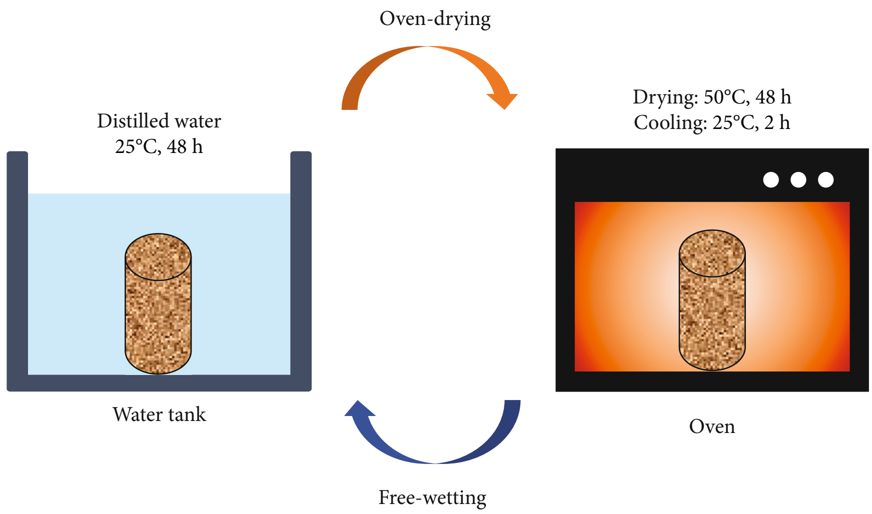

FIGURE 2: Schematic of a whole wetting-drying treatment process.

hours. For each type of rock, we design five groups of specimens experiencing 0, 10, 20, 30, and 40 WD cycles for testing. Each group prepares five specimens.

2.2. Experimental Setup. A servocontrolled material testing system (MTS 332) is used to perform all uniaxial compressive tests are performed on a servocontrolled material testing system (MTS 332), as seen in Figure 3. The MTS 332 has a global stiffness of 1370 kN/mm and a loading capacity of 500 kN. The displacement-control loading approach is adopted. During tests, the displacement speed is maintained at 0.24 mm/min until specimen failure, i.e., the axial deformation rate of the specimen is nearly $4 \times 10^{-5}\,s^{-1}$. The applied axial load is recorded by a load cell in the machine. The axial deformation of the specimen is determined by a linear variable differential transformer attached besides the specimen.

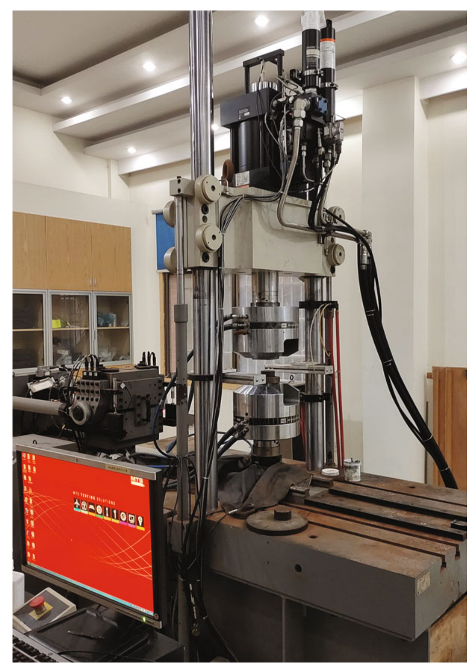

FIGURE 3: Photographic view of the loading apparatus.

3. Test Results and Discussion

3.1. Effect of WD Cycles on Rock Strength. Figure 4 shows the uniaxial compressive strength (UCS) of the tested sandstones after cyclic WD treatments. We can observe that, for the original specimen, the rank of UCS is S3 > S2 > S1. With the increasing number of WD cycles (n), the UCS of each sandstone decreases with different declining rates. For S1 and S2, their UCS experiences relatively remarkable changes with the increasing cyclic number. However, the UCS of S1 has very slight reduction induced by cyclic WD.

Figure 5 further presents the normalized UCS of the tested sandstones. It is found that the UCS of the three tested sandstones drops dramatically in the first ten WD cycles and then stabilizes. This phenomenon agrees with test data in many prior studies [10–12, 14, 20]. After 40 WD cycles, the percentage of UCS reduction for S1, S2, and S3 is 29.99%, 17.78%, and 7.15%, respectively.

As reported by Zhou et al. [20], the relationships between rock properties and the number of WD cycles (n) can be characterized by the exponential form:

$$\sigma_c(n) = a + be^{-cn}, \tag{1}$$

where σ_c is UCS and a, b, and c are fitting constants. Specifically, the term of b is a dimensionless constant, which represents the strength reduction rate as the increase of n. The higher value of b means the stronger sensitivity of UCS to WD cycles.

To compare the UCS sensitivity of the tested sandstones to WD cycles, we fit the test data according to Equation (1) as shown in Figure 4. The specific relation expressions are

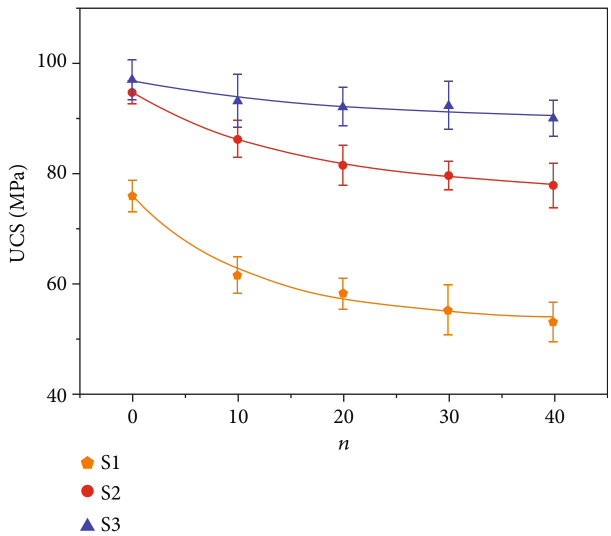

Figure 4: Variation in the UCS of tested sandstones versus the number of WD cycles.

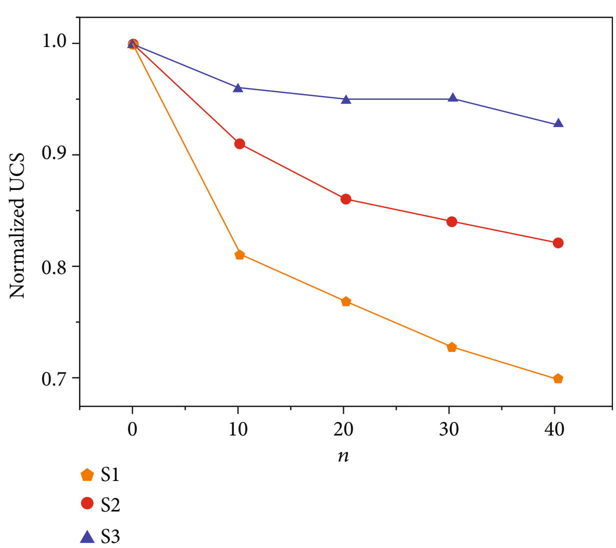

Figure 5: Normalized UCS of tested sandstones versus the number of WD cycles.

$$\begin{cases} \sigma_{c1}(n) = 53.49 + 22.41e^{-0.087n} \left(R^2 = 0.978\right), \\ \sigma_{c2}(n) = 76.84 + 17.92e^{-0.064n} \left(R^2 = 0.999\right), \\ \sigma_{c3}(n) = 89.73 + 7.18e^{-0.053n} \left(R^2 = 0.885\right), \end{cases} \quad (2)$$

where σ_{c1}, σ_{c2}, and σ_{c3} are the UCS of S1, S2, and S3, respectively; R^2 is the coefficient of determination. From Equation (2), we can see that S1 has the largest UCS sensitivity to WD cycles, followed by S2 and S3.

3.2. Effect of WD Cycles on Rock Modulus. Initial modulus and Young's modulus are compared in the section. They are measured from the stress-strain curve. The former is calculated according to the secant modulus at the strain of 0.2%, and the latter is the gradient of the linear portion.

Figure 6 shows the changes in initial modulus and Young's modulus of the tested three sandstones versus the number of WD cycles. From Figure 6(a), for all tested sandstones, the average values of initial modulus decrease as the cyclic number increases. Initially, the average initial modulus of S1, S2, and S3 are 3.59 GPa, 4.28 GPa, and 2.88 GPa, respectively. After 10 cyclic WD treatments, they are decreased to 2.44 GPa, 3.46 GPa, and 2.63 GPa. Thereafter, the initial modulus declines more slowly and tends to become stable as cyclic number rises. It also can be seen from Figure 6(b) that, when a rock specimen is experienced a given number of WD cycle, its Young's modulus is greater than initial modulus. Also, Young's modulus follows a similar decreasing pattern as the initial modulus.

Figure 7 further displays the modulus reduction of sandstones after 40 WD cycles. We can observe that when the tested three sandstones are subjected to 40 WD cycles, the initial modulus of S1, S2, and S3 is reduced by 49.03%, 33.88%, and 16.32%, respectively. The loss percentage of Young's modulus is 38.38%, 18.14%, and 4.16% for S1, S2, and S3, which is much lower than that of initial modulus.

4. Discussion

4.1. Weakening Mechanism for Strength Reduction Induced by WD Cycles. It is extensively shared that the presence of water plays a dominant weakening role on rock strength and stiffness due to physical-chemical-mechanical water-rock interactions [19, 30–34]. Some water-weakening effects will be vanished when the rock is dried again, but some are not and lead to irreversible damage of rock structure [35]. Cyclic WD treatments further aggregate the cumulative damage. The underlying mechanisms for the rock damage induced by WD cycles are as follows [25]:

(1) Mechanical cracking induced by expandable minerals: when the rock is immersed in water, some expandable minerals, e.g., smectite, will absorb water molecules and dilate. The swelling pressure on the pore wall will promote the creation and propagation of intergranular cracks [36]. Also, in the oven-drying period, the swelling pressure will decrease as the free water evaporates. During cyclic WD treatments, the pores containing expandable minerals are actually subjected to repeated tensile loads. This fatigue loading further damages the rock structure [25]

(2) Mineral dissolution: mineral grains are commonly insoluble in distilled water. However, under atmospheric condition, the calcite will react with distilled water due to the presence of gaseous carbon dioxide as follows [37]:

$$\begin{cases} H_2O + CO_2(g) \longrightarrow H^+ + HCO_3{}^- \\ CaCO^3 + H^+ \longrightarrow Ca^{2+} + HCO_3{}^- \end{cases} \quad (3)$$

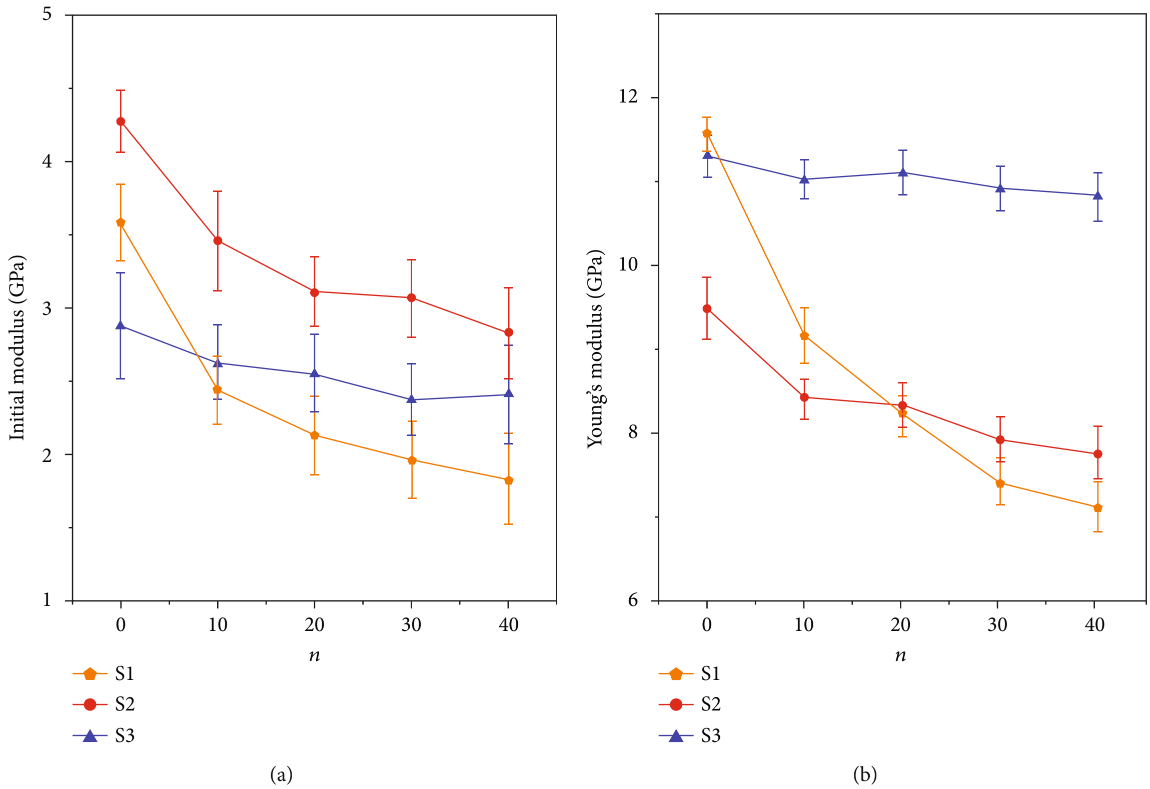

FIGURE 6: Variation in (a) initial modulus and (b) Young's modulus of tested sandstones versus the number of WD cycles.

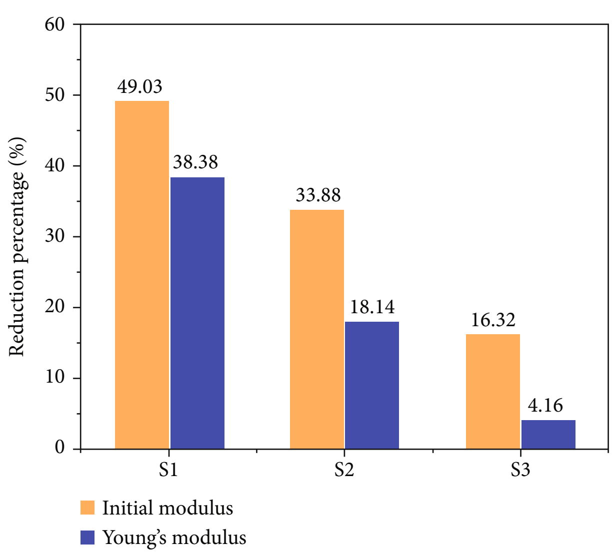

FIGURE 7: Reduction percentage of initial modulus and Young's modulus after 40 WD cycles.

The abovementioned two reactions can increase the crack density in rock, which is verified from scanning electron microscope [13, 25] and computerized tomography [17]. This will further decrease the rock strength. Hence, we can deduce that the strength reduction induced by cyclic WD is highly controlled by the content of expansible minerals (smectite) and soluble minerals (calcite). It can be seen from Figure 8 that the percentage of UCS loss after 40 cycles rises as the percentage of clay mineral increases. However, there is no clear correlation between the UCS loss and calcite content. Thus, we can infer that the smectite swelling plays a more important role in rock deterioration than calcite dissolution. Among the tested three sandstones, S1 has the most content of smectite (9.72%) and a moderate content of calcite (5.26%); thus, it experiences the greatest UCS loss caused by cyclic WD and is most sensitive to cyclic WD. Though there is no smectite in S2, it has a considerable content of calcite, such that the UCS reduction of S2 is the second largest after S1. In S3, no expandable minerals and a little content of calcite exist. These results in the UCS of S3 are not sensitive to WD cycles.

4.2. Weakening Mechanisms for Modulus Reduction Induced by WD Cycles. As known, the initial modulus is an indicator of the volume of microdefects within the rock specimen. The lower initial modulus means the greater volume of initial defects. As discussed in Section 4.1, after cyclic WD treatments, the crack density in rock specimen will increase primarily due to mechanical cracking and mineral dissolution. The decrease of initial modulus verifies our hypothesis to some extent. The loss percentage of modulus is related to the increment of defect volume caused by WD cycles. Similar with UCS, the different sensitivities of modulus to cyclic WD depend on the content of smectite and calcite.

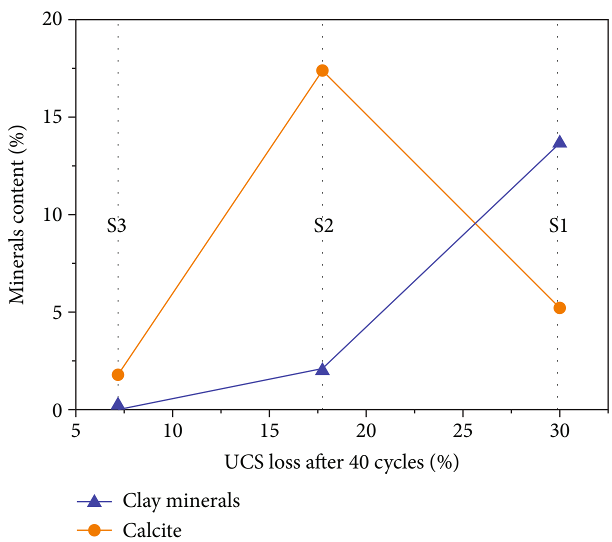

Figure 8: Relationship between UCS loss percentage and mineral content.

4.3. Engineering Significance. Rock strength and modulus are very crucial parameters for rock engineering design and construction [38]. In practice, rock structures are commonly exposed to water erosion and cyclic wetting-drying degradation. Our test results reveal that rock strength and modulus will be decreased after cyclic WD treatments. The declining extent is mainly controlled by the contents of expandable and soluble minerals. Thus, it should be noted that the weakening effects of WD on rock strength and modulus should be considered. Before rock engineering design, the rainy period or the variation of water table should be surveyed; the engineering indicators of rock are predicted according to the water cyclic period and the service life of project. Moreover, some potential protection methods can be adopted to alleviate water-weakening effects [25]:

(1) Rocks containing high contents of expandable (e.g., smectite) and soluble (e.g., calcite) minerals cannot be used for critical structures, such as the key pillar in underground cavern

(2) Waterproof measures must be applied in critical rock structures

(3) To clog the channels of water seepage, specific binders can be used on rock structures to repair the visible fractures and cracks

5. Conclusions

In the present study, we aim to understand the effects of wetting-drying cycles on the strength and modulus of different rocks; uniaxial compressive tests were carried out on three kinds of sandstone specimens suffering different numbers of artificial cyclic wetting-drying treatments (up to 40 cycles). The following specific conclusions can be made:

(1) For the tested sandstones, when they suffer wetting-drying cycles, their uniaxial compressive strength and modulus are decreased in different contents

(2) The losses of strength and modulus are commonly remarkable in the first ten cycles, and then, the declining rate is much gentler

(3) The sensitivity of rock strength and modulus to wetting-drying cycles is controlled by the mineral composition of rock. The clay swelling and calcite dissolution are probably the dominating mechanisms for the degradation of rock properties after wetting-drying cycles

Data Availability

Data can be available from the corresponding author by request.

Conflicts of Interest

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

Acknowledgments

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