

Article

Investigation of Mechanical Degradation and Microstructural Evolution of Red-Bed Soft Rocks Under Wetting–Drying Cycles

Tao Peng ¹, Fanmin He ^{1,*}, Dongxing Ren ¹, Yan Li ¹, Longfei Chen ¹ and Huaping Wu ²

¹ Chengdu Surveying Geotechnical Research Institute Co., Ltd. of MCC, Chengdu 610023, China; ptgeo@foxmail.com (T.P.); rendx07@126.com (D.R.); 13540298482@163.com (Y.L.); chenlf2025@my.swjtu.edu.cn (L.C.)

² Shock and Vibration of Engineering Materials and Structures Key Laboratory of Sichuan, Southwest University of Science and Technology, Mianyang 621010, China; wuhuaping1949@126.com

* Correspondence: simba163@163.com

Abstract

To clarify the water-sensitive deterioration mechanisms of red-bed soft rocks under repeated wetting–drying cycles, mudstone samples from two representative sites in the Sichuan Basin were investigated through multiscale experiments combining mechanical testing, X-ray diffraction (XRD), and scanning electron microscopy (SEM). The results showed that samples from Sampling Site ① exhibited higher compressive strength, elastic modulus, cohesion, and friction angle due to stronger cementation and greater structural integrity, whereas samples from Sampling Site ② showed weaker bonding and more initial structural defects. During wetting–drying cycling, both rock types experienced progressive mechanical degradation, with elastic modulus exhibiting the most pronounced deterioration after eight cycles. XRD analysis indicated that the main mineral assemblages remained stable without obvious phase transformation, while the reduction in calcite and clay minerals was associated with the weakening of cementing materials. SEM observations revealed distinct deterioration pathways: Site ① mainly underwent gradual damage characterized by particle-contact weakening, pore development, and shrinkage cracking, whereas Site ② experienced rapid structural degradation involving cement dissolution, particle debonding, and pore–fracture connectivity. These results indicate that wetting–drying deterioration is governed not only by mineral composition but also by bonding conditions and initial pore–fracture structures. The findings provide insights into the differentiated stability assessment and prevention of red-bed soft rock slopes and subgrades under water-sensitive environments.

Keywords: red-bed soft rock; wetting–drying cyclic deterioration; XRD; SEM; stability assessment



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1. Introduction

Continental red beds of Jurassic to Cretaceous age are widely distributed throughout the Sichuan Basin. They are predominantly composed of interbedded mudstone, silty mudstone, argillaceous siltstone, and sandstone. Owing to differences in clay mineral content, particle cementation, and pore–fracture structure, red-bed soft rocks generally exhibit strong hydrophilicity, water-induced swelling, shrinkage upon drying, and high susceptibility to softening and disintegration [1,2]. Under the combined effects of alternating rainfall and evaporation, reservoir water-level fluctuations, groundwater seepage, and cyclic variations in subgrade moisture, continuous moisture migration, hydration and

dehydration of clay minerals, dissolution of soluble minerals, and debonding at particle interfaces occur within the rock mass. These processes promote the enlargement of existing pores and the initiation of microcracks. As pores and fractures progressively propagate and interconnect, the structural integrity of the rock mass continuously deteriorates, resulting in engineering problems such as surface spalling, immersion-induced disintegration, strength degradation, slope instability, and long-term heave of road subgrades [3,4]. Typical weathering and failure characteristics of red-bed soft-rock slopes are shown in Figure 1.

Water-induced damage in red-bed soft rocks is characterized by pronounced cyclic accumulation and time-dependent effects [5,6]. Multi-cycle slake-durability tests, wetting–drying cyclic mechanical tests, and microstructural characterization techniques have therefore been widely used to evaluate their long-term durability. Studies have shown that the type, content, and occurrence state of clay minerals constitute an important material basis governing water-induced swelling and disintegration, while the dissolution of cementing minerals such as calcite and changes in particle-contact relationships further weaken the rock structure [7,8]. During repeated wetting and drying, incompatible deformation develops among mineral particles, causing local stresses to concentrate along particle boundaries and at the tips of pre-existing fractures. Consequently, particles gradually fragment, pores become more abundant, fractures widen, and particle cementation deteriorates [9,10]. With increasing numbers of cycles, P-wave velocity, elastic modulus, compressive and tensile strengths, cohesion, and internal friction angle may decrease to varying degrees, indicating that macroscopic degradation is the cumulative result of mineral water sensitivity and progressive internal structural damage [11,12].

In recent years, investigations of red-bed soft rocks in the Sichuan Basin and southwestern China have progressively evolved from conventional mechanical characterization toward multiscale analyses involving X-ray diffraction (XRD), scanning electron microscopy (SEM), computed tomography, mercury intrusion porosimetry, nuclear magnetic resonance, and low-temperature nitrogen adsorption [7,13]. Previous studies have demonstrated that mineral composition plays a fundamental role in controlling water absorption, swelling behavior, disintegration susceptibility, and mechanical degradation by influencing particle arrangement, cementation characteristics, pore-size distribution, and fracture propagation [10,14]. However, red-bed soft rocks with different initial structural states may exhibit markedly different water-sensitive responses, including swelling-dominated deformation with gradual degradation and rapid disintegration caused by structural collapse [8,15]. These differences indicate that the deterioration behavior of red-bed soft rocks cannot be adequately interpreted using a single parameter, such as swelling ratio, slake-durability index, or mechanical strength. Instead, the coupled effects of mineral composition, bonding conditions, and pore–fracture evolution need to be further clarified to understand the mechanisms governing different deterioration modes.

Therefore, this study aims to investigate the differentiated water-sensitive deterioration mechanisms of red-bed soft rocks with different initial structural characteristics. Two representative mudstones from the Sichuan Basin were selected, and their mechanical responses, wetting–drying deterioration behaviors, mineralogical changes, and microstructural evolution were systematically investigated through mechanical testing, XRD, and SEM analyses. The objectives are to: (1) characterize the differences in mechanical degradation under repeated wetting–drying cycles; (2) identify the role of mineral composition and bonding conditions in controlling pore–fracture evolution; and (3) establish a multiscale mechanism linking mineral alteration, structural damage, and macroscopic deterioration. The findings provide insights into the stability assessment and water-resistant design of red-bed soft rock slopes and subgrades.

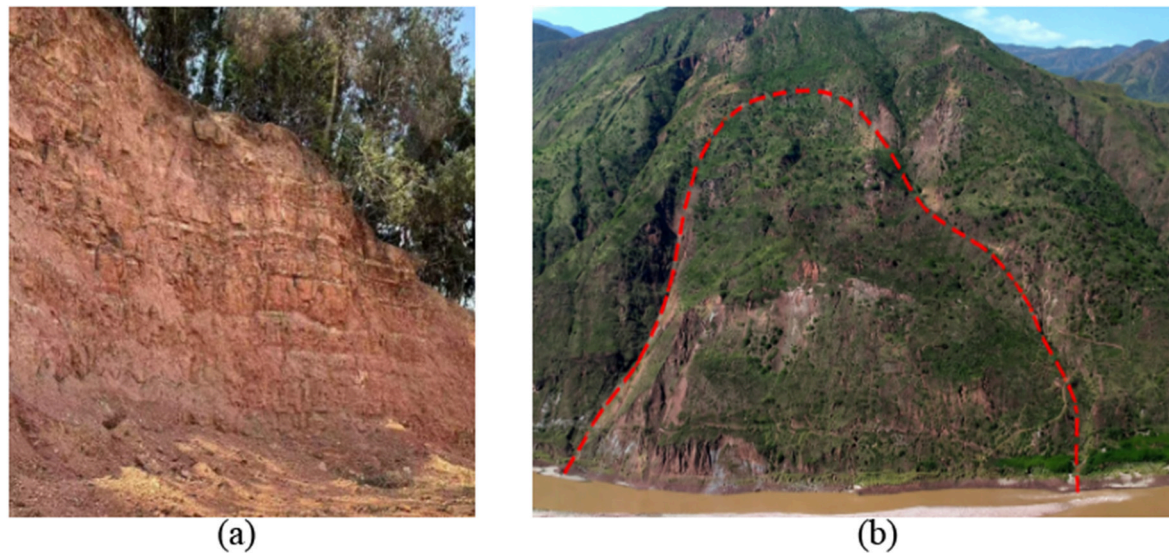


Figure 1. Weathering and failure characteristics of red-bed soft-rock slopes: (a) Weathered exposed surface of red-bed soft rock slope. (b) Landslide failure site of red-bed soft rock slope [16].

2. Experimental Materials, Methods, and Basic Physicomechanical and Water-Sensitivity Characteristics

The rock samples were collected from two representative sampling sites in Mianyang City, Sichuan Province, China. Sampling Site 1 is located in Santai County, whereas Sampling Site 2 is located in Fucheng District, near Bo'ai Xincun, Wujia Town. The geographical locations of the study area and the two sampling sites are shown in Figure 2.

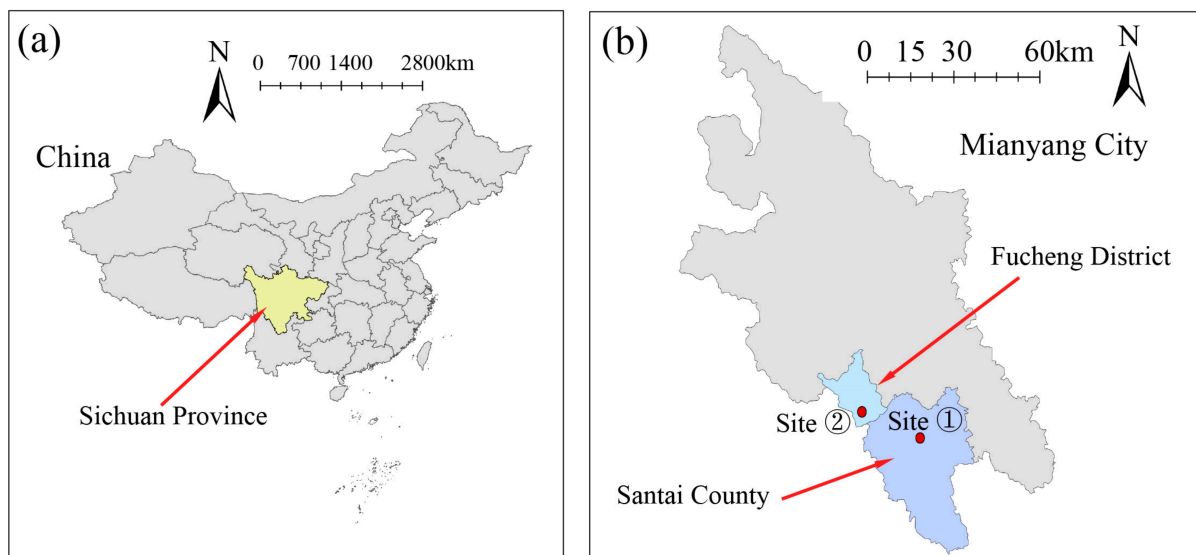


Figure 2. Location of the study area and sampling sites: (a) location of Sichuan Province in China; (b) locations of Sampling Sites 1 and 2 in Mianyang City, Sichuan Province, China.

The collected materials are representative red-bed soft rocks from the Sichuan Basin. They mainly consist of brick-red to reddish-brown mudstone and silty mudstone, with locally developed sandy or carbonate-cemented microzones. Rock samples were collected from representative and relatively intact portions of the two sampling sites, while highly weathered, visibly fractured, or mechanically disturbed materials were excluded as far as practicable. After sampling, the rock blocks were sealed to minimize moisture exchange with the surrounding environment and were carefully packed during transportation to

reduce impact, vibration, and additional mechanical disturbance. Sample acquisition, preservation, and specimen preparation were carried out in accordance with the relevant requirements of GB/T 50266—2013 [17] and SL/T 264—2020 [18]. Before specimen preparation, the collected blocks were visually inspected, and samples showing obvious transportation-induced damage or severe cracking were excluded. Representative intact blocks were then prepared as cylindrical or block-shaped specimens. The specimens used for uniaxial compression testing were 50 mm in diameter and 100 mm in height. Before testing, the end-surface flatness, parallelism, and dimensional tolerances of each specimen were examined.

Representative macroscopic photographs of the red-bed soft rocks and their typical failure characteristics during laboratory testing are shown in Figure 3. The images illustrate the initial appearance of the samples from Sampling Sites ① and ②, as well as the visible fragmentation, spalling, cracking, and splitting failure observed after mechanical testing.



Figure 3. Representative macroscopic appearance and typical failure characteristics of red-bed soft rocks during laboratory testing: (a) representative rock block from Sampling Site ①; (b) representative rock block from Sampling Site ②; (c) fragmentation and spalling failure after mechanical testing; (d) cracking and splitting failure after mechanical testing.

Subsequent tests of physical properties, swelling characteristics, slake durability, uniaxial compressive strength, and deformation properties were conducted with reference to the Standard for Test Methods of Engineering Rock Masses (GB/T 50266—2013) [17]. Relevant procedures for rock testing in water conservancy and hydropower engineering were performed with reference to the current Specification for Rock Tests in Water and Hydropower Projects (SL/T 264—2020) [18]. The testing apparatus and representative failure modes for the uniaxial compression, Brazilian splitting, direct shear, and swelling tests are shown in Figure 4.

All numerical values reported in this study were obtained from the original experimental records, and no fabricated or artificially generated samples were introduced. Where individual exported tables, statistical values, or descriptive conclusions in earlier versions of the manuscript were inconsistent with the original records, the results were recalculated using the original experimental data. The verified and corrected results were subsequently adopted throughout the analysis.

The basic physical and mechanical properties of red-bed soft rocks provide an important basis for analyzing their water sensitivity and deterioration under wetting–drying cycles. Water-induced swelling of red-bed mudstone exhibits a pronounced time-dependent response and is strongly influenced by environmental humidity, the original rock structure, and fracture distribution [12,19]. In this study, samples collected from Sampling Sites ① and ② were subjected to tests of natural water content, saturated water content, natural density, dry density, uniaxial compressive strength, Brazilian splitting tensile strength, and direct shear strength. Five parallel specimens were prepared for each test group, and the results are presented in Table 1.

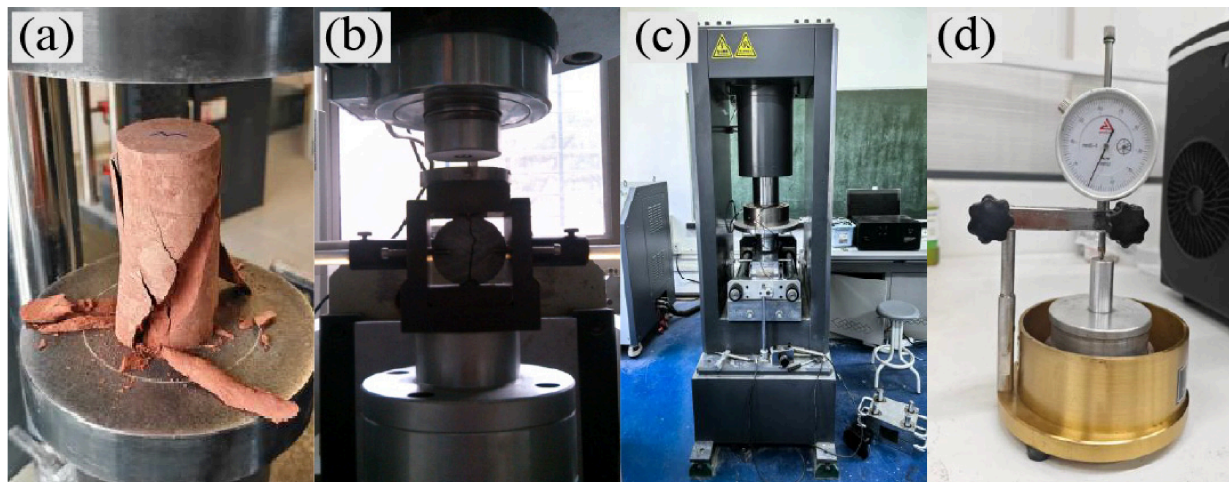


Figure 4. Testing Apparatus and Typical Failure Modes of Red-Bed Soft Rocks: (a) Uniaxial compression test and typical failure mode; (b) Brazilian splitting test; (c) direct shear test; (d) swelling test.

Table 1. Basic Physical and Mechanical Parameters of Red-Bed Soft Rocks.

Group	Sample Number	Natural Water Content (%)	Saturated Water Content (%)	Natural Density ($\text{g}\cdot\text{cm}^{-3}$)	Dry Density ($\text{g}\cdot\text{cm}^{-3}$)	Elastic Modulus (MPa)	Splitting Tensile Strength (MPa)	C (MPa)	φ ($^{\circ}$)
① Sampling Site	①-1	3.69	7.10	2.49	2.41	4485.37	0.75	2.13	39.0
	①-2	3.68	7.10	2.49	2.41	4589.50	0.70	2.42	36.8
	①-3	3.63	7.02	2.49	2.42	4172.97	0.76	2.17	37.0
	①-4	3.69	7.04	2.49	2.41	4612.75	0.83	2.58	38.5
	①-5	3.60	7.10	2.48	2.41	4554.72	0.69	2.75	38.2
	Mean $\pm$ SD	3.66 ± 0.04	7.07 ± 0.04	2.488 ± 0.004	2.412 ± 0.004	4483.06 ± 179.89	0.746 ± 0.056	2.41 ± 0.26	37.90 ± 0.96
② Sampling Site	②-1	3.50	6.20	2.46	2.38	3548.88	0.88	1.27	29.8
	②-2	3.55	6.25	2.45	2.37	3215.72	0.82	0.95	26.5
	②-3	3.48	6.18	2.44	2.36	3400.54	0.89	1.39	25.3
	②-4	3.52	6.22	2.45	2.38	3350.15	0.97	0.88	28.6
	②-5	3.50	6.20	2.46	2.39	3480.36	0.81	0.97	33.2
	Mean $\pm$ SD	3.51 ± 0.03	6.21 ± 0.03	2.452 ± 0.008	2.376 ± 0.011	3399.13 ± 127.54	0.874 ± 0.064	1.09 ± 0.22	28.68 ± 3.08

Note: Values in the “Mean $\pm$ SD” rows are presented as mean $\pm$ standard deviation (SD), based on five parallel specimens for each sampling site ($n = 5$).

As shown in Table 1, the average natural water content, saturated water content, natural density, and dry density of the samples from Sampling Site ① were 3.66%, 7.07%, 2.49 g/cm^3 , and 2.41 g/cm^3 , respectively. The corresponding values for the samples from Sampling Site ② were 3.51%, 6.21%, 2.45 g/cm^3 , and 2.38 g/cm^3 , respectively. The water contents and densities of the samples from Sampling Site ① were generally slightly higher than those of the samples from Sampling Site ②, indicating differences between the two groups in their initial moisture conditions and structural characteristics. Previous studies have shown that moisture migration can induce particle rearrangement, pore expansion, and fracture evolution in mudstone [9,13].

The average elastic modulus and uniaxial compressive strength of the samples from Sampling Site ① were 4483.06 MPa and 16.95 MPa, respectively, whereas those of the samples from Sampling Site ② were 3399.13 MPa and 13.57 MPa, respectively. The samples from Sampling Site ① exhibited greater load-bearing capacity and resistance to deformation, suggesting differences between the two groups in structural integrity and particle-cementation

conditions. Water infiltration weakens interparticle cementation, thereby reducing the compressive strength and elastic modulus of mudstone [2,5].

The splitting tensile strengths of both groups were lower than 1 MPa, with average values of 0.746 MPa for the samples from Sampling Site ① and 0.874 MPa for those from Sampling Site ②, indicating that the red-bed soft rocks in the study area generally possessed low tensile resistance. Although the samples from Sampling Site ② exhibited slightly higher tensile strength, their compressive strength and elastic modulus were lower, suggesting that different mechanical parameters are not necessarily governed by the same factors. Brazilian splitting results for mudstone are readily affected by mineral heterogeneity, bedding, pre-existing fractures, loading direction, and specimen integrity [11,20]. Therefore, these results alone should not be used to evaluate the overall structural quality of the two sample groups.

It should also be noted that the basic-property tests and wetting–drying cycle tests were conducted using parallel specimens from different batches. The corresponding strength values were mainly used for comparisons within their respective test sequences and should not be directly matched on a one-to-one basis across different batches.

The direct shear tests showed that the average cohesion and internal friction angle of the samples from Sampling Site ① were 2.41 MPa and 37.9°, respectively, whereas those of the samples from Sampling Site ② were 1.09 MPa and 28.7°, respectively. The markedly higher shear-strength parameters of the samples from Sampling Site ① indicate stronger particle cementation and frictional interlocking. In contrast, weak planes or microcracks may have been more extensively developed in the samples from Sampling Site ②. Previous wetting–drying studies have shown that cyclic water–rock interaction promotes fracture propagation and strength deterioration and that cohesion and tensile strength are commonly more sensitive than the internal friction angle [5,21].

In the swelling tests, the free swelling ratio, laterally confined swelling ratio, and swelling pressure of the samples from Sampling Site ① were 18.6%, 5.2%, and 227.5 kPa, respectively, all of which were higher than the corresponding values of 12.65%, 3.1%, and 177.5 kPa for the samples from Sampling Site ②. The swelling deformation of both groups tended to stabilize after approximately 8 h. Moisture-induced swelling of red-bed mudstone is characterized by long-term and delayed behavior and can become more pronounced with increasing environmental humidity or repeated wetting and drying [12,19].

In the disintegration tests, the samples from Sampling Site ① remained largely intact after 15 days of immersion, whereas those from Sampling Site ② began to disintegrate after approximately 1.5 min and became completely softened into mud after approximately 10 min. These results demonstrate that swelling and disintegration are not simply correlated. The disintegration of red-bed soft rocks is jointly controlled by water infiltration, pore and fracture propagation, particle detachment, changes in particle size and shape, migration of soluble or fine-grained components, and cementation failure [4,22,23].

The comprehensive analysis indicates that the samples from Sampling Site ① had higher density, uniaxial compressive strength, elastic modulus, and shear-strength parameters, suggesting relatively high overall structural integrity and a greater degree of particle cementation. However, they also exhibited more pronounced water-induced swelling. In contrast, the samples from Sampling Site ② had relatively lower density, compressive strength, and shear strength and displayed strong disintegration characteristics. At the intergroup scale, density showed a broadly consistent variation trend with uniaxial compressive strength, elastic modulus, and shear-strength parameters. However, tensile strength, swelling ratio, and disintegration behavior did not exhibit a simple synchronous relationship. This indicates that the physical, mechanical, and water-sensitive properties of red-bed soft rocks are jointly controlled by multiple factors, including pore structure, fracture distribution, mineral composition, particle orientation, and cementation conditions [10,24].

3. Macroscopic and Microscopic Deterioration Characteristics and Mechanisms of Red-Bed Soft Rocks Under Wetting–Drying Cycles

3.1. Experimental Program and Testing Methods

Red-bed soft rocks in the Sichuan Basin are subjected to long-term alternation between rainfall infiltration and evaporative drying. The resulting repeated changes in rock moisture conditions can induce weakening of particle cementation, propagation of pores and fractures, and deterioration of mechanical properties [5,9]. To investigate the evolution of the macroscopic mechanical properties and internal structure of red-bed mudstone during wetting–drying cycles, rock samples from Sampling Sites ① and ② were selected for uniaxial compression tests, with simultaneous determination of the elastic modulus, and Brazilian splitting tests after different numbers of cycles. X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses were also conducted to explain the differences in deterioration between the two sample groups from the perspectives of mineral composition and microstructural characteristics.

Ten moisture conditions were considered in the wetting–drying cycle tests, including the oven-dry state, the initially saturated state, and states after one to eight cycles. For each sampling site, moisture condition, and destructive mechanical test, three parallel specimens were prepared. Because the uniaxial compression and Brazilian splitting tests are destructive, different specimens had to be used for different wetting–drying conditions. To minimize inter-specimen variability, specimens from the same sampling site were prepared using consistent dimensions and specimen-preparation procedures and were subjected to identical wetting–drying procedures, saturation and drying conditions, and mechanical testing protocols. Therefore, the mechanical results obtained at different cycling stages represent group-level responses under comparable experimental conditions rather than the continuous damage evolution of individual specimens. The oven-dried and initially saturated specimens were designated as Groups I and II, respectively, with the initially saturated state defined as zero wetting–drying cycles. Groups III–X corresponded to one to eight wetting–drying cycles, respectively.

To minimize abrupt structural disturbance caused by rapid immersion, a stepwise immersion procedure was adopted. Water was first added to one-quarter of the specimen height. The water level was then raised to one-half and three-quarters of the specimen height at 2 h intervals, and the specimens were fully submerged after 6 h. After continuous immersion for 48 h, the specimens were placed in an oven at 60 °C and dried for 48 h. One wetting–drying cycle was considered complete when the specimen mass had become approximately stable. After the prescribed number of cycles had been reached, the specimens were resaturated for 48 h using the same stepwise immersion procedure. Uniaxial compression and Brazilian splitting tests were then conducted under a consistent saturated condition to determine the uniaxial compressive strength, splitting tensile strength, and elastic modulus.

To distinguish the effects of the initial moisture-state transition from the subsequent cumulative effects of wetting–drying cycles, the mechanical parameters measured in the initially saturated state ($n = 0$) were adopted as the reference values. The relative deterioration degrees of uniaxial compressive strength, splitting tensile strength, and elastic modulus at different numbers of cycles were calculated separately using Equation (1). This index represents the variation relative to the ($n = 0$) state and is not equivalent to the total damage that includes the softening process from the natural state to the saturated state.

$$D_i(n) = \frac{X_i(0) - X_i(n)}{X_i(0)} \times 100\%, \quad (1)$$

where i denotes uniaxial compressive strength, splitting tensile strength, and elastic modulus, respectively; $X_i(0)$ is the i th mechanical parameter measured in the initially saturated state, and $X_i(n)$ is the corresponding parameter measured under the same saturated testing condition after n wetting–drying cycles. It should be emphasized that D_i is a normalized relative index calculated independently for each sampling site using its own Cycle 0 value as the reference. Therefore, differences in D_i do not directly represent differences in absolute residual mechanical strength between the two sampling sites.

For the XRD tests, rock samples from both sampling sites were selected before wetting–drying cycling and after eight cycles. Five subsamples were collected for each sampling site and each condition. After oven drying, crushing, and grinding, the subsamples were prepared as homogeneous powders and tested using an Empyrean X-ray diffractometer (PANalytical B.V., Almelo, the Netherlands). Phase identification and semi-quantitative analysis of relative mineral contents were conducted with reference to standard Powder Diffraction File (PDF) cards. Particular attention was given to changes in the principal mineral phases, diffraction peaks, and relative mineral contents before and after cycling.

SEM observations were performed using an Ultra 55 field-emission scanning electron microscope (Carl Zeiss, Oberkochen, Germany) on representative fracture surfaces of samples from both sampling sites before cycling and after eight wetting–drying cycles. Low-magnification images were used to identify the overall structure and the distribution of pores and fractures, whereas high-magnification images were used to examine particle-surface morphology, particle-contact modes, and local cementation characteristics. Considering the heterogeneity of natural rock samples, qualitative comparisons were based on common features observed across multiple representative regions. Because SEM–EDS analysis was not performed, individual mineral grains were not identified directly from morphology alone. Mineralogical interpretation of the SEM images was therefore made qualitatively and in conjunction with the XRD results. The resulting observations were used to interpret trends in structural evolution rather than as quantitative measurements of porosity or fracture density, consistent with the qualitative role of SEM in prior multiscale pore-structure studies [13,25]. In the SEM images presented in Section 3.3.2, red ellipses are used to highlight representative microstructural features, such as pores, microcracks, particle exfoliation, locally loosened particle contacts, and apparent debonding regions, to facilitate qualitative comparison before and after wetting–drying cycling. These annotations are illustrative and are not used for quantitative image analysis. Quantitative characterization of pore-size distribution, crack density, and pore connectivity will require dedicated image-analysis or pore-structure characterization techniques in future studies.

3.2. Deterioration of Mechanical Parameters Under Wetting–Drying Cycles

As shown in Tables 2–4 and Figures 5–7, the uniaxial compressive strength, splitting tensile strength, and elastic modulus of the red-bed mudstone samples from Sampling Sites ① and ② generally decreased with increasing numbers of wetting–drying cycles. This indicates that repeated wetting and drying progressively weakened the structural integrity and load-bearing capacity of the specimens, consistent with previously reported deterioration trends for red-bed rocks [5,6]. It should be noted that three independent parallel specimens were originally tested under each cycling condition. However, for part of the archived cyclic mechanical dataset, only the group-averaged values are currently available, and the individual replicate values required for retrospective calculation of standard deviations, confidence intervals, and statistical significance could not be fully recovered. Therefore, the mechanical deterioration curves and the differences between the two sampling sites are primarily interpreted descriptively, and small numerical differences are not regarded as statistically significant. To improve the visualization and interpreta-

tion of the overall deterioration trends, trend-fitting curves were added to Figures 5–7, together with the corresponding coefficients of determination (R^2). These fitted curves are used only to describe the overall variation in mechanical properties with the number of wetting–drying cycles and are not intended to represent statistically validated predictive deterioration models.

Table 2. Mechanical Parameters and Deterioration Degrees of Red-Bed Mudstone from Site ①.

Number of Wetting–Drying Cycles, n	Uniaxial Compressive Strength, σ_c (MPa)	Splitting Tensile Strength, σ_t (MPa)	Elastic Modulus, E (MPa)	Di Deterioration Degree, D_i		
				$\frac{\sigma_{c0} - \sigma_c(n)}{\sigma_{c0}} \times 100\%$	$\frac{\sigma_{t0} - \sigma_t(n)}{\sigma_{t0}} \times 100\%$	$\frac{E_0 - E(n)}{E_0} \times 100\%$
0	14.90	1.58	3826.72	0	0	0
1	14.33	1.55	3419.45	3.83	1.90	10.64
2	13.59	1.51	3062.18	8.79	4.43	19.98
3	12.97	1.42	2741.63	12.95	10.13	28.36
4	12.22	1.37	2450.91	17.99	13.29	35.95
5	11.89	1.35	2183.26	20.20	14.56	42.95
6	10.13	1.22	1947.58	32.01	22.78	49.11
7	9.58	1.09	1729.34	35.70	31.01	54.81
8	9.11	1.05	1536.80	38.86	33.54	59.84

Table 3. Mechanical Parameters and Deterioration Degree of Red-Bed Mudstone at Site ②.

Number of Wetting–Drying Cycles, n	Uniaxial Compressive Strength, σ_c (MPa)	Splitting Tensile Strength, σ_t (MPa)	Elastic Modulus, E (MPa)	Di Deterioration Degree, D_i		
				$\frac{\sigma_{c0} - \sigma_c(n)}{\sigma_{c0}} \times 100\%$	$\frac{\sigma_{t0} - \sigma_t(n)}{\sigma_{t0}} \times 100\%$	$\frac{E_0 - E(n)}{E_0} \times 100\%$
0	14.25	1.57	3865.60	0	0	0
1	13.87	1.51	3480.56	2.67	3.82	9.96
2	12.59	1.48	3102.70	11.65	5.73	19.74
3	12.11	1.40	2696.24	15.02	10.83	30.25
4	11.65	1.35	2374.39	18.25	14.01	38.58
5	11.42	1.21	2157.36	19.86	22.93	44.19
6	10.10	1.17	1849.84	29.12	25.48	52.15
7	9.21	1.07	1632.50	35.37	31.85	57.77
8	8.87	1.04	1475.39	37.75	33.76	61.83

Table 4. Comparison of Wetting–Drying Cycle Deterioration Characteristics of Red-Bed Mudstone at the Two Sampling Sites.

Comparison Item	Sampling Site ①	Sampling Site ②
Elastic Modulus Loss after the First Cycle	10.64%	9.96%
Deterioration Degree of σ_c after Eight Cycles	38.86%	37.75%
Deterioration Degree of E after Eight Cycles	59.84%	61.83%
Deterioration Degree of σ_t after Eight Cycles	33.54%	33.76%
Residual σ_c after Eight Cycles (MPa)	9.11	8.87
Ranking of Deterioration Sensitivity	$E > \sigma_c > \sigma_t$	$E > \sigma_c > \sigma_t$
σ_t Deterioration after the First Cycle	Relatively Slight (1.90%)	Relatively Severe (3.82%)

Note: Deterioration degrees are normalized relative to the respective Cycle 0 values of each sampling site and therefore should not be interpreted as direct indicators of absolute residual strength. Small differences between the two sampling sites are interpreted descriptively because statistical significance could not be reliably evaluated from the available archived replicate data.

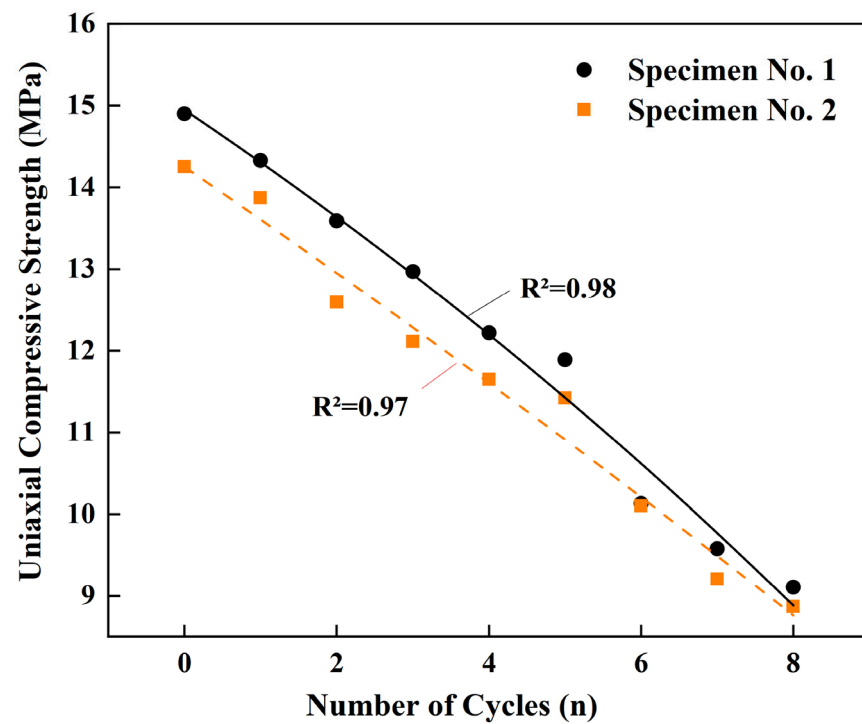


Figure 5. Variation in uniaxial compressive strength of red-bed mudstone from the two sampling sites with the number of wetting–drying cycles. The fitted curves and corresponding R^2 values are provided to describe the overall deterioration trends.

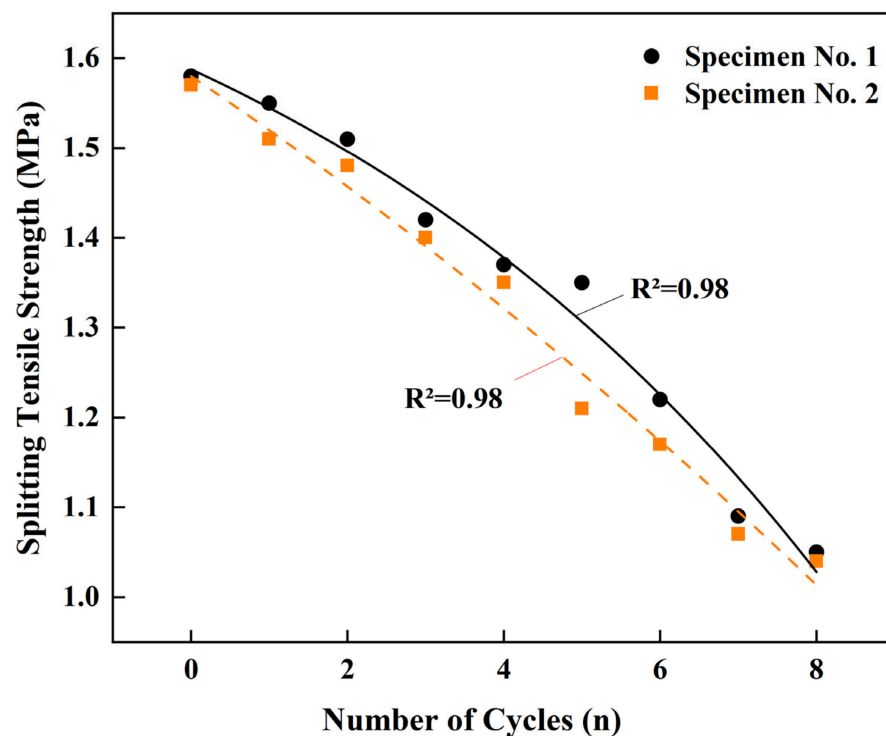


Figure 6. Variation in splitting tensile strength of red-bed mudstone from the two sampling sites with the number of wetting–drying cycles. The fitted curves and corresponding R^2 values are provided to describe the overall deterioration trends.

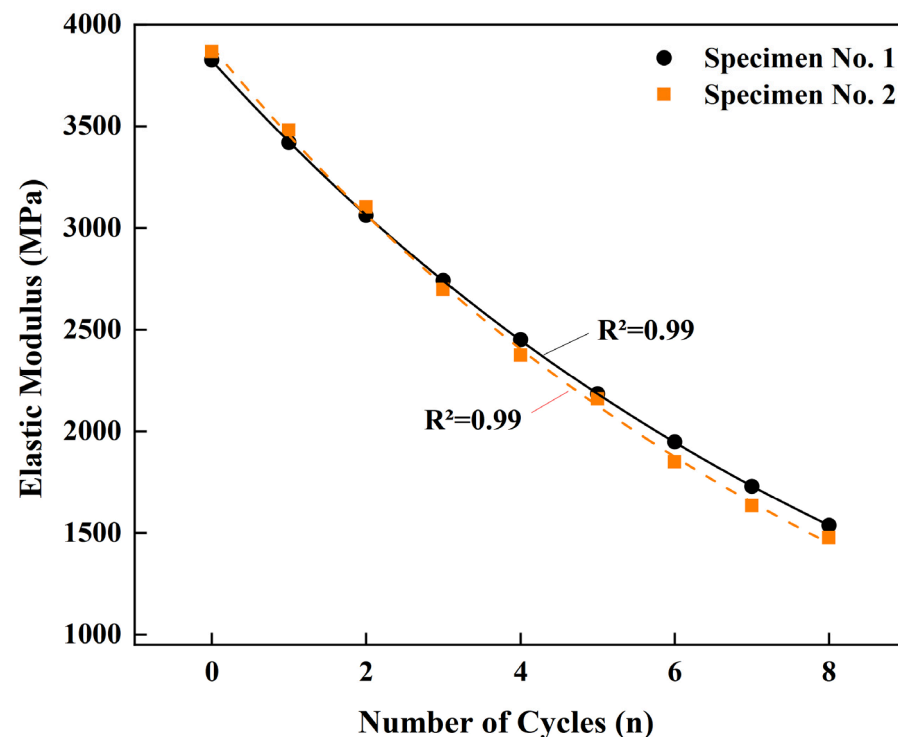


Figure 7. Variation in elastic modulus of red-bed mudstone from the two sampling sites with the number of wetting–drying cycles. The fitted curves and corresponding R^2 values are provided to describe the overall deterioration trends.

3.2.1. Variations in Mechanical Parameters with the Number of Cycles

When the specimens changed from the oven-dry state to the initially saturated state, the uniaxial compressive strength of the samples from Sampling Site ① decreased from 16.80 MPa to 14.90 MPa, while the elastic modulus decreased from 4485.37 MPa to 3826.72 MPa, corresponding to reductions of 11.31% and 14.68%, respectively. For the samples from Sampling Site ②, the uniaxial compressive strength decreased from 14.91 MPa to 14.25 MPa, representing a reduction of 4.43%. However, the elastic modulus increased from 3591.22 MPa to 3865.60 MPa, corresponding to an apparent increase of 7.64%. Because independent specimens were used for the different moisture conditions and no statistical measures of data dispersion were available, this opposite variation in the elastic modulus of the samples from Sampling Site ② cannot be interpreted as saturation-induced strengthening. It may instead be related to rock heterogeneity or inter-specimen variability. Therefore, the initial change in moisture condition is discussed only descriptively, and the subsequent cyclic deterioration is evaluated uniformly relative to the ($n = 0$) state.

As shown in Figure 5, with increasing numbers of wetting–drying cycles, the uniaxial compressive strength of both groups decreased continuously. After eight wetting–drying cycles, the strength of the samples from Sampling Site ① decreased from 14.90 MPa at zero cycles to 9.11 MPa, corresponding to a deterioration degree of 38.86%. The strength of the samples from Sampling Site ② decreased from 14.25 MPa to 8.87 MPa, corresponding to a deterioration degree of 37.75%. The final compressive strengths and cumulative reductions in the two groups were relatively similar, indicating that repeated wetting and drying caused substantial losses in load-bearing capacity under the present test conditions.

As shown in Figure 6, the splitting tensile strength of both groups generally decreased with increasing numbers of wetting–drying cycles. For the samples from Sampling Site ①, it decreased from 1.58 MPa at zero cycles to 1.05 MPa after eight cycles, corresponding to a deterioration degree of 33.54%. For the samples from Sampling Site ②, it decreased from

1.57 MPa to 1.04 MPa, corresponding to a deterioration degree of 33.76%. The cumulative reductions at the end of the test were similar for the two groups. In light of previous studies, this variation may be associated with the progressive weakening and coalescence of pre-existing fractures, bedding-related weak planes, and interparticle cementation [11,26]. However, because no in situ crack-tracking observations were performed in this study, the specific crack-evolution pathways cannot be determined from these results alone.

As shown in Figure 7, the elastic modulus of both groups decreased progressively with increasing numbers of wetting–drying cycles, and its relative reduction was greater than that of the two strength parameters. After eight wetting–drying cycles, the elastic modulus of the samples from Sampling Site ① decreased from 3826.72 MPa to 1536.80 MPa, corresponding to a deterioration degree of 59.84%. For the samples from Sampling Site ②, it decreased from 3865.60 MPa to 1475.39 MPa, corresponding to a deterioration degree of 61.83%. The elastic modulus of both groups decreased by approximately 60%, indicating that, at the end of the test, stiffness exhibited a greater relative response to wetting–drying cycling than the peak-strength parameters. Similar high sensitivity of deformation parameters to cyclic microstructural damage has been reported in previous multiscale studies [6,7].

3.2.2. Deterioration Degree and Differences Between Sampling Sites

Taking the initially saturated state as the baseline at Cycle 0, after the first wetting–drying cycle, the deterioration degrees of uniaxial compressive strength, splitting tensile strength, and elastic modulus for samples from Sampling Site ① were 3.83%, 1.90%, and 10.64%, respectively. The corresponding values for samples from Sampling Site ② were 2.67%, 3.82%, and 9.96%, respectively. For both groups of rock samples, the reduction in elastic modulus after the first cycle was greater than the reductions in the two strength parameters measured over the same period.

After eight wetting–drying cycles, the deterioration degrees of uniaxial compressive strength were 38.86% for Sampling Site ① and 37.75% for Sampling Site ②. The difference was only 1.11 percentage points. It should be noted that these values are relative reductions normalized to the respective Cycle 0 strengths. The corresponding absolute compressive strengths after eight cycles were 9.11 MPa and 8.87 MPa, respectively, indicating that Sampling Site ① still retained a slightly higher absolute compressive strength. Therefore, the slightly higher relative deterioration degree at Sampling Site ① does not represent a reversal of the overall mechanical-strength relationship between the two sampling sites. Given the limitations of the archived replicate data, the 1.11-percentage-point difference is interpreted descriptively and is not treated as evidence of a statistically significant difference.

After eight cycles, both groups exhibited the greatest relative reduction in elastic modulus. Overall, the differences among the deterioration degrees of the mechanical parameters and between the two sampling sites are interpreted descriptively rather than statistically.

A comprehensive comparison indicates that the deterioration sensitivity of the mechanical properties of both groups of rock samples follows the order:

$$E > \sigma_c > \sigma_t \quad (2)$$

The elastic modulus is relatively sensitive to particle-contact conditions, initial pore compaction, interfacial weakening, and distributed microcracks. These changes can reduce the slope of the stress–strain curve before a continuous failure surface has formed, whereas substantial changes in peak compressive and tensile strengths generally require further crack propagation and coalescence [6,27]. Therefore, the elastic modulus may serve as

a candidate indicator for characterizing structural changes during the early stages of wetting–drying cycling. However, its applicability still needs to be further verified through repeatability analysis, wave-velocity measurements, and quantitative characterization of pore structures.

Overall, samples from Sampling Site ① exhibited higher strength and stiffness under natural conditions and greater softening when transitioning from the oven-dry state to the initially saturated state. Samples from Sampling Site ② showed relatively lower natural mechanical properties. Their elastic modulus exhibited an apparent increase from the oven-dry state to the initially saturated state, which was inconsistent with the conventional softening trend and should therefore not be interpreted mechanistically. At the end of eight wetting–drying cycles, the deterioration degrees of compressive and tensile strengths were relatively similar for the two groups of rock samples, whereas the deterioration degree of the elastic modulus of samples from Sampling Site ② was 1.99 percentage points higher than that of samples from Sampling Site ①. This difference is presented only as a descriptive comparison, and its underlying causes should be discussed cautiously in conjunction with X-ray diffraction (XRD), scanning electron microscopy (SEM), and statistical analysis of data variability.

3.3. Mineral Composition and Microstructural Evolution

3.3.1. XRD Phase Composition and Changes in Mineral Content

(1) Phase Characteristics of Sampling Site ①.

As shown in Figure 8, the principal diffraction peaks of the subsamples from Sampling Site ① matched well with the standard PDF reference patterns of quartz, albite, calcite, and illite. The representative characteristic peaks are labeled as Q, Ab, Cal, and Ill, respectively. Quartz exhibited a distinct strong peak at approximately $2\theta = 26.6^\circ$, together with additional characteristic reflections at higher diffraction angles, whereas albite showed several secondary peaks over a relatively broad angular range. Together, quartz and albite constituted the principal detrital framework of the rock samples. The calcite peaks were comparatively weak, which is consistent with the relatively low abundance of calcite in the samples. Calcite in red-bed argillaceous rocks commonly occurs as a cementing or pore-filling component [7,10]. Identifiable illite peaks indicated that the samples possessed a certain degree of argillaceous character.

The positions of the principal diffraction peaks were generally consistent among the different subsamples, indicating a relatively stable mineral assemblage within Sampling Site ①. Differences in the intensities of some weak peaks may reflect heterogeneity in mineral content and spatial distribution. After wetting–drying cycling, the principal peak positions and overall diffraction-pattern characteristics remained essentially unchanged, and no obvious new diffraction peaks or disappearance of the principal existing peaks was observed. These results indicate that no evident transformation of the major mineral phases occurred during cycling. Variations in the intensities of some weak peaks were mainly associated with changes in relative mineral proportions, particle size, and preferred orientation and should not be regarded as direct evidence of corresponding changes in absolute mineral contents [7,27].

(2) Phase Characteristics of Sampling Site ②.

As shown in Figure 9, the principal diffraction peaks of the samples from Sampling Site ② matched well with the standard PDF reference patterns of quartz, albite, and calcite. The representative characteristic peaks are labeled as Q, Ab, and Cal, respectively. Quartz exhibited a pronounced strong peak at approximately $2\theta = 26.6^\circ$, whereas albite displayed several groups of secondary peaks over a relatively broad diffraction-angle range. Calcite

was also identified in all subsamples from its characteristic diffraction peaks, indicating that the basic mineral assemblage was generally consistent among the samples.

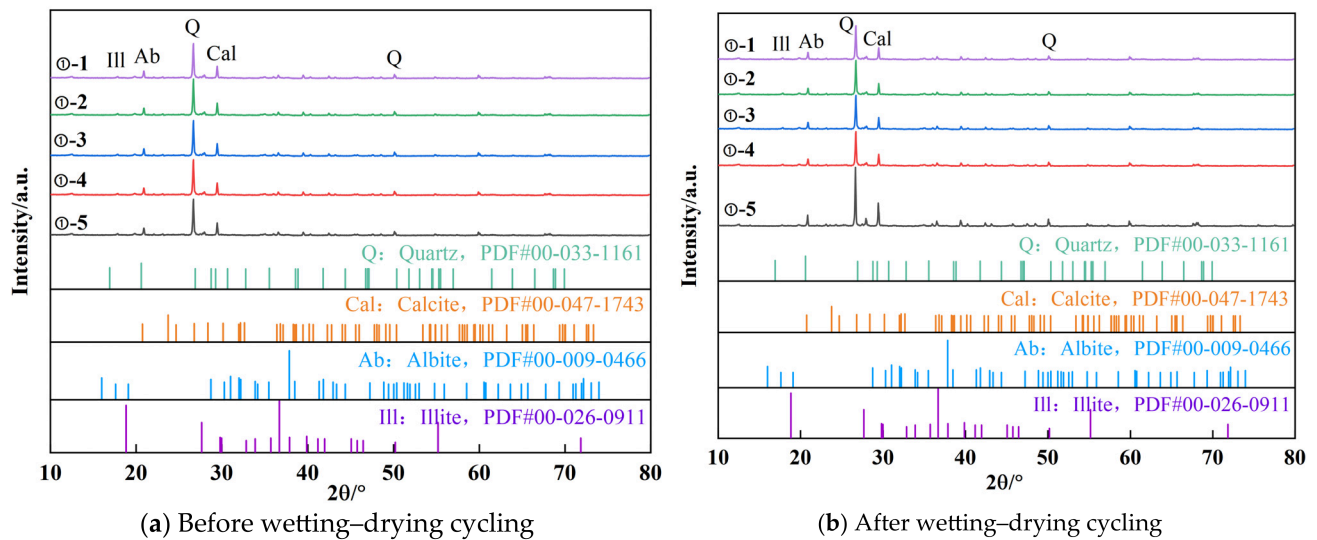


Figure 8. XRD patterns and phase identification of red-bed soft rock from Sampling Site ①: (a) before wetting–drying cycling; (b) after wetting–drying cycling. The principal diffraction peaks were identified by comparison with standard PDF reference patterns of quartz (Q), calcite (Cal), albite (Ab), and illite (Ill), and the corresponding reference peak positions are shown below the experimental patterns. Different curve colors are used only to distinguish individual specimens and have no mineralogical significance.

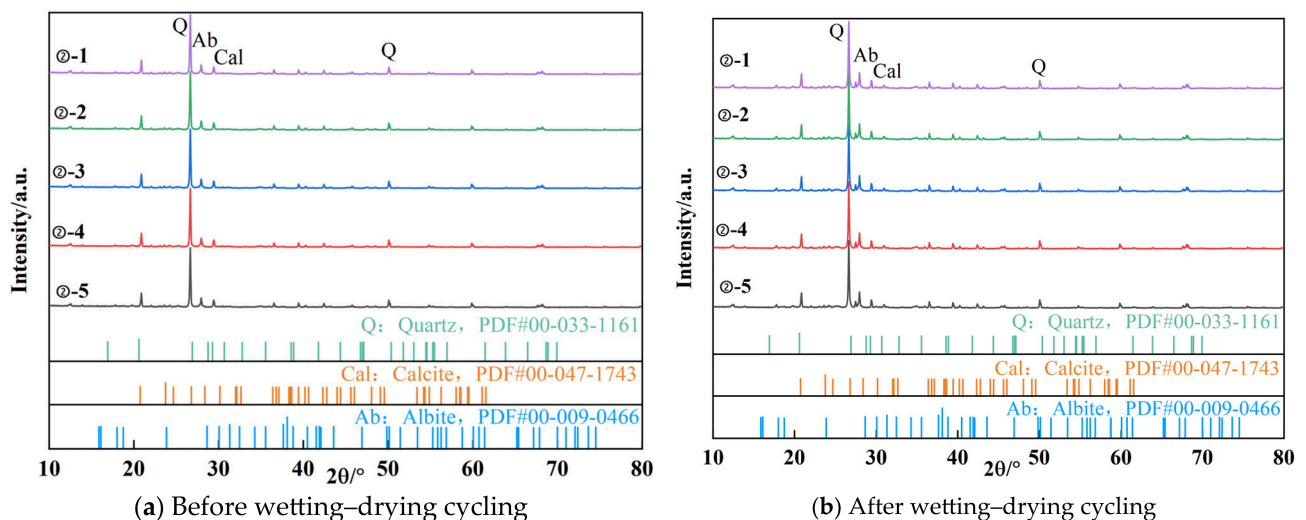


Figure 9. XRD patterns and phase identification of red-bed soft rock from Sampling Site ②: (a) before wetting–drying cycling; (b) after wetting–drying cycling. The principal diffraction peaks were identified by comparison with standard PDF reference patterns of quartz (Q), calcite (Cal), and albite (Ab), and the corresponding reference peak positions are shown below the experimental patterns. Different curve colors are used only to distinguish individual specimens and have no mineralogical significance.

Compared with Sampling Site ①, no distinct and independent characteristic peaks of illite were identified in the samples from Sampling Site ②. However, clay-mineral peaks in whole-rock XRD patterns can be affected by mineral content, crystallinity, peak overlap, and specimen preparation. Therefore, this result only indicates that the diffraction

contribution of illite was relatively weak and does not demonstrate the complete absence of clay minerals from the rock samples [10,25].

Comparison of the XRD patterns before and after wetting–drying cycling showed that the principal diffraction peaks remained at essentially the same 2θ positions and continued to match the same standard PDF reference patterns. No obvious new diffraction peaks or disappearance of the principal existing peaks was observed. These results indicate that wetting–drying cycling did not cause an evident transformation of the major mineral phases. The observed variations were mainly manifested as changes in peak intensity and semi-quantitative relative mineral proportions rather than the formation of new crystalline phases.

(3) Changes in Relative Mineral Contents and Comparison Between Sampling Sites.

As shown in Figure 10, the rock samples from both sampling sites were mainly composed of quartz, albite, and clay minerals, with a small amount of calcite. After wetting–drying cycling, the relative contents of quartz and albite generally increased, whereas those of calcite and total clay minerals decreased.

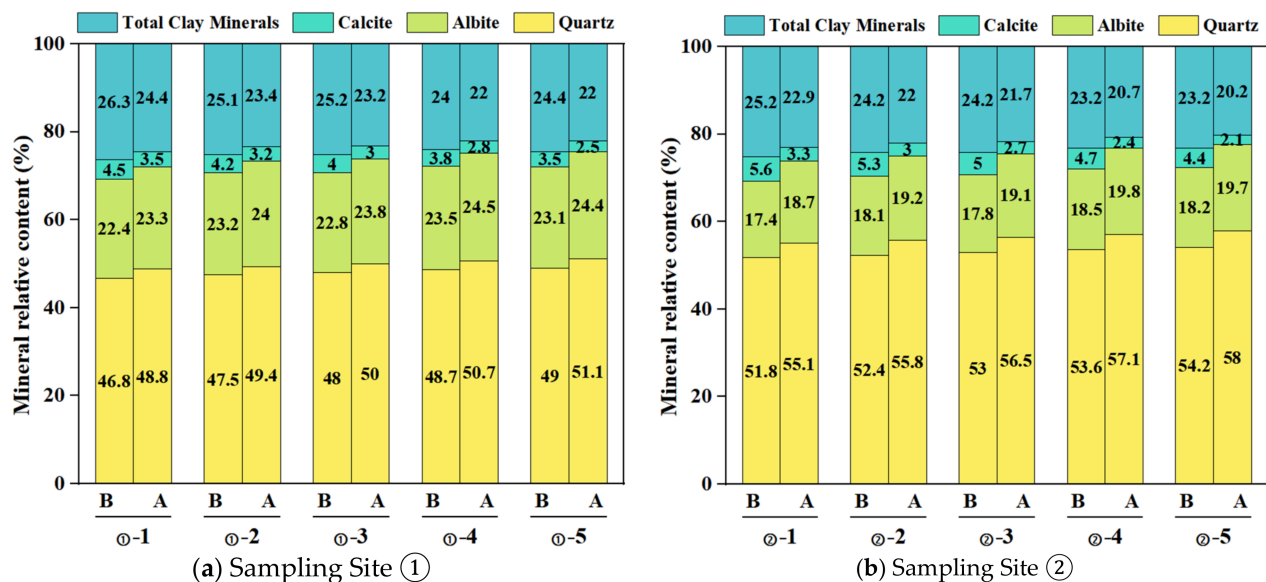


Figure 10. Comparison of the Relative Contents of Major Minerals in Red-Bed Soft Rock from the Two Sampling Sites Before and After Wetting–Drying Cycling (B: Before Cycling; A: After Cycling): (a) Sampling Site ①; (b) Sampling Site ②.

At Sampling Site ①, the average quartz content increased from 48.0% to 49.8%, and the albite content increased from 23.0% to 24.1%. In contrast, the calcite content decreased from 4.0% to 3.1%, while the total clay-mineral content decreased from 25.0% to 23.0%. The overall changes were relatively small, indicating that the mineral framework at this sampling site had relatively good stability.

At Sampling Site ②, the average quartz content increased from 53.0% to 56.5%, and the albite content increased from 18.0% to 19.3%. Meanwhile, the calcite content decreased from 5.0% to 2.7%, and the total clay-mineral content decreased from 24.0% to 21.5%. In particular, the calcite content decreased by 2.3 percentage points, a markedly greater change than that observed at Sampling Site ①. This indicates that the carbonate components at Sampling Site ② were more strongly affected during wetting–drying cycling.

It should be emphasized that the apparent increases in the relative contents of quartz and albite do not indicate the formation of new quartz or albite during wetting–drying cycling. The XRD results showed that the positions of the major diffraction peaks remained stable and no new mineral phases were detected. Therefore, the observed increases are

interpreted mainly as relative enrichment effects rather than mineral neoformation. During repeated water–rock interaction, comparatively reactive or mobile components, particularly calcite and part of the fine-grained clay fraction, may be preferentially dissolved, dispersed, or removed from the analyzed material. Because the semi-quantitative XRD mineral contents are expressed as normalized relative proportions of the identified crystalline phases, the reduction in these components can increase the relative proportions of the remaining framework minerals even if their absolute amounts do not increase. Under the present experimental conditions, quartz showed relatively high persistence, whereas albite also exhibited an apparent increase in relative proportion. Accordingly, the observed increases in quartz and albite are interpreted primarily as compositional redistribution associated with the selective loss of other mineral components rather than as evidence of mineral formation. Previous studies on red-bed soft rocks have similarly shown that wetting–drying cycling can induce mineral dissolution, mass loss, and redistribution of relative mineral proportions [7,14,27].

The pronounced decrease in calcite content is consistent with possible loss or alteration of calcareous cement during cycling. Calcite commonly acts as a cementing and pore-filling material at particle contacts. Its reduction weakens interparticle bonding and promotes the expansion and progressive interconnection of pre-existing pores. Previous studies have shown that weakening or dissolution of calcareous cement can lead to particle detachment, matrix erosion, pore development, landslide-zone weakening, and irreversible mechanical degradation [16]. This suggests that the evaluation of the water sensitivity of red-bed soft rock should consider not only the content of clay minerals but also the content and modes of occurrence of cementing minerals.

The reduction in total clay-mineral content may be associated with water-induced dispersion of clay particles, migration of fine particles, and surface spalling, while also being affected by mineral crystallinity and preferred orientation introduced during sample preparation. Although illite is less expansive than montmorillonite, its particle surfaces remain hydrophilic. Repeated wetting and drying can alter the thickness of water films on particle surfaces and interfacial forces, thereby loosening clay aggregates and intensifying incompatible deformation between clay particles and the rigid mineral framework [8,9].

Before wetting–drying cycling, the quartz content at Sampling Site ② was higher than that at Sampling Site ①, whereas the diffraction characteristics of albite and clay minerals were more pronounced at Sampling Site ①. This indicates that Sampling Site ② had a higher proportion of quartz in its mineral framework, while Sampling Site ① exhibited relatively stronger argillaceous characteristics.

The mineral changes at the two sampling sites followed generally consistent trends after wetting–drying cycling, although the magnitudes of these changes differed. At Sampling Site ①, a decrease in total clay-mineral content was observed, and characteristic illite peaks could be identified. Its water-induced deterioration may therefore have been more strongly influenced by water absorption and desorption by clay minerals, dispersion of clay aggregates, and incompatible deformation at particle interfaces. At Sampling Site ②, the decrease in calcite content was greater, suggesting that its structural damage may have been controlled more strongly by the dissolution of calcareous cement and debonding between particles [10,16].

Therefore, the water sensitivity of the two groups of rock samples cannot be evaluated solely on the basis of total clay-mineral content. Even where mineral compositions are similar, the types of clay minerals, the cementation mode of calcite, and the contact relationships among mineral particles may all affect the response of the rock samples to wetting–drying cycling. Previous studies similarly indicate that swelling and disintegration are jointly

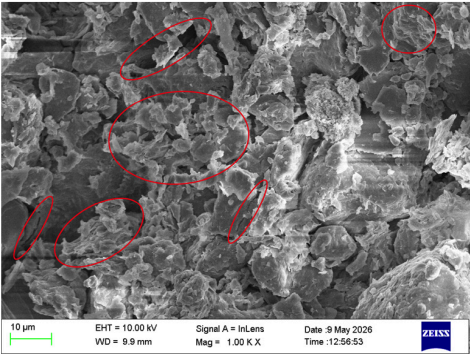
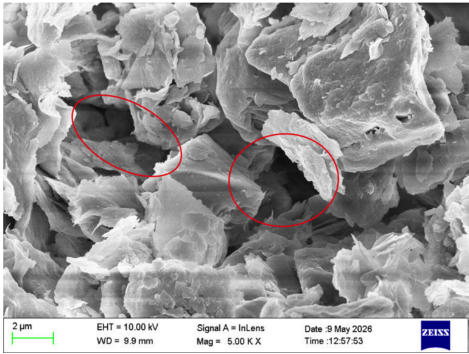
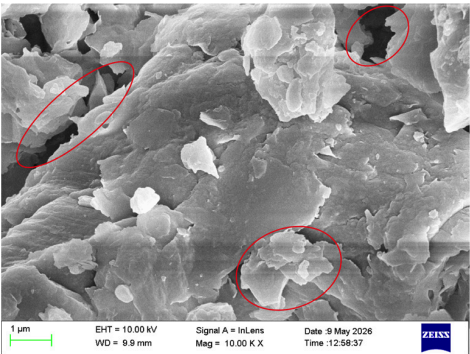
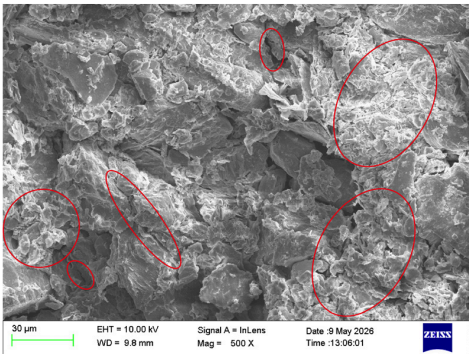
governed by clay-mineral activity, cementation integrity, and pore–fracture structure rather than by clay content alone [1,10].

3.3.2. Evolution of SEM Microstructural Characteristics

(1) Microstructural Evolution at Sampling Site ①.

As shown in Table 5, the samples from Sampling Site ① were generally characterized by aggregates of irregular particles interwoven with platy minerals. In the low-magnification images, the framework particles were mainly in interlocking and face-to-face contact, with local fine-particle infilling and cementation, resulting in a relatively dense structure. Locally developed irregular pores and narrow microcracks were observed along particle boundaries, as highlighted in Table 5. These features indicate that, although the original structure retained relatively good integrity, pre-existing pathways for water ingress were already present.

Table 5. SEM Microstructural Characteristics of Samples from Sampling Site ① Before Wetting–Drying Cycling.

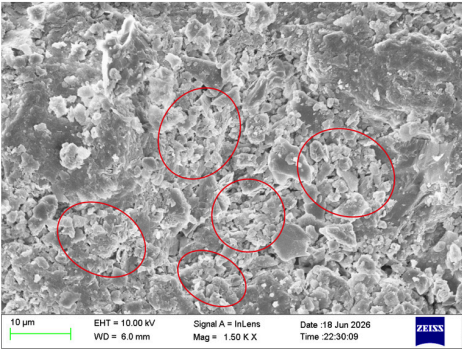
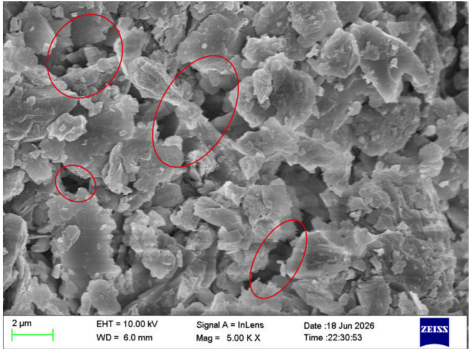
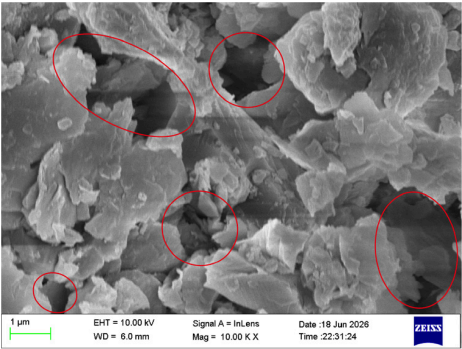
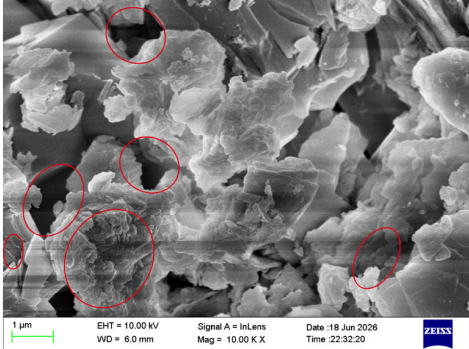
Sampling Location	Specimen Number	SEM Observation Results	
Sampling Site ①	①-2		
			

Note: Red ellipses highlight representative irregular pores, narrow microcracks, and locally loosened particle-boundary regions observed before wetting–drying cycling. The annotations are intended only to facilitate qualitative identification and do not represent quantitative measurements of pore or crack parameters.

In the high-magnification images, aggregates of thin-flake, platy, and flocculent particles could be observed, with some platy particles occurring in stacked or curled forms. Although platy particles may increase the local contact area, their interlayer interfaces also constitute potential weak planes. Combined with the XRD results, the relatively distinct feldspar and illite components at Sampling Site ① suggest that particle boundaries and interlayer interfaces of platy minerals may represent preferential zones for water–rock interaction.

After wetting–drying cycling, the samples from Sampling Site ① retained their original blocky framework, although the particle arrangement appeared looser than before cycling. As highlighted in Table 6, separation was observed along some particle-contact boundaries, together with more evident open interparticle voids and local opening of originally closed or semi-closed pore regions. These observations are consistent with the interpretation that water-induced softening and drying shrinkage promoted the opening and extension of pre-existing weak interfaces.

Table 6. SEM Microstructural Characteristics of Samples from Sampling Site ① After Wetting–Drying Cycling.

Sampling Location	Specimen Number	SEM Observation Results	
Sampling Site ①	①-2		
			

Note: Red ellipses highlight representative open interparticle voids, particle-boundary separation, interlayer opening, and particle exfoliation observed after wetting–drying cycling. The annotations are intended only for qualitative comparison and are not used for quantitative image analysis.

In the high-magnification images, fragmentation of platy-particle edges was more visually evident after cycling, accompanied by exfoliation, warping, and interlayer opening. Some fine-grained materials accumulated along pore margins, suggesting that particle dispersion, migration, and redeposition may have occurred during the cycling process. Although the representative SEM images suggested enhanced local connection among pore and crack features, the principal framework had not completely disintegrated.

Microstructural and pore characteristics can significantly influence the swelling behavior of mudstone. Previous studies have shown that the arrangement and orientation of platy particles, particle-contact patterns, pore size, fractal characteristics, and areal porosity are related to the swelling strain, swelling pressure, and anisotropic deformation of red-bed mudstone [10,24]. These parameters were not quantitatively determined from the present SEM images.

The principal microstructural changes observed at Sampling Site ① after wetting–drying cycling included separation along particle boundaries, interlayer opening of platy

minerals, and the development of more continuous pore–crack pathways in local regions. Water initially entered the rock samples along pre-existing pores and platy weak planes, causing softening of fine-grained infill and particle boundaries. During drying, differential shrinkage further promoted the opening of interlayer cracks. As the effects of cycling accumulated, increasingly continuous pore–crack features were observed locally, accompanied by exfoliation of platy particles. This progressive evolution is consistent with previously reported swelling–shrinkage and cyclic crack-development mechanisms [9,28].

Therefore, the microstructural deterioration of the samples from Sampling Site ① was progressive. Their relatively stable detrital framework and local cementation enabled the samples to retain their overall form after short-term immersion. However, repeated wetting and drying progressively weakened interparticle bonding, which was consistent with the pronounced reduction in elastic modulus and the observed development of surface cracking and spalling. These changes are consistent with the macroscopic characteristics of pronounced swelling but limited susceptibility to rapid disintegration and with previously reported gradual damage modes of red-bed mudstone [1].

(2) Microstructural Evolution at Sampling Site ②.

As shown in Table 7, the samples from Sampling Site ② exhibited a heterogeneous structure characterized by the coexistence of rough blocky particles, stacked platy particles, and local cavities. Some areas appeared relatively dense, probably owing to local infilling or cementation, which is consistent with the presence of carbonate components identified by XRD. However, irregular pores, cracks, and rough fracture surfaces were commonly observed between these locally dense zones, indicating poor overall structural continuity.

Table 7. SEM Microstructural Characteristics of Samples from Sampling Site ② Before Wetting–Drying Cycling.

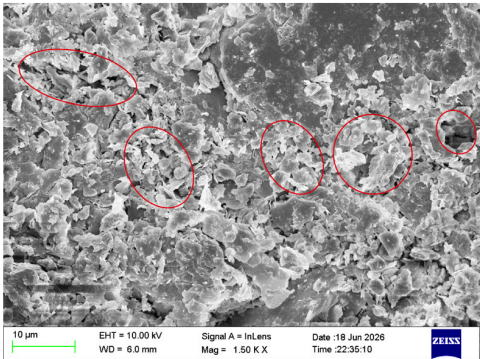
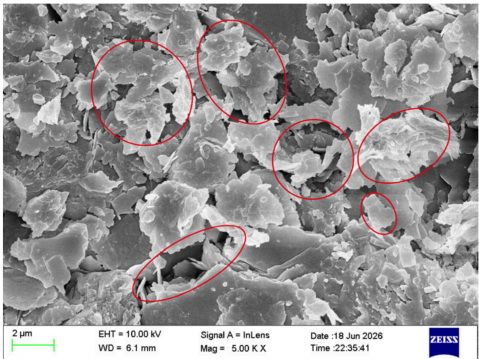
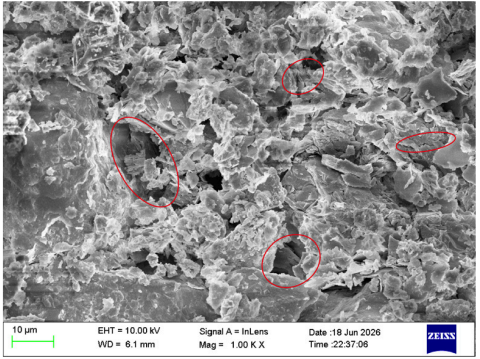
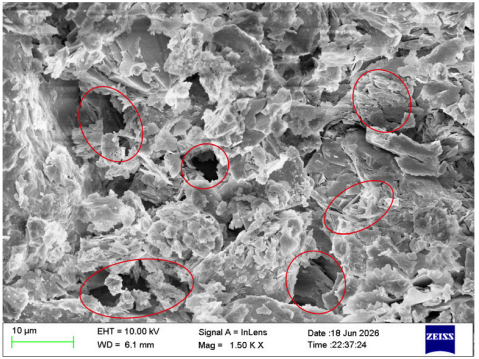
Sampling Location	Specimen Number	SEM Observation Results	
Sampling Site ②	②-2		

Note: Red ellipses highlight representative irregular pores, cracks, local cavities, and weak particle-contact regions observed before wetting–drying cycling. The annotations are illustrative and are used only for qualitative comparison rather than quantitative measurement.

In the high-magnification images, platy, tabular, and fragmental particles were well developed, with broken particle edges. Particle contacts were dominated by point contacts, edge contacts, and local face-to-face contacts. Pores were mainly observed along particle-accumulation boundaries and between layers of platy particles, and locally open or connected pore-like features were also observed. Combined with the XRD results, these observations suggest a heterogeneous structure consisting of a relatively rigid detrital framework, locally developed cemented regions, and pore-rich weak interfaces.

As shown in Table 8, after wetting–drying cycling, the representative SEM fields of Sampling Site ② showed more pronounced open cavities and interparticle gaps than those observed before cycling. Locally cemented regions exhibited fragmentation, particle detachment, and separation along particle boundaries. Previously dense regions were locally segmented by cracks, and connected crack-like pathways were observed in some representative areas. These features were accompanied by a transition from relatively interlocked particle contacts toward locally looser particle arrangements.

Table 8. SEM Microstructural Characteristics of Samples from Sampling Site ② After Wetting–Drying Cycling.

Sampling Location	Specimen Number	SEM Observation Results	
Sampling Site ②	②-2		
			

Note: Red ellipses highlight representative open cavities, interparticle gaps, connected crack-like pathways, particle detachment, and local cementation degradation observed after wetting–drying cycling. The annotations are intended only to facilitate qualitative comparison and do not represent quantitative measurements of pore–fracture characteristics.

In the high-magnification images, exfoliation and interlayer opening of platy particles became more pronounced. Particle edges showed more evident fragmentation and angular features after cycling, while local accumulations of fine particles and argillization were also observed. These observations suggest that the principal microstructural changes at Sampling Site ② after wetting–drying cycling involved local weakening of cementation, development of more continuous pore–crack pathways, and particle fragmentation or

detachment. Such structural changes are consistent with the rapid disintegration behavior observed during immersion.

Wetting–drying cycling tests on red-bed mudstone have shown that the release of soluble components, migration of fine particles, reduction in particle-contact area, changes in particle morphology, and enlargement of pore sizes can jointly promote rock disintegration. During cycling, the proportions of macropores and medium-sized pores may gradually increase [8,15]. However, such quantitative changes in pore-size distribution were not directly measured in the present study.

Qualitatively, the representative SEM images suggest that the microstructural changes at Sampling Site ② were more visually pronounced than those observed at Sampling Site ①. Before cycling, the rock samples were locally supported by cemented regions and a detrital framework; however, the cementation appeared discontinuous, while pores and platy weak interfaces were already evident. After cycling, degradation of locally cemented regions together with pore opening was associated with loss of local structural support. Platy particles showed exfoliation along interlayer weak planes, accompanied by pronounced local structural loosening. Similar coupling among cement dissolution, pore enlargement, and particle debonding has been reported for disintegrating red-bed rocks [7,8].

The rapid disintegration behavior of Sampling Site ② is interpreted as being more closely associated with its initially developed pore–crack features, relatively limited particle-contact areas, and discontinuous cementation than with a high swelling potential. After water entered the samples, local cemented regions may have undergone softening or partial dissolution, while pre-existing pore–crack features became more open and locally more continuous, accompanied by particle separation and progressive mudification. Therefore, the samples from Sampling Site ② exhibited relatively limited swelling but rapid disintegration upon immersion and pronounced loss of structural strength, a response consistent with cementation-loss-controlled disintegration described in previous studies [4].

It should be emphasized that the SEM observations presented in Tables 5–8 are intended for qualitative comparison of representative microstructural features. Because the images were acquired from local fracture surfaces at different magnifications and the natural rock samples exhibit substantial spatial heterogeneity, the highlighted pores, cracks, and particle-boundary features were not used to calculate pore-size distribution, crack density, areal porosity, or fractal parameters. Therefore, the SEM results are interpreted in terms of morphological trends rather than statistically quantified changes. More rigorous quantification of pore–fracture evolution will require standardized SEM image acquisition using consistent magnifications and standardized sampling areas, combined with dedicated image-analysis methods or complementary pore-structure characterization techniques.

3.4. Macro–Micro Response Relationships and the Deterioration Mechanism Induced by Wetting–Drying Cycling

A comprehensive analysis of mechanical properties, XRD results, and SEM observations reveals that wetting–drying cycling mainly induced structural degradation rather than significant mineral phase transformation in the red-bed soft rocks. Although the principal mineral assemblages remained relatively stable before and after cycling, differences in mineral composition, cementation conditions, and initial pore–fracture structures controlled the subsequent deterioration processes. As illustrated in Figure 11, the wetting–drying-induced deterioration of red-bed soft rocks can be interpreted as a progressive process involving mineral–water interaction, weakening of particle bonding, pore–fracture evolution, and mechanical degradation [7,27]. The different responses of the two sampling sites were mainly attributed to their distinct initial structural characteristics and dominant damage mechanisms.

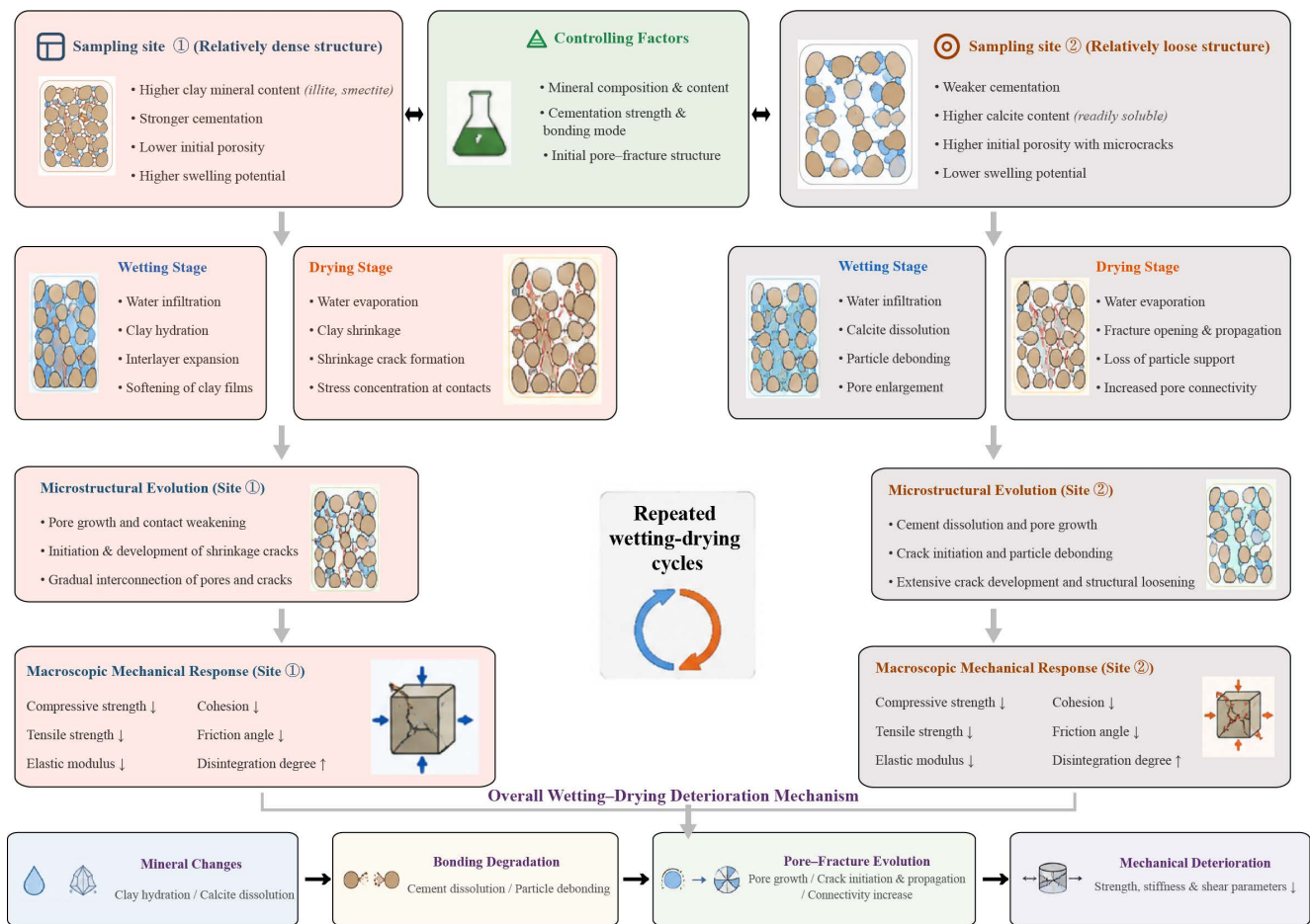


Figure 11. Conceptual framework illustrating mineral-controlled deterioration mechanisms of red-bed soft rocks under wetting–drying cycles. Arrows indicate the progression and causal relationships among mineral changes, bonding degradation, pore–fracture evolution, and mechanical deterioration.

During the wetting stage, water preferentially infiltrated into the rock through primary pores, bedding planes, and microcracks. The increased water content promoted hydration of clay minerals, expansion of water films on particle surfaces, and reductions in interparticle friction and interfacial bonding. Meanwhile, water-induced softening and dissolution of calcareous cement weakened the connection between mineral particles and reduced the integrity of the rock framework. During the subsequent drying stage, differential shrinkage occurred among clay minerals, cementing materials, and relatively rigid mineral particles such as quartz and feldspar. The resulting incompatible deformation generated local stress concentrations around particle boundaries and crack tips, promoting the initiation and propagation of microcracks. With repeated wetting and drying, these processes accumulated progressively, leading to the enlargement and interconnection of pores and fractures and ultimately causing deterioration in mechanical properties [9,28].

The mechanical response characteristics further revealed the different sensitivity of strength and stiffness parameters to cyclic damage. After eight wetting–drying cycles, the reduction in elastic modulus was significantly greater than that of compressive strength and tensile strength for both sampling sites. This behavior can be attributed to the fact that elastic deformation is highly sensitive to particle-contact degradation, interfacial weakening, and distributed microcracks, whereas pronounced strength loss generally requires further crack propagation and coalescence to form critical failure paths. Therefore, elastic modulus may serve as a more sensitive indicator for characterizing early-stage structural deterioration during wetting–drying cycling.

The deterioration pathways of the two sampling sites exhibited distinct characteristics due to differences in their initial structures and bonding conditions. For Sampling Site ①, the relatively dense structure, stronger particle interlocking, and better local cementation provided higher initial mechanical strength and structural stability. During wetting–drying cycling, water infiltration mainly caused weakening of particle contacts, opening of platy mineral interfaces, and gradual expansion and connection of isolated pores. Although the internal structure experienced continuous damage, the overall framework could be maintained for a relatively long period. Therefore, the deterioration behavior of Sampling Site ① was characterized by progressive damage dominated by swelling deformation and cyclic weakening, with gradual reductions in stiffness and strength [1,9].

In contrast, Sampling Site ② exhibited a weaker structural framework characterized by lower cementation strength, more developed initial pores, and abundant weak interfaces. During wetting–drying cycling, the reduction in calcite-related cementation and progressive debonding between particles accelerated the development of interconnected pore–fracture networks. Once the cemented structure was significantly damaged, particle detachment, exfoliation of platy minerals, and rapid structural loosening occurred. Consequently, the samples from Sampling Site ② exhibited a more pronounced disintegration tendency and faster transition from a rock-like structure to a softened and fragmented state. This indicates that the stability of weakly cemented red-bed soft rocks is highly dependent on the preservation of particle bonding and pore–fracture connectivity [16].

Overall, the wetting–drying deterioration of red-bed soft rocks can be regarded as a coupled process controlled by mineral water sensitivity, cementation degradation, and pore–fracture evolution. Although both sampling sites experienced similar deterioration sequences involving water infiltration, bonding degradation, crack development, and mechanical weakening, their dominant failure mechanisms were fundamentally different. Sampling Site ① mainly followed a swelling-controlled cyclic damage mode, whereas Sampling Site ② exhibited a cementation-loss-induced disintegration mode (Figure 11). These findings demonstrate that the water-sensitive behavior of red-bed soft rocks cannot be adequately evaluated using a single mechanical parameter, and that mineral composition, bonding conditions, and microstructural characteristics should be jointly considered for stability assessment and engineering prevention.

4. Conclusions

This study investigated the water-sensitive deterioration behavior and controlling mechanisms of red-bed soft rocks from two representative sites in the Sichuan Basin through multiscale experiments, including mechanical tests, wetting–drying cycles, XRD, and SEM analyses. The main conclusions are summarized as follows.

(1) The two types of red-bed soft rocks exhibited distinct initial structural characteristics. Sampling Site ① showed stronger cementation, higher structural integrity, and greater mechanical strength, whereas Sampling Site ② exhibited weaker bonding, more initial defects, and lower load-bearing capacity. Both rock types showed limited tensile resistance under natural conditions.

(2) Swelling and disintegration were controlled by different mechanisms. Site ① exhibited pronounced swelling but maintained structural integrity after immersion, while Site ② experienced rapid disintegration despite a lower swelling potential. The results indicate that cementation integrity and pore–fracture stability are more critical than swelling magnitude in controlling water-induced collapse.

(3) Wetting–drying cycles caused progressive mechanical degradation in both rock types. After eight cycles, elastic modulus showed the greatest deterioration, followed by

compressive strength and tensile strength. The results demonstrate that stiffness loss is a sensitive indicator for evaluating early-stage cyclic damage.

(4) Wetting–drying cycling mainly induced structural degradation rather than significant mineral transformation. XRD results showed stable major mineral phases, while the reduction in calcite and clay minerals was accompanied by weakening of cementing materials and adjustment of pore structures.

(5) SEM observations revealed different deterioration pathways. Site ① mainly experienced gradual damage characterized by pore enlargement, particle-contact weakening, and shrinkage crack development. Site ② underwent rapid structural collapse involving cement dissolution, particle debonding, pore–crack connectivity, and fragmentation.

(6) The deterioration mechanisms of the two rock types can be summarized as two typical modes: swelling-controlled cyclic damage for Site ① and cementation-loss-induced disintegration for Site ②. Although both experienced water infiltration, bonding degradation, crack evolution, and mechanical weakening, they exhibited distinct dominant deterioration mechanisms and failure manifestations.

(7) The stability evaluation of red-bed soft rocks should adopt a multi-indicator framework rather than relying on a single strength parameter. Natural strength, swelling behavior, disintegration characteristics, wetting–drying deterioration, mineral composition, and pore–fracture connectivity should be jointly considered for engineering assessment and prevention.

From an engineering perspective, the deterioration behavior of red-bed soft rocks should be evaluated according to their water-sensitive response characteristics rather than natural strength alone. For swelling-dominated rocks similar to Site ①, controlling water infiltration and limiting repeated wetting–drying exposure are essential to mitigate progressive deformation and stiffness loss. For strongly disintegrating rocks similar to Site ②, rapid water isolation, surface protection, and timely reinforcement are necessary to prevent sudden structural collapse. Future studies should expand the range of geological settings and sampling sites, integrate quantitative characterization of pore–fracture evolution, and combine laboratory investigations with long-term field monitoring to establish more reliable deterioration criteria and engineering evaluation methods.

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Abbreviations

The following abbreviations are used in this manuscript:

XRD	X-ray diffraction
SEM	scanning electron microscopy
PDF	Powder Diffraction File

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