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Experimental Study on Mechanical Properties and Deterioration Mechanism of Red Sandstone from the Panjiatuo Landslide under Action of Acidic Drying–Wetting Cycles

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Abstract: Due to frequent water level fluctuations and complex hydrochemical environments, rock slopes in reservoir areas progressively deteriorate and become unstable. This study investigated the coupling effect of drying–wetting cycles and acidic solutions on the physical and mechanical properties, strain field evolution, failure mode, and micro-mechanism of red sandstone using a series of laboratory experiments (wave velocity tests, uniaxial compression tests, the digital image correlation method, scanning electron microscopy, and X-ray diffraction). The results showed that with increasing drying–wetting cycles, the mass, P-wave velocity, elastic modulus, and uniaxial compressive strength decreased monotonically, while the water absorption and apparent strain in the strain localization band increased. Moreover, the failure mode transitioned gradually from tensile failure to shear failure or tensile-shear composite failure. The decrease in the solution pH values aggravated the changes in the physical and mechanical parameters and contributed to an increase in the secondary cracks and the occurrence of shear behavior. In addition, the coupling effect of drying–wetting cycles and acidic solutions accelerated the worsening of the microstructure and the dissolution of minerals, resulting in a loose structure with well-developed pores and fissures. These changes provide a favorable explanation for the mechanical property deterioration of red sandstone subjected to acidic drying–wetting cycles.

Keywords: red sandstone; acidic drying–wetting cycle; mechanical property; micro-mechanism; strain field evolution



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1. Introduction

Over the past few decades, China has made great progress with regard to the construction of large-scale water conservancy projects, such as the Three Gorges Dam, the Baihetan Arch Dam, and the Gezhouba Dam. These infrastructures have greatly improved people's lives and the economy, but they have induced a few unnoticed risks to the security of reservoir bank slopes [1–3]. For instance, the water level in the Three Gorges Reservoir area repeatedly fluctuates between 145 m and 175 m throughout the year. The frequent action of drying–wetting cycles can lead to a decline in the performance of slope rocks [4]. Moreover, the water in nature is commonly acidic rather than neutral due to the atmospheric environment, industrial sewage, and acid rain [5,6]. As a consequence, slope rocks are exposed to complex conditions with the coupling effect of drying–wetting cycles and acidic solutions, resulting in a rapid deterioration of the performance of rocks, especially the mechanical properties. This weathering process has a complicated deterioration mechanism and a large degree of deterioration, and it may cause the occurrence of geological disasters. Therefore, studying the deterioration laws and deterioration mechanism of the mechanical properties of rocks under the coupling effect of drying–wetting cycles and acidic solutions is crucial for the prevention of geological disasters and the stability of reservoir bank slopes.

It has long been recognized that the mechanical behavior of rocks changes gradually under the effect of environmental factors, such as water and temperature [7–9]. The action of drying–wetting cycles is actually associated with the two factors [10]. Increasing drying–wetting cycles deteriorates the mechanical parameters of rocks, such as the peak stress, elastic modulus, cohesion, and internal friction angle [11–13]. Liu et al. [14] found that the cyclic drying–wetting could result in the dissolution loss of various minerals, an increase in porosity, and the formation of voids and fractures in the sandstone. These changes ultimately contributed to a reduction in rock strength. Gratchev et al. [15] also observed a decreasing trend in the strength of hard rocks subjected to drying–wetting cycles. Li et al. [16] indicated that more micro-cracks were generated inside the rock with the increase in drying–wetting cycles, and this was the reason for the deterioration in the strength and deformation characteristics. According to the test results of ignimbrites after different drying–wetting cycles, Ozbek [17] proposed linear regression models to evaluate the long-term physical and mechanical properties of building stones under atmospheric conditions. Most of the investigations have focused on the weakening effect of drying–wetting cycles on rocks in a neutral environment, while rocks are more likely to be in an acidic or alkaline condition. A few studies found that the mechanical parameters of rocks also decreased with the increase in the number of drying–wetting cycles in acidic solutions, and the solution with a lower pH value could lead to a more severe deterioration of mechanical properties [18]. For instance, Dehestani et al. [19] and Liang and Fu [20] investigated the fracture characteristics of the sandstone subjected to drying–wetting cycles in solutions with different pH values. They indicated that the acidic solution had the greatest performance degradation, followed by the alkaline and neutral solutions. Shen et al. [21] investigated the uniaxial compressive strength degradation of the basalt under the coupling effect of chemical solutions and drying–wetting cycles. They also pointed out that the degradation effect of drying–wetting cycles on the strength was distinctly different, and the degradation in the acidic solution was more severe than that in the other solutions. Yuan et al. [22] analyzed the attenuation mechanism of the sandstone strength under different drying–wetting cycles and chemical solutions according to the basic principles of chemical thermodynamics and chemical kinetics. The stability of the main minerals in the neutral, alkaline, and acidic solutions was confirmed.

As an advanced non-contact full-field deformation measurement, the digital image correlation (DIC) method is increasingly used in rock mechanics [23,24]. Munoz et al. [25] investigated the strain field and strain localization of the rock surface using the 3D-DIC method. They found that the strain localization occurred gradually and developed at a low rate before the peak stress but became visible after the peak stress. Song et al. [26] observed that the displacement evolution in the deformation localization zone of rock specimens remained linear before the peak stress and showed an accelerating characteristic in the post-peak stage. They further carried out a series of uniaxial compression tests at different loading rates on the rock and proposed that a high loading rate resulted in the more rapid evolution of deformation fields and the greater stress value corresponding to the onset of deformation localization [27]. In essence, the evolution of strain fields during rock deformation and failure reflected the generation and expansion patterns of internal fractures [28]. Nguyen et al. [29] proposed an extended DIC method for discontinuous displacement measurements of soft rock. This method could identify the imperceptible fractures and quantitatively analyze the fracture patterns. Sharafisafa et al. [30] carried out a series of mechanical experiments with the DIC method on 3D-printed rock-like material, and they investigated the fracture initiation and propagation mechanism as well as fracture coalescence.

The above investigations have mainly focused on the variation in the mechanical parameters of rocks subjected to drying–wetting cycles in a neutral environment, and some scholars have realized that rock engineering is mostly exposed to a complex hydrochemical environment. However, there remains a lack of data on the failure mode and deterioration mechanism of rocks under the coupling effect of drying–wetting cycles and acidic solutions.

This study used the red sandstone collected from the Panjiatuo landslide as the experimental object and investigated the coupling effect of drying–wetting cycles and acidic solutions on the physical and mechanical properties. The strain field evolution and failure mode of the red sandstone before and after cyclic drying–wetting treatment in different solutions were highlighted using the DIC method. In addition, the micro-mechanism of mechanical property deterioration was analyzed by combining scanning electron microscopy and X-ray diffraction.

2. Materials and Methods

2.1. Sample Preparation

The Panjiatuo landslide is located in the Yunyang County of Chongqing near the Yangtze River (see Figure 1a). The field investigation showed that due to the repeated fluctuation in the reservoir water, the action of drying–wetting cycles has a significant weakening effect on the rock mass, resulting in the deformation and local instability of the landslide. The red sandstone of the Jurassic Shaximiao Formation (J_{2s}) used in this study was collected from the bedrock of the landslide (see Figure 1b) and sent back to the laboratory for sample preparation. The cylindrical samples were drilled with a height of 100 mm and a diameter of 50 mm, and their appearances met the requirements of the International Society of Rock Mechanics ISRM [31], as illustrated in Figure 1c. In addition, wave velocity tests were carried out to eliminate defective samples, and the residual ones were later used to obtain the physical and mechanical properties using corresponding tests that followed the standards [31,32]. In the natural state, the density of the red sandstone was 2.44 g/cm^3 , the moisture content was 2.80%, and the P-wave velocity was 4050–4150 m/s.

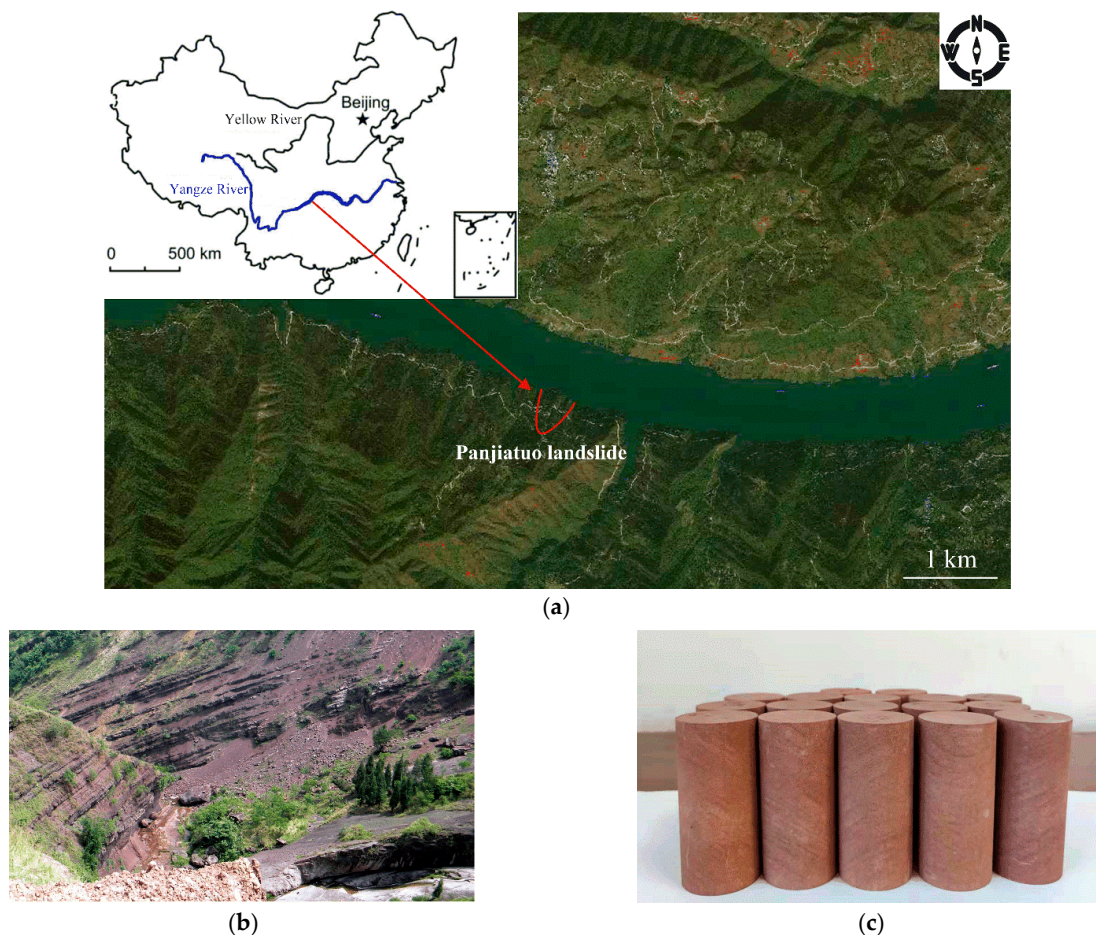


Figure 1. Sampling site of red sandstone: (a) location of the Panjiatuo landslide; (b) exposed bedrock of the Panjiatuo landslide; (c) cylindrical samples.

2.2. Experimental Procedure

To simulate the real hydrochemical environment, the distilled water and the hydrochloric acid solution were used to configure three different pH solutions (pH = 7, 5, and 3). A drying–wetting cycle was divided into two stages, i.e., drying (from saturated to dry state) and wetting (from dry to saturated state) stages. First, the selected samples were placed in a drying oven at 105 °C for 24 h to remove the moisture and then cooled to room temperature. Second, a free immersion method was carried out on the dry samples to reach the saturated state [33], i.e., the prepared solution was added to H/4 for the first time and then increased by H/4 every 2 h (H refers to the sample height). After 6 h, all samples were immersed in the prepared solution for 24 h to ensure complete saturation. The above process was regarded as a complete drying–wetting cycle, and the number of cycles (n) was set to 0, 10, 20, 30, and 40, respectively, as shown in Figure 2. In particular, fresh solutions were regularly added to the immersion solutions to keep the pH stable in the process.

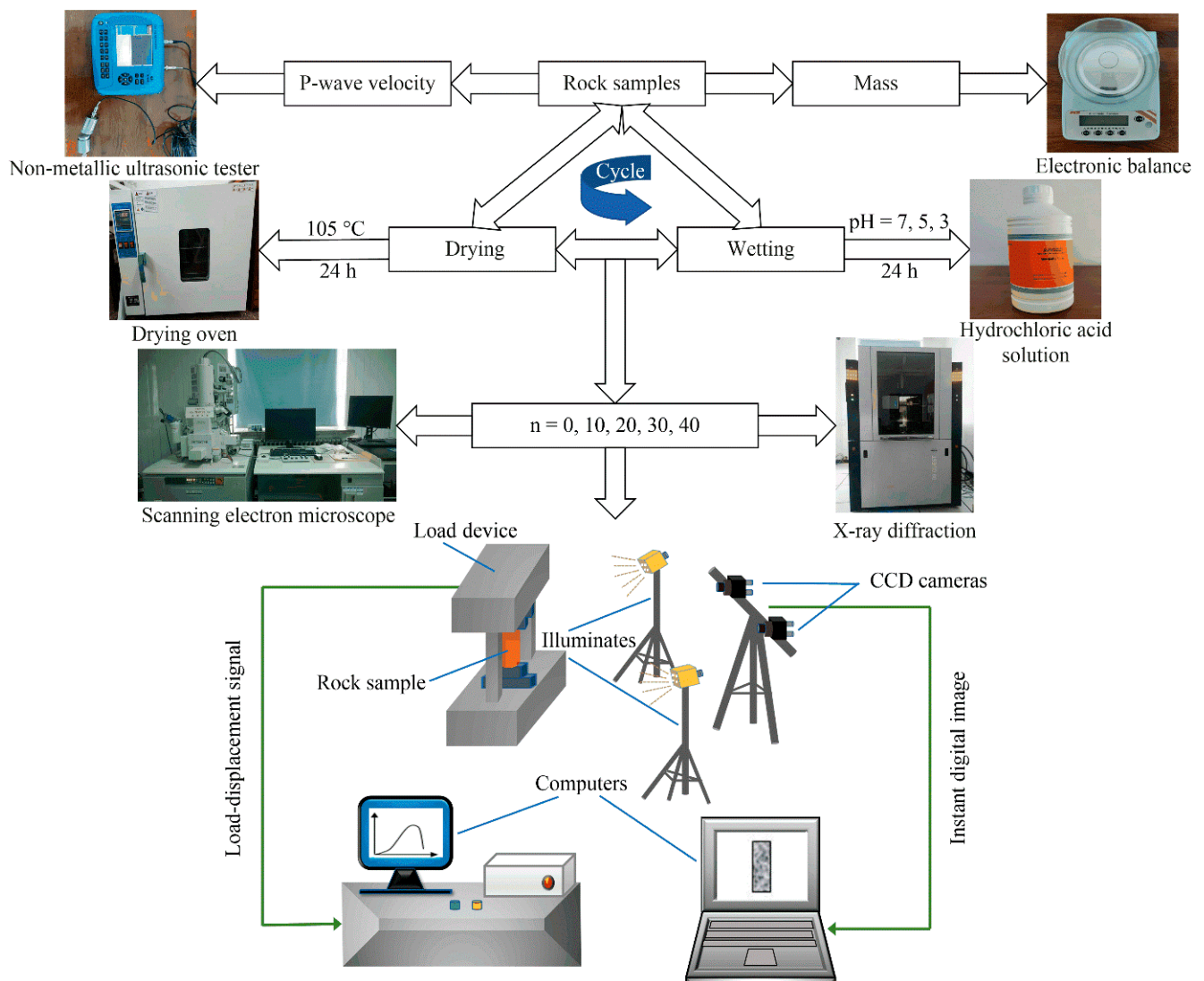


Figure 2. Schematic diagram of experimental procedure.

The mass and P-wave velocity of the samples subjected to different drying–wetting cycles were determined by an electronic balance (accuracy 0.01 g) and a non-metallic ultrasonic tester, respectively. The water absorption was calculated by the masses in the drying and saturating conditions [34]. After testing the physical properties, black and white matt spray paints were used to create a scatter of black dots on a white background on the

sample surface. Then, uniaxial compression tests were carried out on the samples with a speckle pattern. The compression testing machine was the YAW-2000, which provided a maximum axial load of 2000 kN and a measurement accuracy of $\pm 1\%$. It adopted a displacement control loading mode with a loading rate of 0.05 mm/min. The strain field evolution of samples was observed by a VIC-3D system consisting of two CCD cameras (resolution 2448 pixels $\times$ 2048 pixels), two light-emitting diodes, and a computer terminal. The VIC-3D system was initiated with the compression testing machine simultaneously and performed with a capture frame rate of 10 frames per second. A detailed description and specific working principles of the VIC-3D system can be found in previous studies [25]. In addition, scanning electron microscopy (SEM) and X-ray diffraction (XRD) were carried out on the samples before and after cyclic drying–wetting treatment in different solutions to determine the changes in the surface morphology, microscopic pore structure, and mineral content.

3. Results and Discussion

3.1. Physical Properties

Figure 3 shows the variations in the mass, P-wave velocity, and water absorption of the selected samples with increasing drying–wetting cycles in different pH solutions. As the number of drying–wetting cycles increased, the mass and P-wave velocity decreased monotonically, while the water absorption exhibited the opposite trend. For instance, for the acidic solution with pH = 3, the mass loss was 1.72%, 2.50%, 3.08%, and 3.52% as the drying–wetting cycles progressed; the loss of P-wave velocity reached 11.12%, 16.48%, 20.19%, and 21.31%, respectively; and the increment in water absorption was 12.75%, 20.83%, 25.78%, and 29.45%, respectively. These physical parameters changed quickly in the initial stage and slowly afterward, showing obvious non-linear characteristics. This indicates that the damage of drying–wetting cycles on the red sandstone is a step-by-step accumulating process. Furthermore, the changing ranges of physical parameters were highly dependent on the solution pH. As the pH value decreased, the mass loss of the samples subjected to the maximal cycles ($n = 40$) increased from 2.62% to 3.52%; the loss of P-wave velocity increased from 16.88% to 21.31%; and the increment in water absorption increased from 16.40% to 29.45%. These differences demonstrate that the variation in the physical parameters of red sandstone becomes more severe with increasing acid concentration.

The obtained results were consistent with those of previous studies [35,36], and the maximum loss of these physical parameters was approximate. This may be due to the similar mineral compositions and microstructures of these sandstones. The variation in the physical parameters actually represents the response of the microstructure and components of red sandstone to acidic drying–wetting cycles, especially the P-wave velocity and water absorption. The P-wave velocity reflects the developing degree of pores inside the rock. It decreased gradually with increasing drying–wetting cycles and acid concentration, indicating that the rock structure became loose, and the number and size of pores increased. Compared with the P-wave velocity, the water absorption reflects rock porosity in different states more directly. An increase in water absorption indicates the growth in the proportion of pores inside the rock. Hence, the two physical parameters show opposite variation trends with acidic drying–wetting cycles. In addition, the variation in water absorption was more obvious than that of the other parameter. For this reason, water absorption is considered an efficient index to evaluate rock damage under drying–wetting cycles [16].

3.2. Mechanical Properties

Figure 4 shows the stress–strain curves of typical samples under different drying–wetting cycles and pH solutions. On the whole, the curves can be divided into four phases, including the fissure closure, elastic, yielding, and failure phases. At the beginning of the axial load, the primary fractures and pores inside the samples were compressed, which may have caused concave stress–strain curves. However, the phase was inconspicuous in the present study.

During the elastic phase, the stress–strain curves were approximately straight, in accordance with Hooke’s law. As the axial load increased, the stress–strain curves entered the yielding phase, in which new fractures initiated and propagated, and the axial stress experienced a deceleration in growth until the peak stress. Afterward, the axial stress decreased rapidly with increasing axial strain, and the samples were destroyed with the formation of macro-cracks.

It can be seen that as the number of drying–wetting cycles increased, the stress–strain curve gradually moved to the lower right, namely, the slope of the elastic phase and the peak stress decreased, yet the peak strain kept increasing roughly. Moreover, the drying–wetting cycles caused a difference in the shape of post-peak curves. The post-peak curve became flatter with increasing cycles. The reason is probably that the action of drying–wetting cycles can soften the particle cementation and generate new fractures inside the rock, resulting in the weakening of brittleness and the strengthening of ductility [34]. The effect of the solution pH on the stress–strain relationship was similar to that of drying–wetting cycles. As the acid concentration increased, the slope of the elastic phase and the peak stress also decreased. The stress–strain relationship manifested a tendency to change from brittleness to slight ductility.

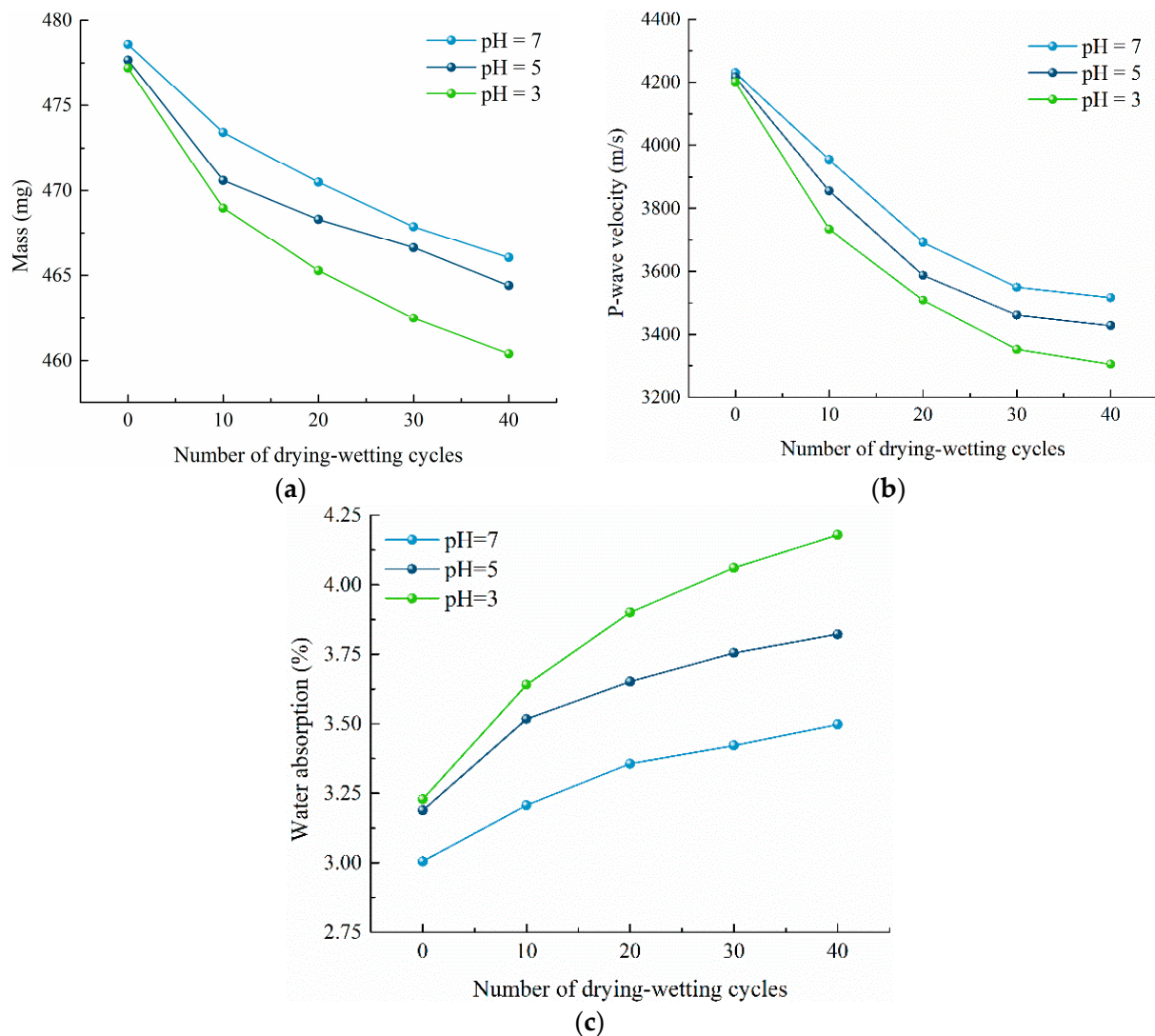


Figure 3. Relationships between the physical parameters of samples and the number of drying–wetting cycles: (a) mass; (b) P-wave velocity; (c) water absorption.

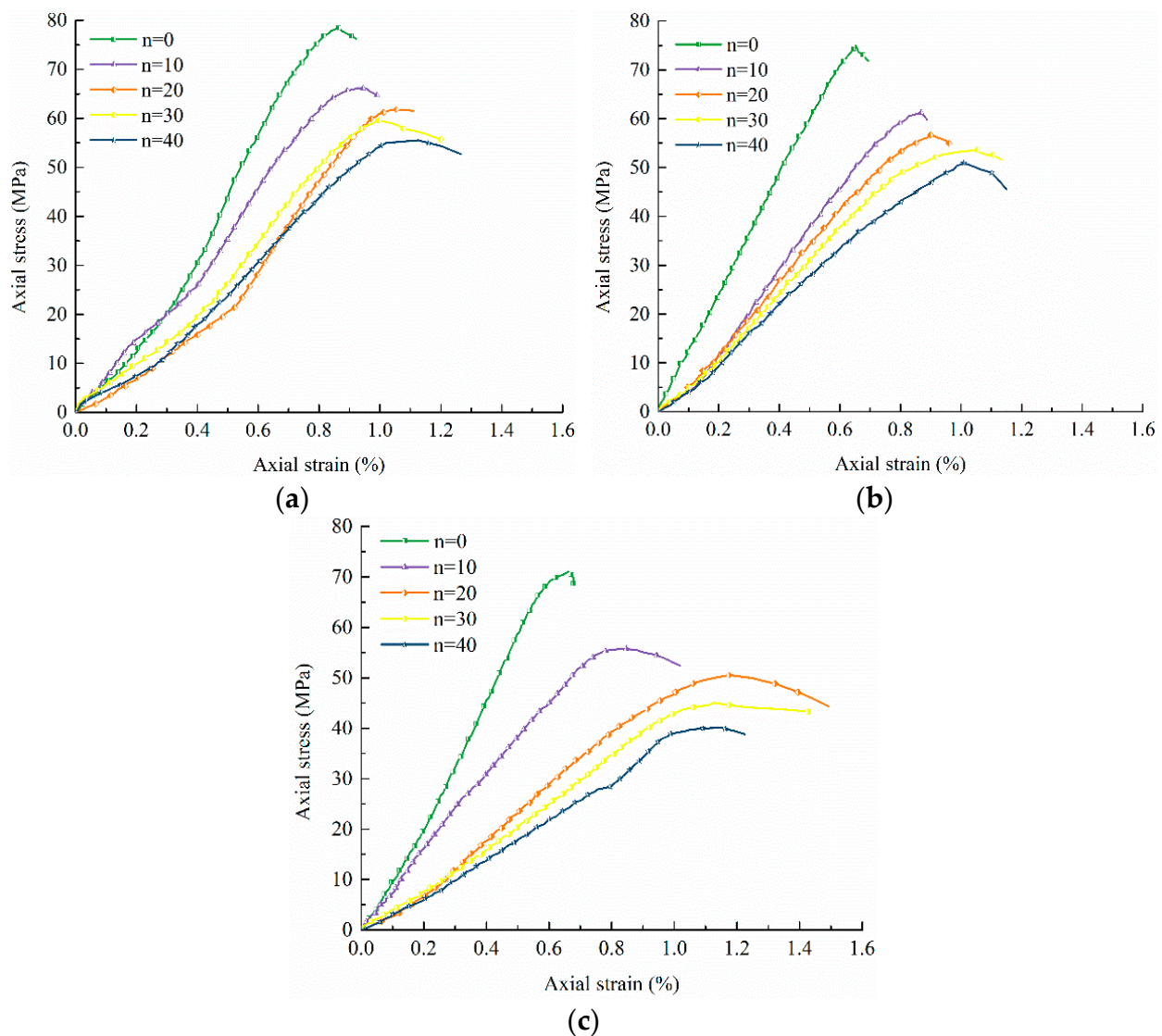


Figure 4. Stress–strain curves of typical samples under different drying–wetting cycles and pH solutions: (a) pH = 7; (b) pH = 5; (c) pH = 3.

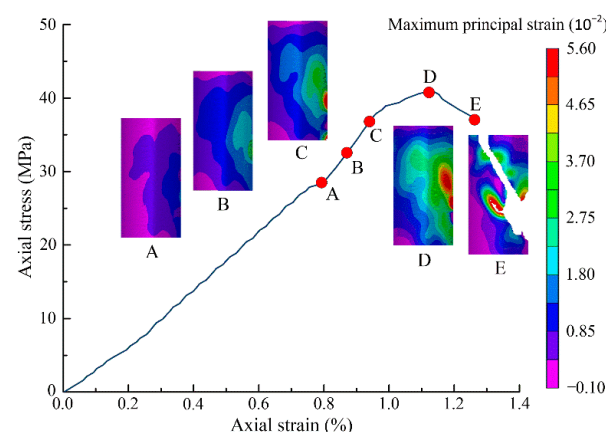
Table 1 lists the elastic modulus and uniaxial compressive strength of the selected samples under different drying–wetting cycles and pH solutions. Both the mechanical parameters decreased monotonically with increasing drying–wetting cycles. For the acidic solution with pH = 3, the elastic modulus decreased by 38.55%, 47.40%, 58.72%, and 66.30% as the cycles progressed; the uniaxial compressive strength decreased by 19.96%, 27.27%, 35.96%, and 41.43%, respectively. Furthermore, the greater the acid concentration was, the more obvious the deterioration of mechanical properties was. After 40 drying–wetting cycles, the elastic modulus of the samples soaked in pH = 7, 5, and 3 solutions decreased by 51.33%, 55.37%, and 66.30%, respectively; the uniaxial compressive strength decreased by 27.28%, 32.63%, and 41.43%, respectively. It can be concluded that the influence of drying–wetting cycles and solution pH on the deformation property of red sandstone is greater than that on the strength property. Some scholars have obtained similar experimental results [36,37]. However, the differences among these results cannot be ignored, especially the deterioration pattern and deterioration degree of mechanical properties. They are mainly dominated by the mineral composition and structure of rocks and experimental conditions [38].

Table 1. Mechanical parameters of samples under different drying–wetting cycles and pH solutions.

Cycles	Elastic Modulus (GPa)			Uniaxial Compressive Strength (MPa)		
	pH = 7	pH = 5	pH = 3	pH = 7	pH = 5	pH = 3
0	13.17	12.57	11.75	77.45	73.98	70.03
10	8.92	8.32	7.22	66.87	62.10	56.05
20	8.71	7.44	6.18	62.88	56.97	50.93
30	7.97	6.76	4.85	58.91	53.81	44.85
40	6.41	5.61	3.96	56.32	49.84	41.02

3.3. Strain Field and Failure Mode

The result obtained by the VIC-3D system showed that the strain fields of the selected samples under the axial load had a similar evolutionary trend and underwent a process from uniform distribution to inhomogeneous distribution. The strain field focused on in this study refers to the maximum principal strain field, which can effectively reflect the propagation and distribution of cracks on the sample surface during the loading process [28]. Figure 5 presents the strain field evolution of the sample subjected to 40 drying–wetting cycles in an acidic solution with pH = 3. Five representative points marked from point A to point E in the stress–strain curve were selected to display the strain field evolution. They corresponded to 70%, 80%, 90%, 100%, and 90% (in the post-peak stage) of the peak stress, respectively. It can be seen that the apparent strain of the sample showed little difference for a long time, and the strain field was uniformly distributed until point B. Afterward, the strain field transitioned to an inhomogeneous distribution, accompanied by the onset of a strain localization band on the right side of the sample. This suggests that a few micro-fractures were generated into the band. The maximal strain value exceeded 5.12×10^{-2} at point C. As the stress level was close to the peak stress, the strain localization band became more apparent and extended to the upper end of the sample progressively. Meanwhile, the area of apparent strain exceeding 5.12×10^{-2} increased significantly. After point D, the strain localization band ultimately evolved into a macro-crack, and the sample was destroyed at point E.

**Figure 5.** Stress–strain curve and strain field nephograms of the sample subjected to 40 drying–wetting cycles in the acidic solution with pH = 3.

The residual samples under the axial load also experienced the strain field evolution from homogenization to localization, as depicted above. It is worth noting that due to the coupling effect of drying–wetting cycles and acidic solutions, the development of strain localization bands and failure mode of the samples had obvious differences. The strain field nephograms at the peak stress and fractured images of the samples under different drying–wetting cycles and pH solutions are shown in Figure 6. There is a certain internal relationship between them, which is the basis for predicting the spatial distribution of rock failure from strain localization bands. However, the crack system of the latter was more

complex and abundant. The reason is that the massive release of elastic energy after the peak stress leads to the formation of secondary cracks [39]. Most of the strain localization bands initiated on the end of samples and extended to the middle or the other end with increasing axial stress. When the axial stress reached the peak stress, the strain localization bands were quite prominent. In addition, the apparent strain in the bands increased with increasing drying–wetting cycles and manifested a poor regularity with the solution pH, which is in agreement with the variation law of peak strains obtained by the compression testing machine.

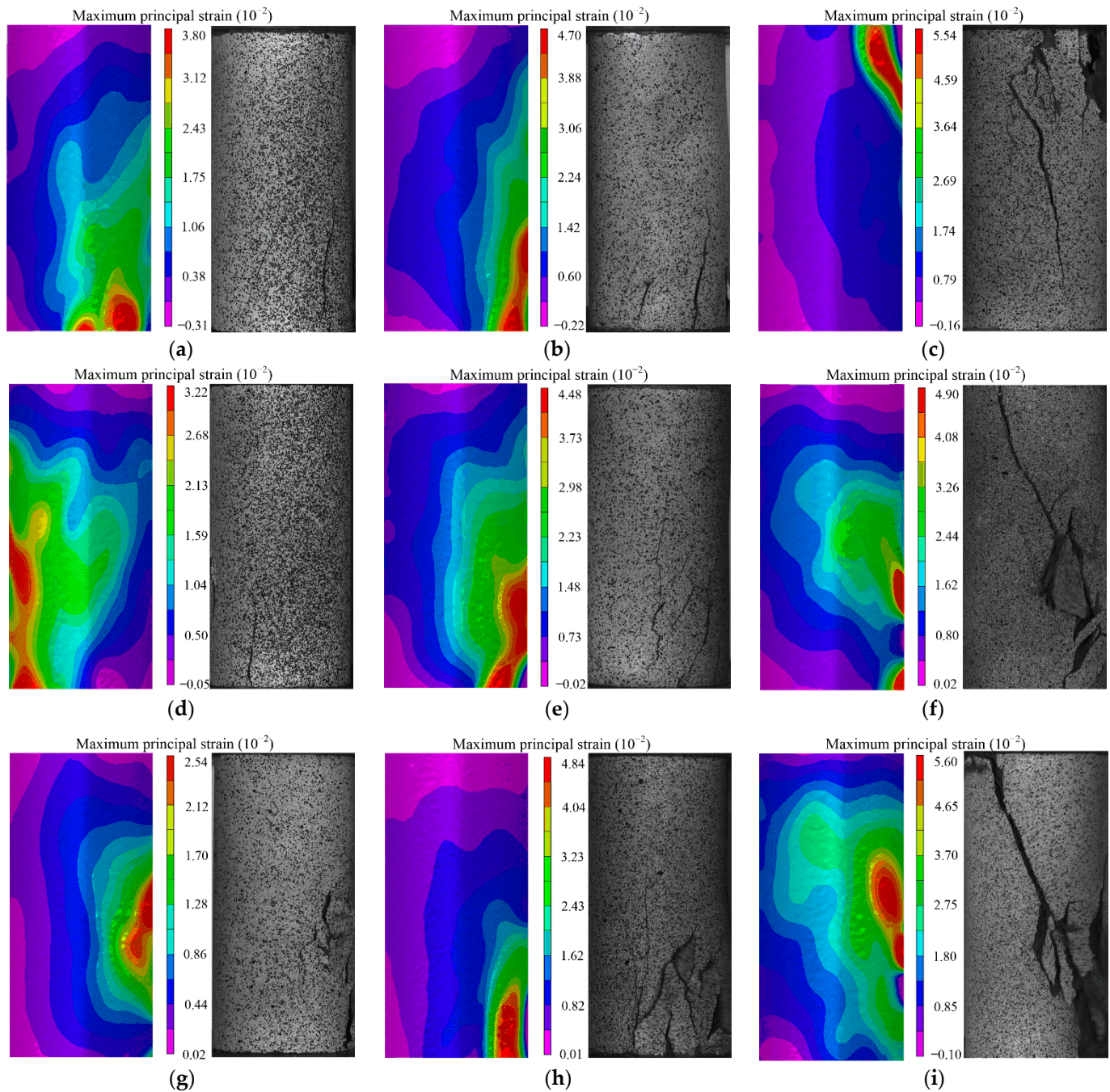


Figure 6. Strain field nephograms at the peak stress and fractured images of samples under different drying–wetting cycles and pH solutions: (a) $n = 0$, pH = 7; (b) $n = 20$, pH = 7; (c) $n = 40$, pH = 7; (d) $n = 0$, pH = 5; (e) $n = 20$, pH = 5; (f) $n = 40$, pH = 5; (g) $n = 0$, pH = 3; (h) $n = 20$, pH = 3; (i) $n = 40$, pH = 3.

The failure mode of red sandstone subjected to acidic drying–wetting cycles can be better investigated by combining the strain field evolution and fractured images. For the untreated samples ($n = 0$), the failure mode was mainly split failure along the loading direction, namely tensile failure. This is the most common mode in the uniaxial compression tests of rocks [40]. When the number of drying–wetting cycles reached 20, the samples still presented tensile failure with abundant secondary cracks. The failure mode changed from tensile failure to shear failure or tensile-shear composite failure until 40 drying–wetting cycles. Unlike the action of drying–wetting cycles, the effect of acid concentration on the failure mode was not evident. When the samples were dominated by tensile failure, the decrease in the solution pH values led to an increase in the secondary cracks and generated a more complex crack system on the sample surface. Moreover, it contributed to the shear behavior of the samples, which caused the sample subjected to 40 drying–wetting cycles in the acidic solution with pH = 3 to present a pure shear failure instead of tensile-shear composite failure. Hence, the effect of acid concentration on the failure mode was essentially consistent with that of drying–wetting cycles, while the latter was dominant.

3.4. Microstructure and Mineral Composition

Figure 7 shows the SEM images of the samples subjected to different drying–wetting cycles in the acidic solution with pH = 3. For the untreated sample ($n = 0$), the surface was smooth and had no obvious fractures and pores. The microstructure was compact, and the mineral particles were well-cemented to each other. After 10 drying–wetting cycles, the sample surface still maintained an appreciable homogeneity with a small number of pores. The majority of pores were fine and irregular and had almost no connectivity with each other. As the number of drying–wetting cycles increased, the pores on the surface increased gradually, and the cementation between the mineral particles became weak, accompanied by a change from granular particles to platy particles. Moreover, some isolated pores gradually expanded and converged into large pores or fractures. These led to a loose microstructure. When the number of drying–wetting cycles reached the maximum, the microstructure of the sample had essentially changed in contrast to the untreated sample. The changes mainly indicated that the intact and dense structure became a loose structure with the stacking of fragmented particles, and the pores and fissures were well-developed.

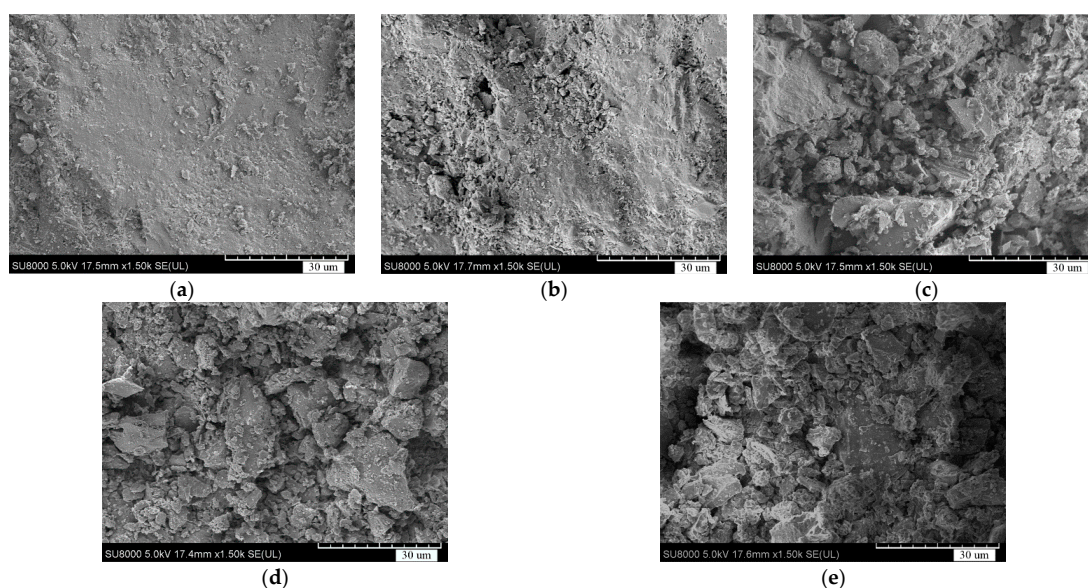


Figure 7. SEM images of samples subjected to different drying–wetting cycles in the acidic solution with pH = 3: (a) $n = 0$; (b) $n = 10$; (c) $n = 20$; (d) $n = 30$; (e) $n = 40$.

In order to investigate the effect of solution pH values on the microstructure of red sandstone, the SEM images of the samples before and after cyclic drying–wetting treatment in the solutions with pH = 7 and 5 were supplemented, as shown in Figure 8. Before cyclic drying–wetting treatment, the microstructures of the samples soaked in different solutions were compact and smooth with a high cementation degree, and they had few significant differences. This indicated that the effect of the solution pH values on the microstructure of the untreated samples was not evident. As expected, the effect reached a maximum after 40 drying–wetting cycles. At pH = 3, the microstructure deterioration was the most serious. The microstructure changed from densification to looseness, accompanied by abundant pores and fissures. The mineral particles became platy and were stacked together in a disorderly manner. The deterioration of microstructures in the solution with pH = 7 was the mildest, and the deterioration in the solution with pH = 5 fell in between that of the other conditions. For the sample subjected to 40 drying–wetting cycles in the neutral solution, the microstructure deteriorated, but some large particles still existed and were not completely fragmented. In short, the microstructure became increasingly worse as the drying–wetting cycles and acid concentration increased.

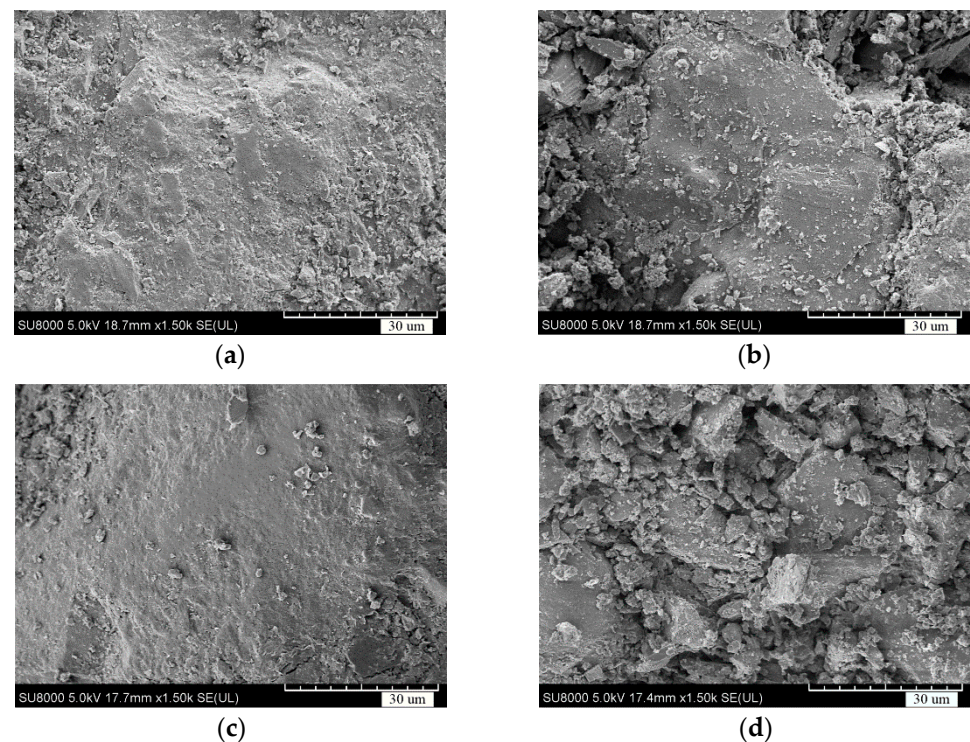


Figure 8. SEM images of samples under different drying–wetting cycles and pH solutions: (a) $n = 0$, pH = 7; (b) $n = 40$, pH = 7; (c) $n = 0$, pH = 5; (d) $n = 40$, pH = 5.

Figure 9 shows the XRD patterns and relative mineral contents of the samples under different drying–wetting cycles and pH solutions. It can be observed that quartz was the most abundant component in the samples, followed by feldspar. The other components included calcite and a small number of clay minerals. Due to the chemical reactions with hydrogen ions (H^+), the contents of the minerals in the acidic solutions were generally less than those in the neutral solution, while the content of quartz showed the opposite trend. At pH = 7, the contents of the minerals decreased slightly with increasing drying–wetting cycles, except quartz. This was the result of the hydrolysis reaction [14]. At pH = 5, the contents of feldspar and calcite decreased significantly with increasing drying–wetting cycles, while the content of quartz increased. The content of clay minerals showed an irregular change. At pH = 3, the maximal variation in the mineral contents is observed. After 40 drying–wetting cycles, the contents of feldspar and calcite decreased by 17.08%

and 29.11%, respectively. On the contrary, the content of quartz increased by 9.51%. Thus, the variation in the mineral contents tended to be obvious as the drying–wetting cycles and acid concentration increased. In the acidic solutions, the cations (K^+ and Na^+) in the feldspar underwent a substitution reaction with H^+ , and they were separated from the rock matrix and became free. Similarly, calcite also reacted with H^+ . These chemical reactions caused the reduction in the minerals [22]. Quartz is relatively stable and hardly reacts in acidic solutions. However, the relative content of quartz inevitably increases with the decline of other minerals.

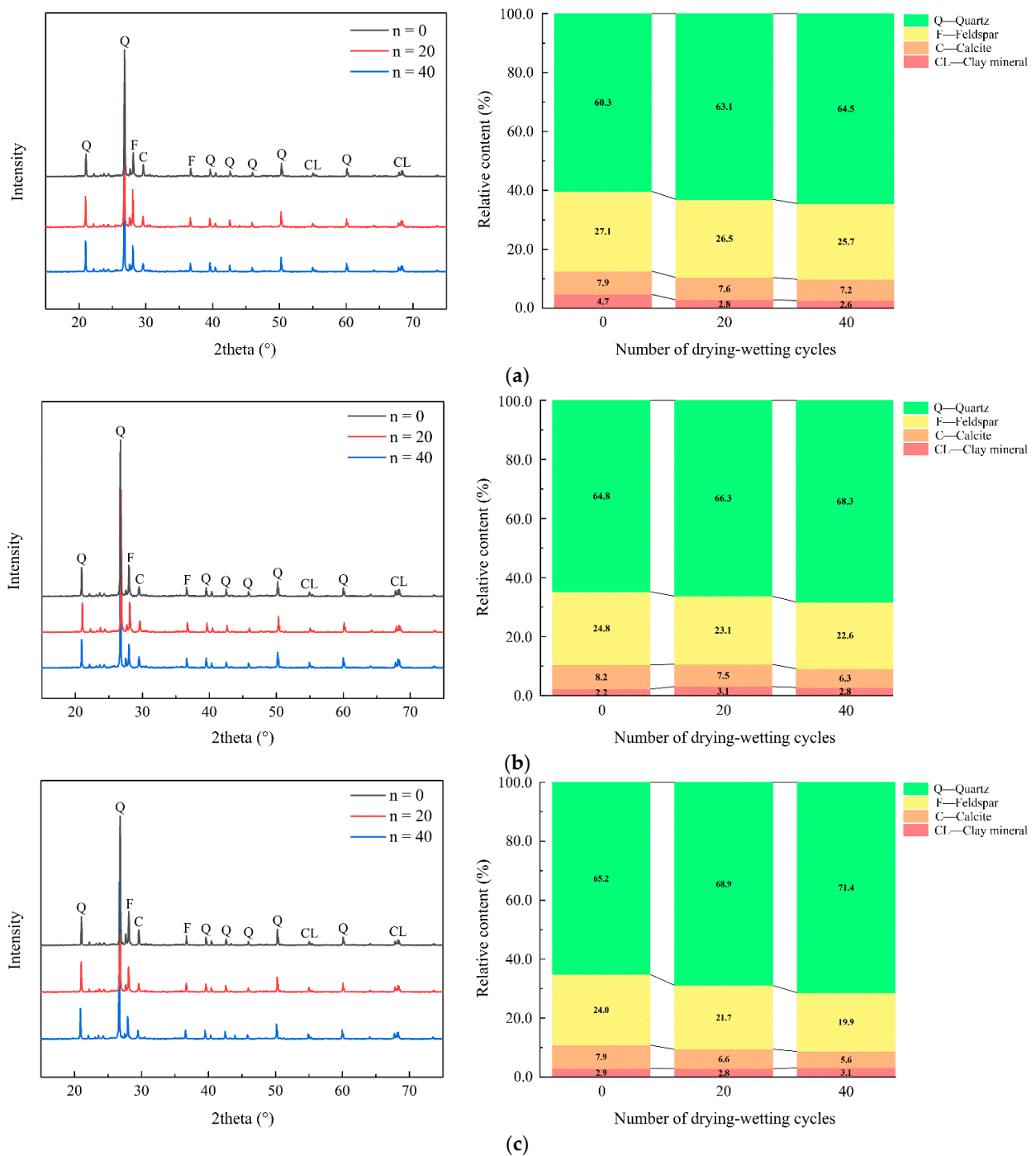


Figure 9. XRD patterns and relative mineral contents of samples under different drying–wetting cycles and pH solutions: (a) pH = 7; (b) pH = 5; (c) pH = 3.

In summary, the changes in the microstructure and mineral composition of red sandstone under acidic drying–wetting cycles were more obvious than those under neutral drying–wetting cycles. The gap between them became greater with increasing cycles and acid concentration, which is the cumulative result of drying–wetting damage and acid corrosion damage. Specifically, drying–wetting cycles focus on mechanical action, and acid corrosion focuses on chemical action. The two actions overlap and promote each other. When the red sandstone was treated with drying–wetting cycles in acidic solutions, water with hydrogen ions slowly infiltrated the interior along the primary fractures from the rock surface, and the cementation dissolved, resulting in the weakening of cohesive force between mineral particles. The water filled the open pores and evaporated constantly. This repeated action of drying and wetting led to the extension of primary fractures and the generation of new fractures. Meanwhile, hydrogen ions reacted with the feldspar and calcite in the rock, and more pores and fractures were formed. This acid corrosion further weakened the cohesive force between mineral particles, which provided better conditions for later drying–wetting cycles. Therefore, the coupling effect aggravated the deterioration of the microstructure and mineral composition of red sandstone and was much sharper than a single effect. The above micro-mechanism provides a favorable explanation for the deterioration of the physical properties, mechanical properties, and failure mode of red sandstone under acidic drying–wetting cycles.

4. Conclusions

In this study, a series of laboratory experiments were conducted to investigate the physical and mechanical properties, strain field evolution, failure mode, and micro-mechanism of red sandstone under different drying–wetting cycles and acidic solutions. The following main conclusions were drawn:

(1) With the increase in the number of drying–wetting cycles and the decrease in the solution pH values, the mass, P-wave velocity, elastic modulus, and uniaxial compressive strength of red sandstone decreased monotonically, while the water absorption increased. The stress–strain relationship showed a tendency to change from brittleness to slight ductility.

(2) Under the axial load, the strain field of red sandstone underwent a process from a uniform distribution to an inhomogeneous distribution. As the number of drying–wetting cycles increased, the apparent strain in the strain localization band increased, and the failure mode transitioned gradually from tensile failure to shear failure or tensile-shear composite failure. The influence of solution pH values on the failure mode was milder than that of drying–wetting cycles. The decrease in the solution pH values contributed to an increase in the secondary cracks and the occurrence of shear behavior.

(3) As the drying–wetting cycles progressed, the microstructure of red sandstone became increasingly loose with the development of pores and fissures, and a few minerals, such as feldspar and calcite, were gradually dissolved and separated from the rock matrix. The decrease in the solution pH values aggravated the changes in the microstructure and mineral composition. These changes provide a favorable explanation for the mechanical property deterioration of red sandstone under the coupling effect of drying–wetting cycles and acidic solutions.

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References

1. Yin, Y.P.; Huang, B.L.; Wang, W.P.; Wei, Y.J.; Ma, X.H.; Ma, F.; Zhao, C.J. Reservoir-induced landslides and risk control in Three Gorges Project on Yangtze River, China. *J. Rock Mech. Geotech. Eng.* **2016**, *8*, 577–595. [\[CrossRef\]](#)
2. Liang, J.; Sui, W. Sensitivity analysis of anchored slopes under water level fluctuations: A case study of Cangjiang bridge—Yingpan slope in China. *Appl. Sci.* **2021**, *11*, 7137. [\[CrossRef\]](#)
3. Mao, J.Z.; Guo, J.; Fu, Y.; Zhang, W.P.; Ding, Y.N. Effects of rapid water-level fluctuations on the stability of an unsaturated reservoir bank slope. *Adv. Civ. Eng.* **2020**, *2020*, 2360947. [\[CrossRef\]](#)
4. Liu, X.R.; Jin, M.H.; Li, D.L.; Zhang, L. Strength deterioration of a shaly sandstone under dry–wet cycles: A case study from the Three Gorges Reservoir in China. *Bull. Eng. Geol. Environ.* **2018**, *77*, 1607–1621. [\[CrossRef\]](#)
5. Chai, S.B.; Song, L.; Liu, H.; Abi, E.; Chai, L.Z. Experimental study on deterioration characteristics of filled jointed rock under dry–wet cycles in acidic environment. *Rock Soil Mech.* **2022**, *43*, 2993–3002.
6. Xie, S.Y.; Wang, S.J.; Yu, Y.; Liu, L.; Zhang, F.Y. Analysis on acid rain status and its change trends in China from 2003 to 2018. *Environ. Monit. China* **2020**, *36*, 80–88.
7. Zhang, C.; Bai, Q.S.; Han, P.H.; Wang, L.; Wang, X.J.; Wang, F.T. Strength weakening and its micromechanism in water–rock interaction, a short review in laboratory tests. *Int. J. Coal Sci. Technol.* **2023**, *10*, 10. [\[CrossRef\]](#)
8. Alzo’ubi, A.K.; Alneasan, M. Experimental study on the effect of thermal treatment on the mechanical properties of clay-rich rocks (mudstone). *Results Eng.* **2022**, *16*, 100728. [\[CrossRef\]](#)
9. Alneasan, M.; Alzo’ubi, A.K. Temperature effect on the fracture behavior of granite under three loading modes (I, I/II, and II). *Rock Mech. Rock Eng.* **2023**, *56*, 2197–2211. [\[CrossRef\]](#)
10. Zhang, C.Y.; Dai, Z.W.; Tan, W.J.; Yang, Y.T.; Zhang, L.H. Multiscale study of the deterioration of sandstone in the Three Gorges Reservoir area subjected to cyclic wetting–cooling and drying–heating. *Rock Mech. Rock Eng.* **2022**, *55*, 5619–5637. [\[CrossRef\]](#)
11. Doostmohammadi, R.; Moosavi, M.; Mutschler, T.; Osan, C. Influence of cyclic wetting and drying on swelling behavior of mudstone in south west of Iran. *Environ. Geol.* **2009**, *58*, 999–1009. [\[CrossRef\]](#)
12. Wu, B.; Liu, Q.; Fu, Q.; Yang, Q.; Chen, Q. Damage mechanism of prefabricated fracture-grouted rock specimens under the action of dry and wet cycles. *Appl. Sci.* **2023**, *13*, 3631. [\[CrossRef\]](#)
13. Momeni, A.; Hashemi, S.S.; Khanlari, G.R.; Heidari, M. The effect of weathering on durability and deformability properties of granitoid rocks. *Bull. Eng. Geol. Environ.* **2017**, *76*, 1037–1049. [\[CrossRef\]](#)
14. Liu, X.R.; Yuan, W.; Fu, Y.; Wang, Z.J.; Miao, L.L.; Xie, W.B. Porosity evolution of sandstone dissolution under wetting and drying cycles. *Chin. J. Geotech. Eng.* **2018**, *40*, 527–532.
15. Gratchev, I.; Pathiranagei, S.V.; Kim, D.H. Strength properties of fresh and weathered rocks subjected to wetting–drying cycles. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2019**, *5*, 211–221. [\[CrossRef\]](#)
16. Li, X.H.; Peng, K.; Peng, J.; Hou, D. Experimental investigation of cyclic wetting–drying effect on mechanical behavior of a medium-grained sandstone. *Eng. Geol.* **2021**, *293*, 106335. [\[CrossRef\]](#)
17. Ozbek, A. Investigation of the effects of wetting–drying and freezing–thawing cycles on some physical and mechanical properties of selected ignimbrites. *Bull. Eng. Geol. Environ.* **2014**, *73*, 595–609. [\[CrossRef\]](#)
18. Fereidooni, D.; Khajevand, R. Correlations between slake-durability index and engineering properties of some travertine samples under wetting–drying cycles. *Geotech. Geol. Eng.* **2018**, *36*, 1071–1089. [\[CrossRef\]](#)
19. Dehestani, A.; Hosseini, M.; Beydokhti, A.T. Effect of wetting–drying cycles on mode I and mode II fracture toughness of sandstone in natural (pH = 7) and acidic (pH = 3) environments. *Theor. Appl. Fract. Mec.* **2020**, *107*, 102512. [\[CrossRef\]](#)
20. Liang, H.; Fu, Y. Fracture properties of sandstone degradation under the action of drying–wetting cycles in acid and alkaline environments. *Arab. J. Geosci.* **2020**, *13*, 68. [\[CrossRef\]](#)
21. Shen, L.F.; Dong, W.S.; Wang, Z.L.; Xu, Z.M.; Zhu, W.M. Experimental study on the mass transfer-deterioration process of basalt under drying–wetting cycles and chemical reaction. *Chin. J. Rock Mech. Eng.* **2021**, *40*, 2662–2672.
22. Yuan, W.; Liu, X.R.; Fu, Y. Chemical thermodynamics and chemical kinetics analysis of sandstone dissolution under the action of dry–wet cycles in acid and alkaline environments. *Bull. Eng. Geol. Environ.* **2019**, *78*, 793–801. [\[CrossRef\]](#)
23. Okubo, S.; Tang, Y.; Xu, J.; Peng, S.J. Application of 3D-DIC system in rock mechanic test. *Rock Soil Mech.* **2019**, *40*, 3263–3273.
24. Wang, L.N.; Tao, C.Q.; Yin, X.M.; Han, J.; Yang, L.; Zhang, G.P. Evolution of deformation field and energy of organic-rich oil shale under uniaxial compression. *Rock Soil Mech.* **2022**, *43*, 1557–1570.
25. Munoz, H.; Taheri, A.; Chanda, E.K. Pre-peak and post-peak rock strain characteristics during uniaxial compression by 3D digital image correlation. *Rock Mech. Rock Eng.* **2016**, *49*, 2541–2554. [\[CrossRef\]](#)
26. Song, Y.M.; Jiang, Y.D.; Ma, S.P.; Yang, X.B.; Zhao, T.B. Evolution of deformation fields and energy in whole process of rock failure. *Rock Soil Mech.* **2012**, *33*, 1352–1356.
27. Song, Y.M.; Xing, T.Z.; Deng, L.L.; Zhao, Z.X. Experimental study of evolution characteristics of rock deformation field at different loading rates. *Rock Soil Mech.* **2017**, *38*, 2773–2779.

28. Jin, A.B.; Wang, S.L.; Wang, B.X.; Sun, H.; Zhao, Y.Q. Study on the fracture mechanism of 3D-printed-joint specimens based on DIC technology. *Rock Soil Mech.* **2020**, *41*, 3214–3224.
29. Nguyen, T.L.; Hall, S.A.; Vacher, P.; Viggiani, G. Fracture mechanisms in soft rock: Identification and quantification of evolving displacement discontinuities by extended digital image correlation. *Tectonophysics* **2011**, *503*, 117–128. [[CrossRef](#)]
30. Sharafisafa, M.; Shen, L.; Xu, Q. Characterisation of mechanical behaviour of 3D printed rock-like material with digital image correlation. *Int. J. Rock Mech. Min.* **2018**, *112*, 122–138. [[CrossRef](#)]
31. ISRM. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **1979**, *16*, 135–140.
32. ASTM C127-15; Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. ASTM International: West Conshohocken, PA, USA, 2015.
33. Chu, Z.X.; Zhou, G.Q.; Wang, Y.J.; Mo, P.Q.; Tang, R. Thermal–physical properties of selected geomaterials: Coal, sandstone and concrete based on basic series and parallel models. *Environ. Earth Sci.* **2018**, *77*, 181. [[CrossRef](#)]
34. An, W.B.; Wang, L.G.; Chen, H. Mechanical properties of weathered feldspar sandstone after experiencing dry–wet cycles. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 6268945. [[CrossRef](#)]
35. Huang, X.; Pang, J.Y. Study on the change of physical properties of sandstone under action of acidic drying–wetting cycles and discrete element simulation. *Bull. Eng. Geol. Environ.* **2021**, *80*, 7773–7790. [[CrossRef](#)]
36. Yuan, P.; Bu, H.; Wei, N.N. Effect of pH value on static uniaxial mechanical properties of sandstone under dry–wet cycle. *Bull. Chin. Ceram. Soc.* **2021**, *40*, 2232–2239.
37. Qin, Z.; Chen, X.X.; Fu, H.L. Damage features of altered rock subjected to drying–wetting cycles. *Adv. Civ. Eng.* **2018**, *2018*, 5170832. [[CrossRef](#)]
38. Khanlari, G.; Abdilor, Y. Influence of wet–dry, freeze–thaw, and heat–cool cycles on the physical and mechanical properties of Upper Red sandstones in central Iran. *Bull. Eng. Geol. Environ.* **2015**, *74*, 1287–1300. [[CrossRef](#)]
39. Yang, Y.M.; Ju, Y.; Chen, J.L.; Gao, F. Cracks development features and energy mechanism of dense sandstone subjected to triaxial stress. *Chin. J. Rock Mech. Eng.* **2014**, *33*, 691–698.
40. Huang, Z.; Gu, Q.X.; Wu, Y.F.; Wu, Y.; Li, S.J.; Zhao, K.; Zhang, R. Effects of confining pressure on acoustic emission and failure characteristics of sandstone. *Int. J. Min. Sci. Technol.* **2021**, *31*, 963–974. [[CrossRef](#)]

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