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Shiguang Xu¹

Kunming University of Science and Technology

Mengna Zhang¹

Kunming University of Science and Technology

Ping Yan³

People's Government of Boshan Town, Linxiang District

Zikuang Xu

xzk99882008@vip.qq.com

Yunnan Land and Resources Vocational College

Yi Yang

Kunming University of Science and Technology

Chuanjiao Wang

Kunming University of Science and Technology

Jun Gong

Yunnan Geology and Mineral Engineering Survey Group Co., Ltd

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Multiscale Mechanisms and a Physicochemical Coupling Model of Schist Degradation under Water–Rock Interaction

Shiguang Xu^{1,2}, Mengna Zhang¹, Ping Yan³, Zikuang Xu⁴, Yi Yang¹, Chuanjiao Wang⁵, Jun Gong²

1. School of Public Safety and Emergency Management, Kunming University of Science and Technology, Kunming, Yunnan, China

2. Yunnan Geology and Mineral Engineering Survey Group Co., Ltd., Kunming, Yunnan, China

3. People's Government of Boshan Town, Linxiang District, Lincang City, Yunnan Province, China

4. Yunnan Land and Resources Vocational College, Kunming, Yunnan, China

5. Faculty of Land Resources Engineering, Kunming University of Science and Technology

Abstract : As open-pit mines become progressively deeper, schist-slope instability associated with water – rock interaction has become an increasingly important engineering concern. To clarify how differences in mineral composition govern the water-induced softening of layered schists, three representative lithologies—chlorite schist, two-mica schist, and two-mica quartz schist—were investigated in a geologically complex mining area in Yunnan Province, China. A 70-day laboratory immersion experiment combined with point-load testing was used to characterize the temporal evolution of rock strength under different immersion durations. X-ray diffraction (XRD), scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM – EDS), and temporal monitoring of representative ion concentrations in the immersion solutions were conducted to evaluate mineralogical variations, microstructural evolution, and changes in solution chemistry. The results show that the estimated uniaxial compressive strength of all three schist types decreases nonlinearly with increasing immersion duration, with the most rapid deterioration occurring during the initial immersion stage. Softening sensitivity is primarily governed by the abundance of hydrophilic clay minerals, particularly montmorillonite. Deterioration is most pronounced in chlorite schist, followed by two-mica schist and two-mica quartz schist. Multiscale observations indicate that macroscopic strength degradation results from coupling between physical hydration and chemical reactions. Hydration and swelling of clay minerals generate local wedging stresses, enlarge pores and fractures, and promote disintegration of the mineral skeleton. Simultaneously, interlayer ion exchange and dissolution of mineral cements weaken interparticle bonding and facilitate microcrack propagation and coalescence. These processes mutually reinforce one another, thereby establishing a self-reinforcing positive-feedback cycle. On this basis, a multiscale physicochemical conceptual model of water-induced schist degradation is proposed. The findings provide a

mechanistic basis for evaluating the long-term stability of metamorphic-rock slopes and developing disaster-mitigation measures under complex hydrogeological conditions.

Keywords : layered schist; water – rock interaction; water-induced softening; clay minerals; mechanical degradation; physicochemical coupling

1. introduction

As mineral resource extraction advances to greater depths worldwide, the stability of high and steep slopes has become a critical factor affecting operational safety and economic performance in open-pit mining. Water – rock interaction driven by rainfall infiltration and groundwater migration is widely recognized as one of the principal triggers of slope instability [1 – 3]. As mining depth increases, rock masses are subjected to increasingly complex hydrogeological conditions. Metamorphic soft rocks rich in hydrophilic minerals are particularly susceptible to strength degradation and structural disintegration under prolonged water infiltration. Consequently, the resulting time-dependent instability has become an important research topic in engineering geology [4,5]. Therefore, elucidating the mechanical responses and microscale deterioration mechanisms of soft rocks under water – rock interaction is of substantial theoretical and practical importance for assessing the long-term stability of slopes under complex hydrogeological conditions [6].

The Neoproterozoic schists of the Xinzhai Formation, including chlorite schist, two-mica schist, and two-mica quartz schist, are widely exposed in the tectonically complex region of southwestern China. These rocks have undergone intense metamorphism, exhibit pronounced anisotropy, and contain variable proportions of hydrophilic phyllosilicate minerals, including montmorillonite and chlorite. During open-pit mining, the eastern slope has been subjected to prolonged rainfall infiltration and fluctuations in groundwater level. Upon water exposure, the three schist types exhibit different degrees of softening and disintegration, resulting in pronounced lithology-dependent variations in slope deformation and failure. Therefore, characterizing the macroscopic mechanical degradation and microscale deterioration mechanisms of schists with contrasting metamorphic mineral assemblages under water-bearing conditions is directly relevant to slope-stability assessment in the study area and in regions with comparable geological settings.

Extensive research has investigated the water-induced mechanical deterioration of rocks.

Since the pioneering work of Colback and Wiid, numerous studies have confirmed that water can substantially reduce rock strength [7]. Baud et al. quantified the influence of water content on the strength of porous rocks, including sandstone [8]. Studies by Erguler et al. and Yilmaz reported marked reductions in uniaxial compressive strength and deformation modulus under saturated conditions, with losses exceeding 50% for some water-sensitive soft rocks [9,10]. Clay-bearing rocks commonly exhibit pronounced softening and stress relaxation upon wetting, and expansive clay minerals such as montmorillonite are widely regarded as major controls on this behavior [11]. For layered and anisotropic rocks, water infiltration has been shown to reduce shear resistance along foliation or other weak structural planes [12,13], and Yin et al. further demonstrated that water-bearing conditions intensify the strength anisotropy of quartz – mica schist [14]. Azhar et al. also found that the elastic modulus and hardness of clay-rich sandstone decreased progressively with increasing saturation time [15]. Collectively, these studies provide a robust basis for understanding the macroscopic mechanical effects of water – rock interaction.

At the microscale, rock softening is generally understood as a coupled process involving physical hydration and chemical reactions [16]. Valès et al. and Vergara et al. showed that hydration of layered silicate minerals, particularly expansive clays such as montmorillonite, can induce substantial matrix swelling [17,18], while Taylor et al. identified expansive clay minerals as a major cause of water-induced disintegration in argillaceous rocks [19]. Molecular dynamics simulations by Lu et al. distinguished two complementary softening mechanisms: weakening of interparticle tensile resistance by adsorbed water films and disintegration of particle aggregates during immersion [20]. Chemical processes also contribute to mechanical degradation by altering mineral surfaces and interparticle bonding. Dissolution of cementing phases can weaken interparticle bonds and facilitate structural deterioration [21]. Immersion experiments on red-bed soft rocks have indicated that feldspar hydrolysis and associated clay-mineral formation can dominate long-term deterioration [22], whereas temporal changes in solution chemistry reveal stage-dependent ion exchange and dissolution of cementing materials [23]. Despite these advances, three important knowledge gaps remain. First, most previous studies have focused on individual lithologies, and systematic comparisons among schists with contrasting metamorphic mineral assemblages under the same geological and hydrochemical conditions remain limited. Consequently, the quantitative influence of mineralogical differences on water resistance and

softening behavior has not been sufficiently constrained. Second, many investigations have compared only dry and saturated end states, whereas time-resolved datasets linking mechanical degradation, microstructural evolution, and solution chemistry during prolonged immersion remain scarce. The dominant processes and transition times associated with different softening stages therefore remain uncertain. Third, physical swelling and chemical dissolution are frequently considered separately, and a multiscale framework explicitly linking mineral composition, microstructural disintegration, and macroscopic strength loss is still lacking. In particular, the positive-feedback relationship between physical and chemical processes has not been explicitly represented. Addressing these gaps can support preventive and resource-efficient slope-management strategies, thereby contributing to safer and more sustainable mining operations.

To address these gaps, this study investigates three representative schist types—chlorite schist, two-mica schist, and two-mica quartz schist—from the eastern slope of an open-pit mine in southeastern Yunnan Province, China. Point-load tests were conducted on a total of 420 specimens under dry and water-saturated conditions to compare the softening behavior of the three schist types, while X-ray diffraction (XRD) was employed to characterize their mineral assemblages and examine the relationship between montmorillonite content and softening susceptibility. A 70-day laboratory immersion program, with observations at 0, 10, 20, 30, and 70 d, was conducted to quantify the time-dependent evolution of water content and estimated uniaxial compressive strength derived from point-load testing. Changes in pH and major-ion concentrations, including Ca^{2+} , Mg^{2+} , Na^+ , K^+ , and SO_4^{2-} , were monitored to identify stages of aqueous geochemical evolution, and scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM–EDS) was used to characterize microstructural deterioration at different immersion stages. Based on these observations, a multiscale physicochemical coupling model was developed to describe the positive feedback among clay-mineral swelling, microstructural damage, and chemical reactions. The findings are intended to improve long-term slope-stability assessment and inform targeted drainage and support measures. These outcomes may reduce failure-related disruptions and unnecessary remedial resource consumption, thereby supporting safer and more sustainable open-pit mining.

2. Materials and Methods

2.1 Geological Setting and Basic Physical Properties of the Rock Specimens

The study site is an open-pit mine located in southeastern Yunnan Province, China. The Neoproterozoic Xinzhai Formation (Pt_3x) is extensively exposed throughout the mining area and is subdivided into six lithologic members based on their lithologic assemblages. The principal units exposed on the eastern slope are chlorite schist of the first lithologic member (Pt_3x^1), two-mica schist of the second lithologic member (Pt_3x^2), and two-mica quartz schist of the third lithologic member (Pt_3x^3). The exposed strata occur at elevations of 920–1365 m, and the maximum mining depth is approximately 140 m. The mining area is structurally complex, and a brittle fault developed along its eastern side provides a preferential pathway for groundwater flow. The sampling locations are shown in Figure 1a.

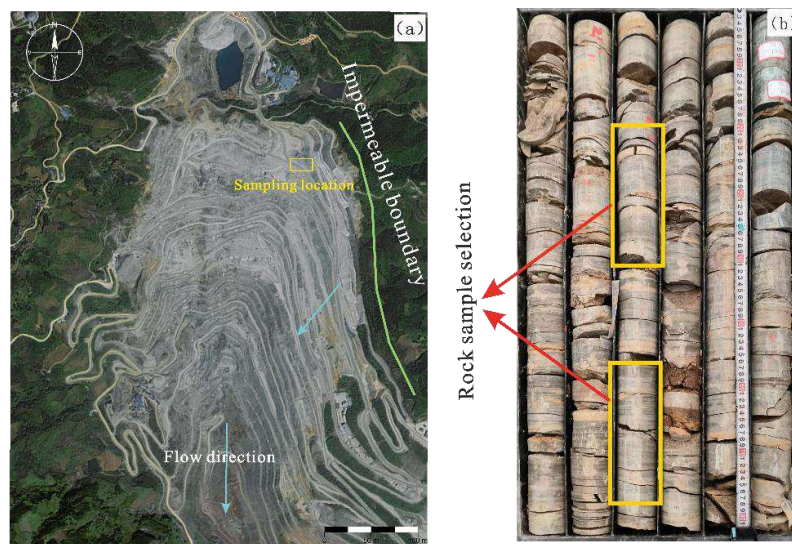


Figure 1. (a) Overview of the study area and sampling locations, including the impermeable boundary; (b) schematic illustration of rock-block selection and the inferred groundwater-flow direction.

Blocks of chlorite schist, two-mica schist, and two-mica quartz schist were collected from exploration boreholes on the eastern side of the mining area. Specimens with comparable textures and relatively homogeneous appearances were selected to minimize variability in the test results, as illustrated in Figure 1b.

The basic physical properties of the three schist types were determined using conventional laboratory tests, and the results are summarized in Table 1. Chlorite schist exhibited the highest

porosity (2.3%) and water absorption (0.72%), indicating a relatively open pore structure. In contrast, two-mica quartz schist had the highest dry and saturated densities, the lowest porosity (2.0%), and the lowest water absorption (0.21%), suggesting a comparatively dense structure and limited initial water uptake.

Table 1. Basic physical properties of the three schist types

Lithology	Air-dry density (g/cm ³)	Saturated density (g/cm ³)	Porosity (%)	Water absorption (%)	Softening coefficient	Mean RQD (%)
Chlorite schist	2.52	2.54	2.3	0.72	0.65	33.5
Two-mica schist	2.53	2.55	2.1	0.70	0.73	41.3
Two-mica quartz schist	2.60	2.62	2.0	0.21	0.80	43.0

Note: The softening coefficient is defined as the ratio of saturated to dry uniaxial compressive strength. The values listed in this table were obtained from conventional uniaxial compression tests and are broadly consistent with those estimated from the point-load tests presented in Section 3, although small differences exist because of differences in specimen geometry and testing method.

2.2 Experimental Program

The experimental program comprised four components: (1) point-load tests under dry and water-immersed conditions to evaluate the softening behavior of the three schist types; (2) a 70-day immersion experiment to characterize the time-dependent evolution of water content and mechanical strength; (3) X-ray diffraction and SEM–EDS analyses to investigate mineralogical and microstructural changes; and (4) hydrochemical analyses of the immersion solutions to identify changes in pH and major-ion concentrations.

2.2.1 Point-Load Testing

(1) Point-Load Tests under Dry and Water-Immersed Conditions

Point-load tests were conducted on specimens under dry and water-immersed conditions using an STDZ-3 point-load testing apparatus. Specimens assigned to the water-immersed condition were submerged in water collected from the mining area for 24 h before testing. During each test, the load was applied continuously until specimen failure, and at least 15 valid results were obtained for each test subgroup. A total of 420 specimens were tested, comprising 120 chlorite schist specimens, 160 two-mica schist specimens, and 140 two-mica quartz schist specimens. The specimen allocation

for each lithology and moisture condition is summarized in Table 2.

Table 2 Allocation of specimens for point-load testing under dry and water-immersed conditions

Lithology	Dry condition	Water-immersed condition	Total
Chlorite schist	60	60	120
Two-mica schist	80	80	160
Two-mica quartz schist	70	70	140
Total	210	210	420

According to the results of the point load test, the point load strength index $I_s(50)$ is first calculated. For irregular block samples, the following formula is calculated.

$$I_s(50) = \frac{P}{D_e^2} \quad (1)$$

In the formula : P is the ultimate failure load (N) ; D_e is the equivalent core diameter (mm), calculated by $D_e^2 = 4A/\pi$, where A is the minimum cross-sectional area (mm²) through the contact point of the two pressure plates.

The estimated uniaxial compressive strength, R_c , was derived from $I_s(50)$ using the following empirical relationship:

$$R_c \approx k \times I_s(50) \quad (2)$$

where k is the empirical conversion coefficient. Calibration against direct uniaxial compression tests conducted under dry and water-immersed conditions indicated that $k=23$ provided an appropriate conversion for the three schist types when loading was applied normal to foliation. The same conversion coefficient was applied at all immersion stages to maintain consistency when comparing temporal trends in estimated strength. For all point-load tests, the loading axis was oriented perpendicular to the foliation plane to minimize the influence of directional variability on comparisons among immersion stages..

2.2.2 Time-Dependent Immersion Tests

Specimens of the three schist types were immersed in groundwater collected from the mining area. Five test conditions were established for each lithology: an unimmersed dry condition and immersion durations of 10, 20, 30, and 70 d. Seven replicate specimens were assigned to each lithology at each test condition, resulting in 15 lithology–time groups. The experimental grouping

is summarized in Table 3. At each scheduled time point, the specimens were removed from the immersion solution, and their water contents and point-load strength indices were measured. The estimated uniaxial compressive strength was subsequently calculated using the conversion relationship described in Section 2.2.1 to characterize the time-dependent degradation behavior.

Table 3. Experimental groups and immersion durations for the time-dependent softening tests

Lithology	Dry, 0 d	Immersion, 10 d	Immersion, 20 d	Immersion, 30 d	Immersion, 70 d
Chlorite schist	1-1	2-1	3-1	4-1	5-1
Two-mica schist	1-2	2-2	3-2	4-2	5-2
Two-mica quartz schist	1-3	2-3	3-3	4-3	5-3

Note: Each lithology–time group contained seven replicate specimens.

2.2.3 Mineralogical and Microstructural Characterization

(1) X-Ray Diffraction Analysis

For each schist type, specimens representing the dry condition and 70 d of immersion were selected for X-ray diffraction analysis, as listed in Table 4. Approximately 60 g of material from each selected specimen was analyzed to characterize differences in mineral assemblage and relative mineral content before and after immersion.

Table 4. Specimens selected for X-ray diffraction analysis

Lithology	Dry condition	Immersion for 70 d
Chlorite schist	1-1	5-1
Two-mica schist	1-2	5-2
Two-mica quartz schist	1-3	5-3

(2) SEM–EDS Analysis

An EVO 18 scanning electron microscope was used to examine the microstructures of specimens under the dry condition and after immersion for 10, 20, 30, and 70 d. All specimens were examined at a nominal magnification of 778× using secondary-electron and backscattered-electron imaging modes. Energy-dispersive X-ray spectroscopy was performed on selected regions to identify their elemental compositions. The SEM specimens were selected from the lithology–time groups listed in Table 3, whereas the XRD analysis included only the dry and 70 d specimens listed in Table 4.

2.2.4 Hydrochemical Analysis of the Immersion Solutions

Groundwater collected before contact with the rock specimens was used as the initial reference solution. Immersion solutions for the three schist types were collected after 30 and 70 d for hydrochemical analysis. The measured parameters included pH, salinity, and the concentrations of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , sulfate, chloride, dissolved Al, dissolved Fe, and dissolved Si. Changes in solution chemistry were used to evaluate water–rock reactions, including mineral dissolution, redistribution of dissolved ions, and interlayer cation exchange associated with clay minerals. The solution-sampling scheme is summarized in Table 5.

Table 5. Sampling scheme for the hydrochemical analysis of immersion solutions

Lithology	Initial groundwater	Immersion solution, 30 d	Immersion solution, 70 d
Chlorite schist	Initial reference	3-1	5-1
Two-mica schist	Initial reference	3-2	5-2
Two-mica quartz schist	Initial reference	3-3	5-3

3. Results

3.1 Effects of Immersion on Macroscopic Mechanical Properties

3.1.1 Evolution of Estimated Uniaxial Compressive Strength with Immersion Time

The estimated uniaxial compressive strength (UCS) of the three schist types under the dry condition and after immersion for 10, 20, 30, and 70 d was derived from the point-load strength index. As shown in Figure 2, the estimated UCS decreased nonlinearly with increasing immersion time. The most rapid reduction occurred during the first 20 d, after which the rate of strength loss gradually decreased. The magnitude of strength degradation differed markedly among the three lithologies. Chlorite schist exhibited the greatest strength loss, decreasing from approximately 17.0 MPa in the dry condition to 11.1 MPa after 70 d of immersion (equivalent to a softening coefficient of 0.65, consistent with the conventional uniaxial compression tests in Table 1). Two-mica schist showed an intermediate response, decreasing from approximately 13.9 to 10.2 MPa (softening coefficient 0.73), whereas two-mica quartz schist exhibited the smallest reduction, from approximately 32.6 to 26.1 MPa (softening coefficient 0.80), indicating comparatively low sensitivity to immersion.

The temporal pattern of strength loss was compared with the microstructural and

hydrochemical observations presented in Sections 3.2 and 3.3. The rapid strength reduction during the first 20 d coincided with pronounced particle separation and pore enlargement observed in the corresponding SEM images. These concurrent observations are consistent with the involvement of hydration-induced microstructural damage during the early immersion stage. After 20 d, the rate of strength reduction decreased substantially. This slower stage was accompanied by less pronounced changes in the observed microstructure, while the solution chemistry approached a less rapidly changing state between 30 and 70 d. The physicochemical interpretation of these trends is discussed in Section 4.

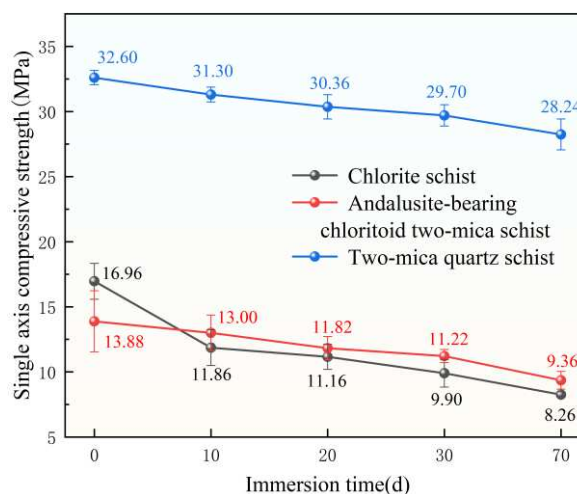


Figure 2. Evolution of the estimated uniaxial compressive strength of the three schist types with immersion time.

3.1.2 Softening Coefficients and Potential Controlling Factors

(1) Distribution of Softening Coefficients

Softening coefficients were calculated from the point-load strengths measured under dry and water-immersed conditions, as shown in Figure 3. Chlorite schist had softening coefficients ranging from 0.58 to 0.72, with a mean value of 0.68. The corresponding range for two-mica schist was 0.64–0.90, with a mean of 0.72, whereas two-mica quartz schist exhibited the highest values, ranging from 0.76 to 0.98, with a mean of 0.87. Thus, chlorite schist showed the greatest overall sensitivity to water exposure, whereas two-mica quartz schist showed the lowest sensitivity.

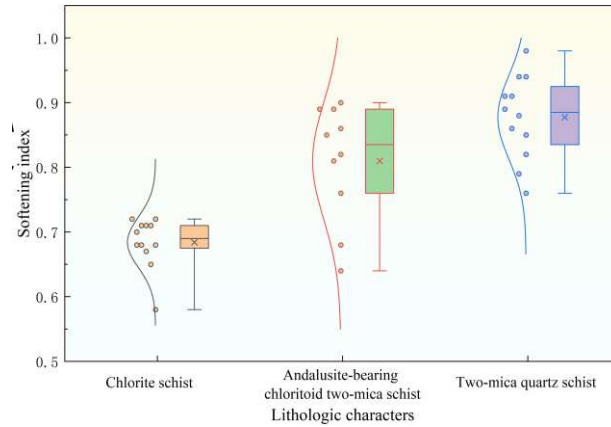


Figure 3. Distribution of softening coefficients for the three schist types.

(2) Relationship between the Softening Coefficient and RQD

The mean RQD values were 33.5% for chlorite schist, 41.3% for two-mica schist, and 43.0% for two-mica quartz schist (Table 1). As shown in Figure 4, the softening coefficient increased with RQD for chlorite schist and two-mica schist, indicating that specimens with better rock-mass integrity generally exhibited lower water sensitivity. In contrast, the relationship was weak for two-mica quartz schist, whose softening coefficients remained comparatively high over the investigated RQD range. These results suggest that RQD alone cannot fully explain the differences in softening behavior among the three lithologies.

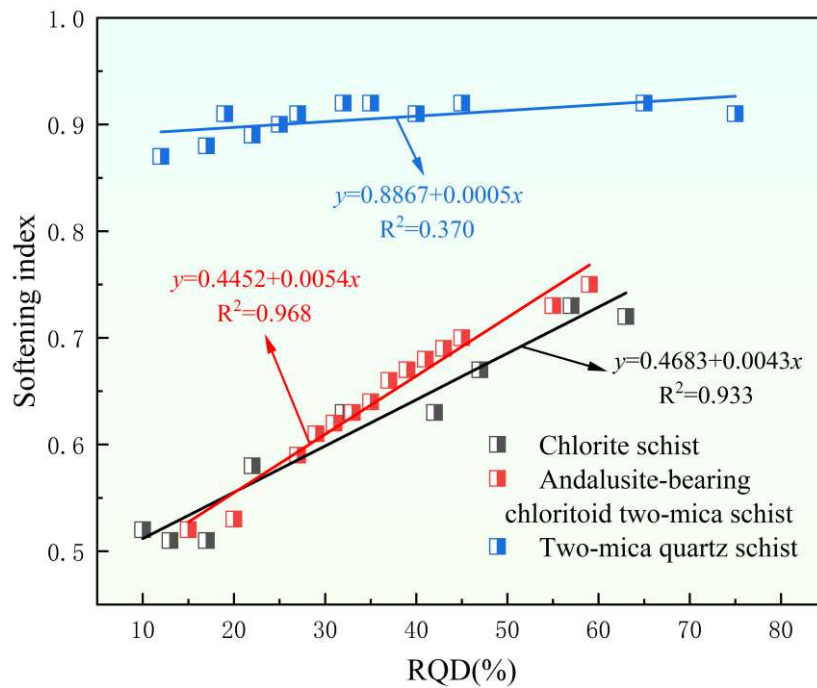


Figure 4. Relationships between the softening coefficient and rock quality designation (RQD) for the three schist types.

(3) Relationship between the Softening Coefficient and Montmorillonite Content

The contrasting relationships between RQD and the softening coefficient indicate that structural integrity alone may not account for the observed lithological differences. XRD analysis showed that the initial montmorillonite contents were 15.6% in chlorite schist, 6.6% in two-mica schist, and 1.1% in two-mica quartz schist (Table 6). Across the available dataset, higher montmorillonite contents were associated with lower softening coefficients. An exploratory linear fit yielded $Y=0.9312-0.0292X$, with $R^2=0.943$, where Y is the softening coefficient and X is the montmorillonite content (%). However, because each lithology was represented by a single XRD-derived montmorillonite value, this regression should be interpreted as a site-specific association rather than a universally applicable predictive relationship.

Montmorillonite has a highly hydrophilic 2:1 layered structure and a high cation-exchange capacity, making it more susceptible to hydration-induced swelling than the other major phyllosilicates identified in the specimens. The porosities of the three schist types varied only slightly, from 2.0% to 2.3%, whereas their montmorillonite contents differed substantially. The combined results therefore suggest that mineralogical composition, particularly montmorillonite abundance, contributed to the contrasting softening responses. The detailed physicochemical mechanisms are discussed in Section 4.

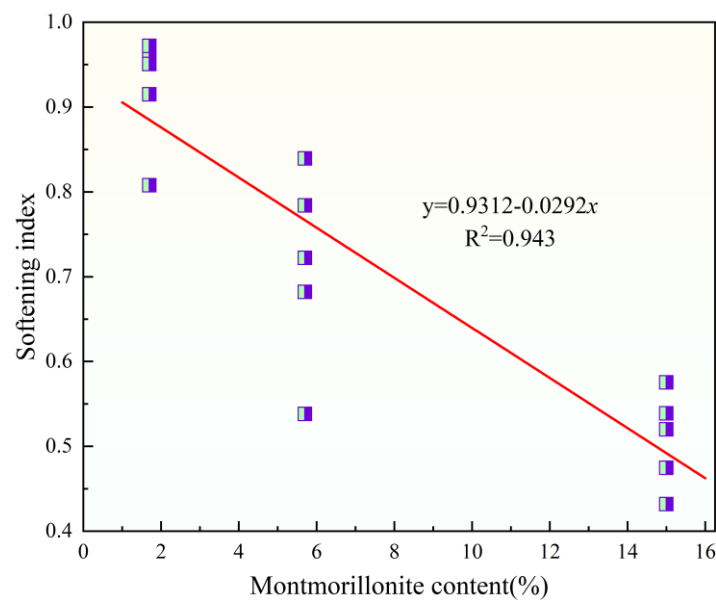


Figure 5. Exploratory relationship between montmorillonite content and the softening coefficient.

(4) Relationships of the Softening Coefficient with Weathering Degree and Burial Depth

As shown in Figure 6, lower softening coefficients were generally observed in the completely

to strongly weathered zones than in the moderately to slightly weathered zones, indicating greater water sensitivity in the more intensely weathered rock masses. The lowest values were concentrated near burial depths of approximately 20–30 m, corresponding to the lower part of the strongly weathered zone at the investigated site. However, no consistent monotonic relationship was observed between the softening coefficient and burial depth over the full depth range. These results indicate that burial depth alone was not a reliable predictor of softening behavior and that lithology, weathering condition, and fracture development should be considered jointly.

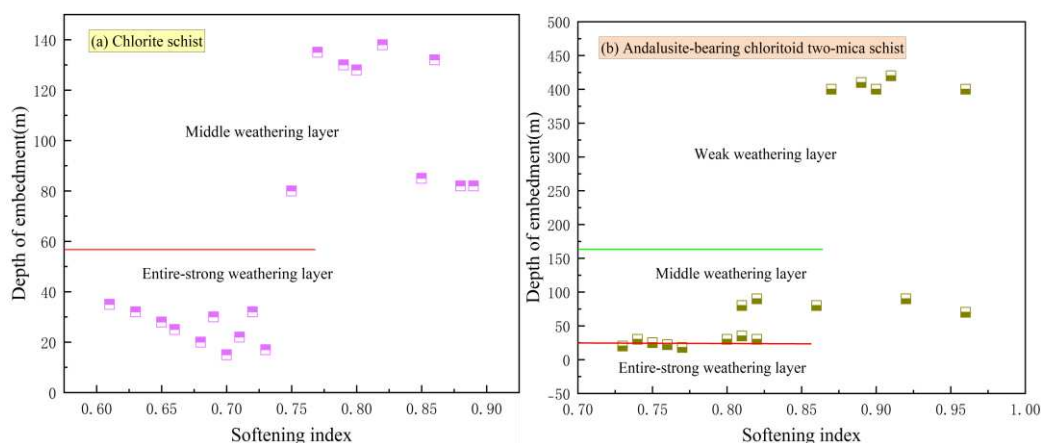


Figure 6. Relationships of the softening coefficient with burial depth and weathering degree: (a) chlorite schist; (b) two-mica schist.

3.2 Mineralogical and Microstructural Evolution

3.2.1 The change of mineral composition of schist

X-ray diffraction (XRD) was used to characterize the mineral assemblages and relative mineral contents of the three schist types under the dry condition and after 70 d of immersion. The corresponding XRD patterns are presented in Figures 7 and 8.

The mineral assemblages and relative contents determined for the dry specimens are summarized in Table 6. Chlorite schist consisted predominantly of chlorite (47.0%), muscovite (32.0%), and montmorillonite (15.6%), with minor illite, K-feldspar, albite, quartz, and plagioclase. Two-mica schist was dominated by muscovite (55.0%) and chlorite (30.0%) and contained smaller proportions of montmorillonite (6.6%), quartz (5.7%), feldspars, and albite. The dry two-mica quartz schist contained muscovite (45.0%), chlorite (30.0%), quartz (12.7%), and plagioclase (7.3%), together with minor montmorillonite, K-feldspar, and albite. These results demonstrate substantial mineralogical differences among the three lithologies, particularly in their

montmorillonite and quartz contents.

The same principal mineral phases were identified before and after immersion, indicating that no fundamental change in mineral assemblage occurred during the 70 d test. Nevertheless, variations were observed in the relative phase proportions. In chlorite schist, the relative chlorite content decreased from 47.0% to 40.0%, whereas muscovite, illite, K-feldspar, and albite showed modest increases. The montmorillonite and quartz contents remained nearly unchanged. In two-mica schist, the relative muscovite content decreased from 55.0% to 45.0%, while chlorite increased from 30.0% to 45.0%; montmorillonite and quartz exhibited moderate decreases. In two-mica quartz schist, the relative contents of muscovite and plagioclase decreased, whereas those of chlorite, quartz, montmorillonite, and albite increased. Because these values are semi-quantitative and may be influenced by specimen heterogeneity, powder preparation, and normalization, the observed differences should be interpreted as changes in relative XRD proportions rather than direct evidence of mineral formation or transformation.

Table 6. Relative mineral contents of the three schist types under dry and 70 d immersion conditions

Sample No.		mineral composition and content (%)							
		Muscovite (%)	Chlorite (%)	Montmorillonite (%)	Quartz (%)	Illite (%)	K-feldspar (%)	Albite (%)	Plagioclase (%)
Chlorite schist	1-1	32.00	47.00	15.60	0.80	1.50	1.50	1.50	0.20
	5-1	35.00	40.00	15.00	0.80	2.60	3.00	3.20	0.30
Two-mica schist	1-2	55.00	30.00	6.60	5.70	0	1.00	1.10	1.60
	5-2	45.00	45.00	5.10	1.20	0	1.30	1.30	1.10
Two-mica quartz schist	1-3	45.00	30.00	1.10	12.70	0	2.00	1.90	7.30
	5-3	29.00	40.00	2.40	22.50	0	1.40	2.70	2.00

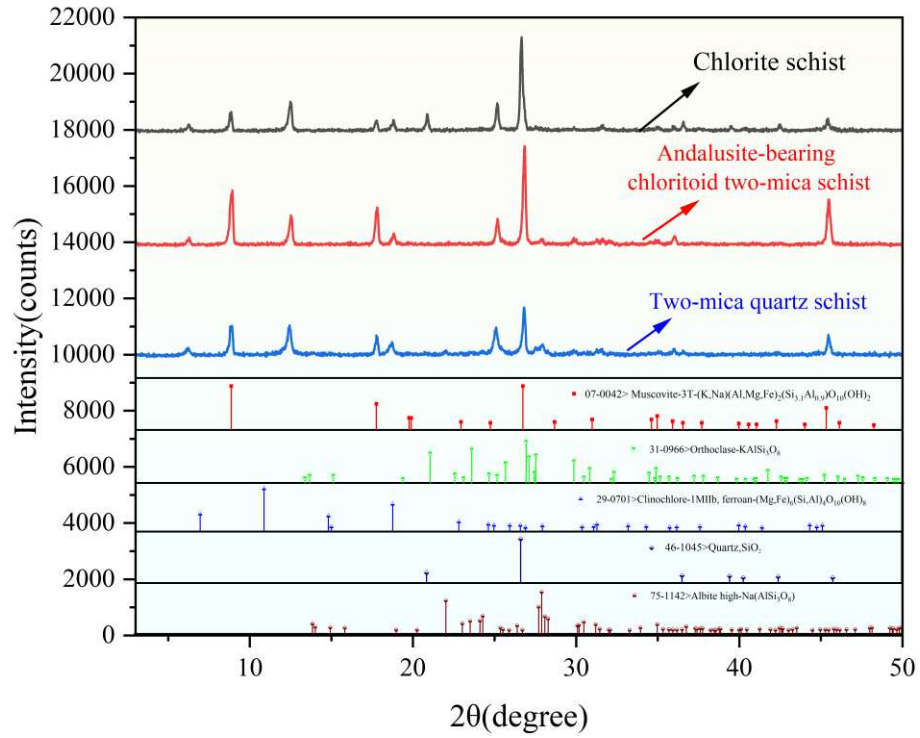


Figure 7. X-ray diffraction analysis pattern of dry state sample

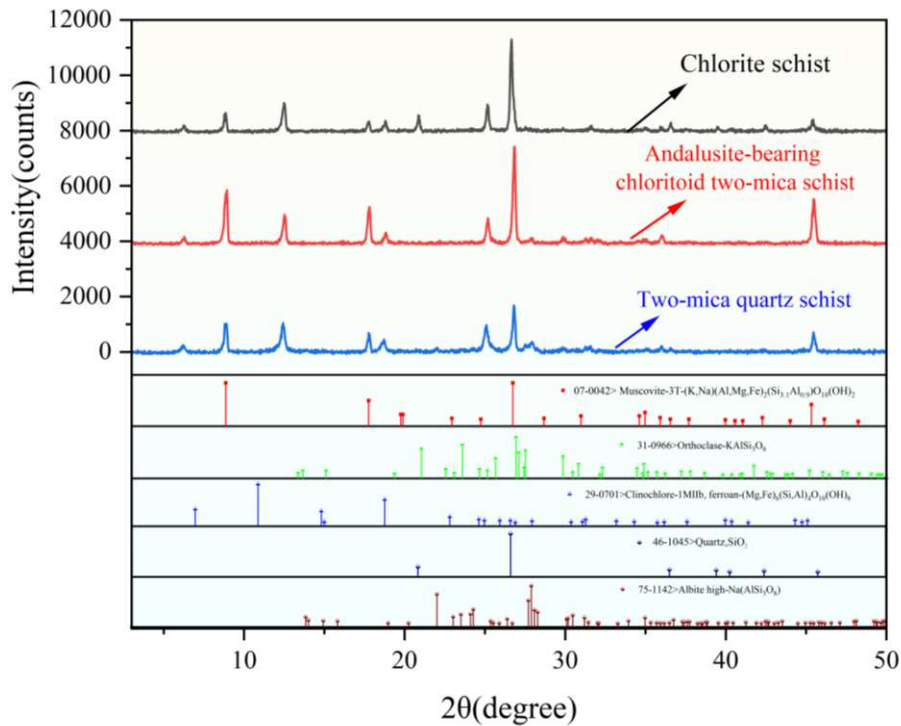


Figure 8. X-ray diffraction analysis of samples immersed in water for 70 days

3.2.2 SEM Observations of Microstructural Evolution

The microstructures of the three schist types at different immersion stages were examined by SEM at a nominal magnification of 778×. Under the dry condition, the specimens were characterized primarily by stacked platy particles with relatively smooth surfaces and predominantly

face-to-face contacts. With increasing immersion time, particle edges generally became more rounded, interparticle voids enlarged, and the fabrics became progressively looser. The extent of these changes differed substantially among the three lithologies, as described below.

(1) Chlorite schist

Under the dry condition, chlorite schist exhibited a compact fabric of stacked platy particles with smooth surfaces and predominantly face-to-face contacts. Representative apparent pore widths measured in the selected SEM images were approximately 5.3–5.6 μm . After 10–20 d of immersion, particle edges became increasingly rounded, the face-to-face contacts began to loosen, and the apparent pore widths increased to approximately 6.0–6.2 μm . After 30 d, some larger particles showed fragmentation, and the original face-to-face fabric was locally replaced by edge-to-face contacts. Dissolution-like surface features and loss of interstitial material were also observed, with apparent pore widths ranging from approximately 5.4 to 7.1 μm . After 70 d, the microstructure was markedly looser, the particles were irregularly aggregated, and many observed voids were wider than approximately 6.8 μm . Extensive separation of platy particles produced a loose coarse-particle framework containing flocculent fine material, with substantially reduced continuity of interparticle contacts (Figure 9).

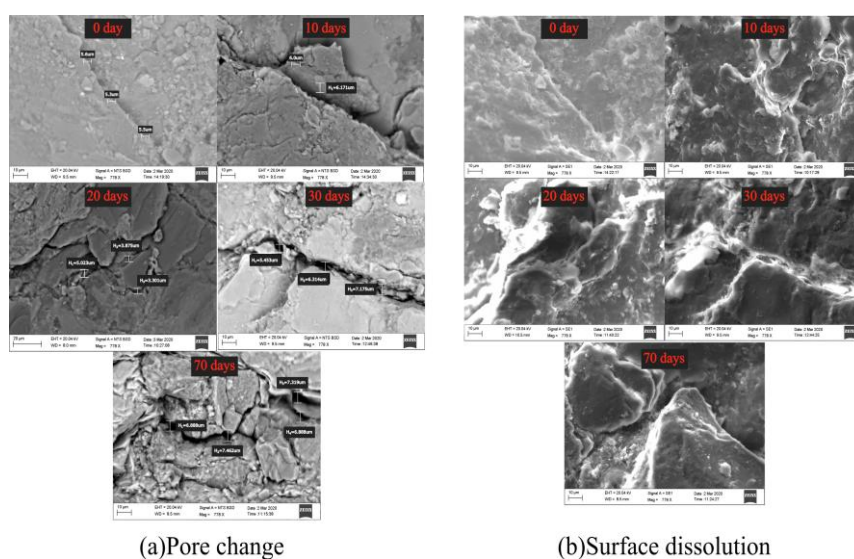


Figure 9. SEM images showing the microstructural evolution of chlorite schist under the dry

condition and after different immersion durations (778 $\times$).

(2) Two-mica schist

Under the dry condition, two-mica schist exhibited a well-developed platy fabric with relatively flat particle surfaces and pronounced preferred orientation. Face-to-face contacts were dominant, and representative apparent pore widths ranged from approximately 3.0 to 4.2 μm . After 30 d of immersion, the edges of some platy particles became slightly rounded, interlayer openings increased, and the apparent pore widths increased to approximately 4.7–6.0 μm , although the overall face-to-face fabric remained recognizable. After 70 d, many observed voids were wider than 7 μm , with a maximum apparent width of approximately 13.2 μm in the selected images. Some particles showed edge expansion, fragmentation, and separation into coarser fragments. The irregular arrangement of platy and coarse particles resulted in a looser fabric and reduced continuity of interparticle contacts (Figure 10).

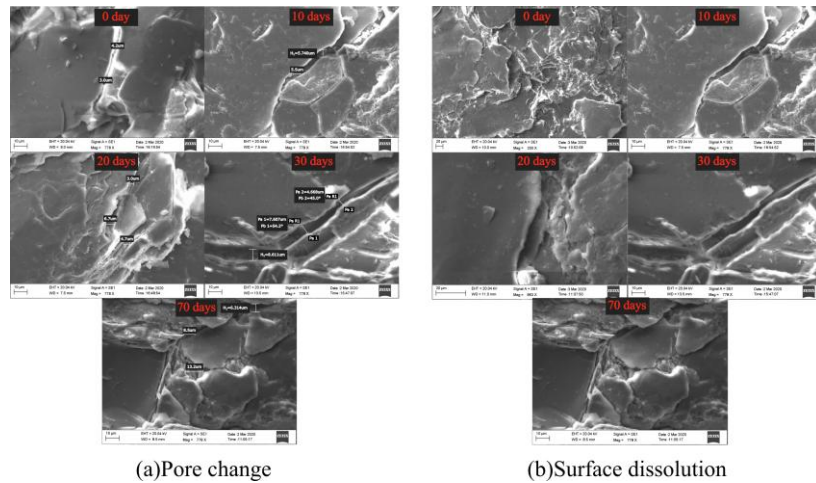


Figure 10. SEM images showing the microstructural evolution of two-mica schist under the dry condition and after different immersion durations (778 $\times$).

(3) Two-mica quartz schist

Under the dry condition, two-mica quartz schist exhibited a comparatively compact microstructure with flat particle surfaces, pronounced preferred orientation, and predominantly face-to-face contacts. Few visible microcracks were observed in the selected field of view. After 70 d of immersion, only limited changes were evident: some particle edges became slightly rounded, and minor expansion of fine material was observed within local interparticle openings. Most apparent pore widths remained below approximately 3.5 μm , and the overall fabric retained relatively close particle contacts (Figure 11). These observations indicate that the microstructure of

two-mica quartz schist was less sensitive to immersion than those of chlorite schist and two-mica schist.

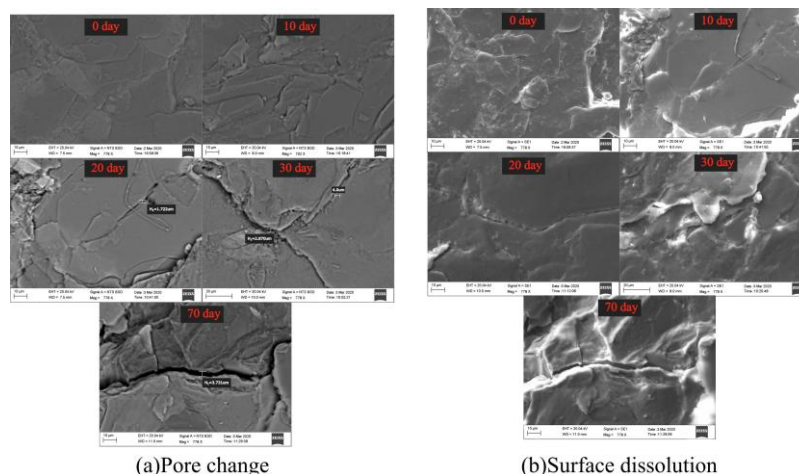


Figure 11. SEM images of two-mica quartz schist under the dry condition and after 70 d of immersion (778 $\times$).

Overall, the extent of microstructural alteration followed the order chlorite schist > two-mica schist > two-mica quartz schist. This ranking was consistent with the corresponding differences in estimated strength loss. The agreement between the mechanical and SEM observations supports the interpretation that particle separation, enlargement of interparticle voids, and progressive loosening of the microfabric contributed to the water-induced mechanical degradation of the schists.

3.2.3 EDS Characterization of Selected Microstructural Features

After immersion, chlorite schist exhibited flocculent fine material, separated platy particles, and partial infilling of interparticle voids. EDS spectra collected from selected flocculent and fine-particle regions indicated high abundances of Fe and O, together with Al, Si, and Mg. This elemental association is consistent with the presence of Fe–Mg-bearing chlorite identified by XRD, although EDS alone cannot unambiguously determine the mineral phase or elemental oxidation states. Sheet-like and flocculent phases were also observed within some pores. When considered together with the XRD results, these phases may be associated with clay minerals such as montmorillonite and illite. Local surface etching, particle separation, and flocculation were particularly evident in the immersed chlorite schist (Figure 12).

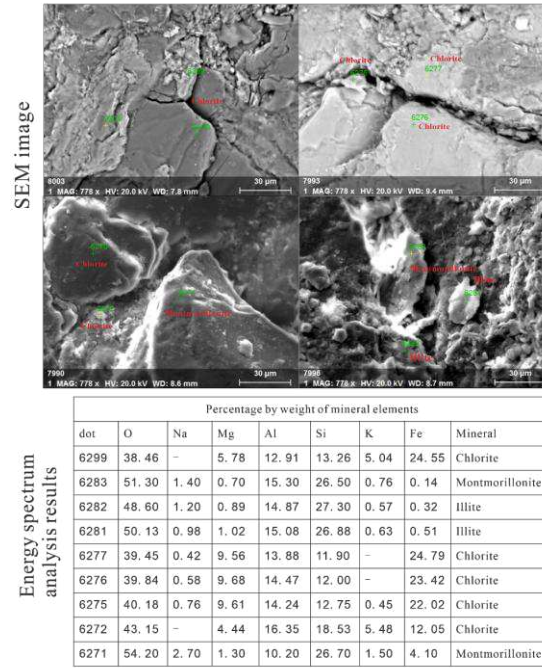


Figure 12. SEM–EDS characterization of selected microstructural features in chlorite schist after immersion.

In two-mica schist, EDS spectra from selected platy regions were dominated by O, K, Al, and Si, an elemental association consistent with K-bearing mica. Spectra obtained from smaller particles contained relatively high proportions of O and Fe, together with Mg, Al, and Si, which is consistent with Fe–Mg-bearing chlorite. Compared with chlorite schist, the immersed two-mica schist exhibited less pronounced surface etching, particle separation, and flocculent material in the selected SEM fields. These observations indicate a lower degree of microstructural alteration over the investigated immersion period (Figure 13).

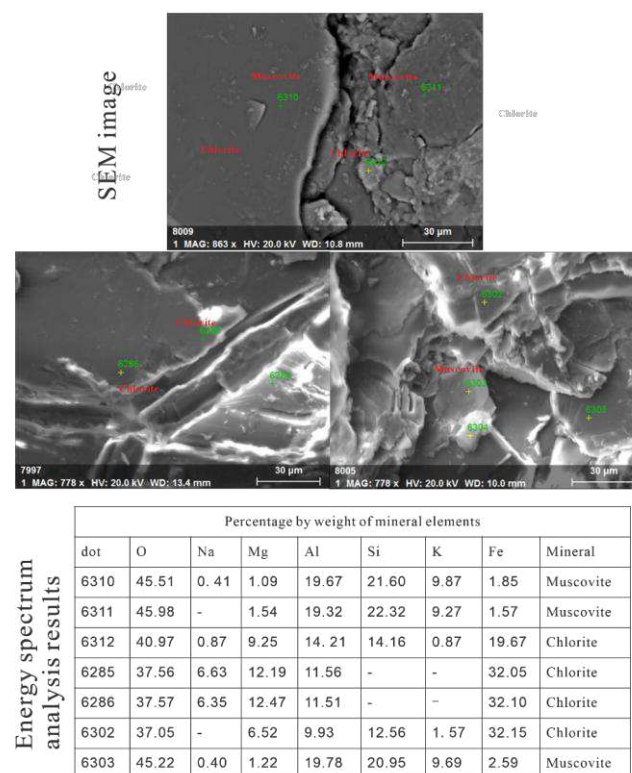


Figure 13. SEM–EDS characterization of selected microstructural features in two-mica schist after immersion.

In summary, the SEM observations revealed particle separation, enlargement of interparticle voids, and progressive loosening of the microfabric, particularly in chlorite schist. The EDS results showed elemental associations consistent with the principal phyllosilicate minerals identified by XRD and provided supporting evidence for localized mineral-surface alteration. Taken together, these observations demonstrate clear lithology-dependent differences in microstructural response to immersion. The physicochemical mechanisms responsible for these differences are discussed in Section 4.

3.3 Hydrochemical Evolution of the Immersion Solutions

To evaluate the aqueous geochemical processes associated with water–rock interaction, immersion solutions collected after 30 and 70 d were analyzed and compared with the initial groundwater. Particular attention was given to temporal changes in pH and major-ion concentrations. These measurements were used to assess possible mineral dissolution, ion exchange, adsorption, and secondary precipitation during immersion.

3.3.1 Changes in pH

Changes in the pH of the immersion solutions are shown in Figure 14. The initial groundwater

had a pH of 7.73, indicating near-neutral to slightly alkaline conditions. After 30 d of immersion, the pH increased to approximately 8.29–8.34 for the three lithologies, corresponding to weakly alkaline conditions. After 70 d, the pH decreased slightly to approximately 8.12–8.15 but remained higher than that of the initial groundwater. The magnitude of the pH increase was slightly greater for the chlorite schist and two-mica schist solutions than for the two-mica quartz schist solution. The initial increase may reflect proton-consuming reactions associated with silicate hydrolysis and the dissolution of alkaline mineral phases. The subsequent slight decrease suggests that the rate of net proton-consuming reactions diminished between 30 and 70 d. However, additional measurements of alkalinity and dissolved inorganic carbon would be required to identify the dominant reactions more precisely.

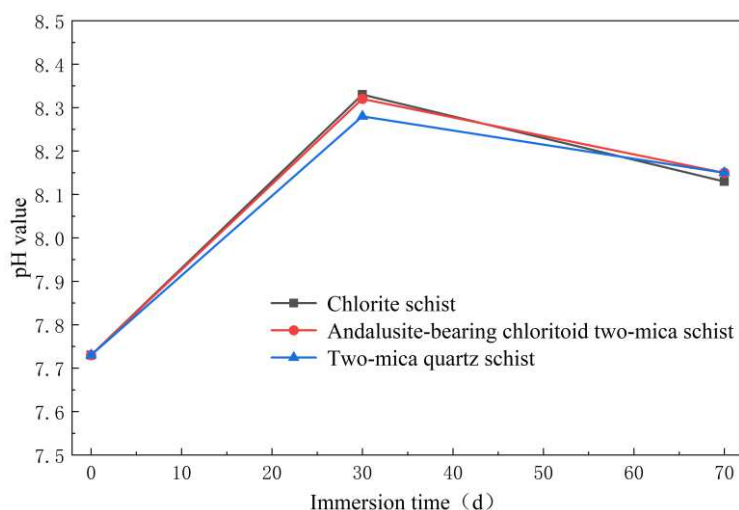


Figure 14. Changes in the pH of the immersion solutions for the three schist types with immersion time.

3.3.2 Changes in Major-Ion Concentrations

Changes in the major-ion concentrations of the immersion solutions are shown in Figure 15. The Ca^{2+} concentration in the chlorite schist solution increased from 58.7 mg/L in the initial groundwater to 82.1 mg/L after immersion, whereas smaller increases were observed in the two-mica schist and two-mica quartz schist solutions. This increase is consistent with the release of Ca from Ca-bearing mineral phases or exchange sites, although it does not provide definitive evidence of calcite-cement dissolution.

The SO_4^{2-} concentration decreased in all three immersion solutions, with the largest reduction occurring in the chlorite schist solution, from 149 to 55.8 mg/L. This decrease may have resulted

from adsorption, incorporation into secondary precipitates, or other solid–solution redistribution processes. The available data do not distinguish among these mechanisms.

The K^+ concentration in the chlorite schist solution increased from 1.72 to 3.71 mg/L, whereas decreases were observed in the two-mica schist and two-mica quartz schist solutions. These contrasting trends suggest that the balance between K release from K-bearing phases and K removal through adsorption, exchange, or secondary-phase formation differed among the three lithologies. The Na^+ concentration decreased from an initial value of 12.7 mg/L to approximately 2.57–6.18 mg/L in all three solutions, indicating that Na removal from solution exceeded its net release.

The Mg^{2+} concentration initially decreased and subsequently increased in the chlorite schist and two-mica schist solutions, with the largest variation occurring for chlorite schist. This pattern may reflect competition between Mg uptake during the earlier stage and release from Mg-bearing minerals during the later stage. Dissolved Al and Fe were below the analytical detection limits or present at very low concentrations, consistent with low solubility, adsorption, or secondary precipitation under near-neutral to weakly alkaline conditions.

Among the three lithologies, the chlorite schist solution exhibited the largest overall changes in Ca^{2+} , K^+ , Mg^{2+} , and SO_4^{2-} concentrations, whereas the two-mica quartz schist solution generally showed smaller variations. This ranking was consistent with the relative magnitudes of strength loss and microstructural alteration. However, the observed concentration changes represent the net result of multiple simultaneous aqueous and surface reactions rather than direct evidence of a single chemical mechanism.

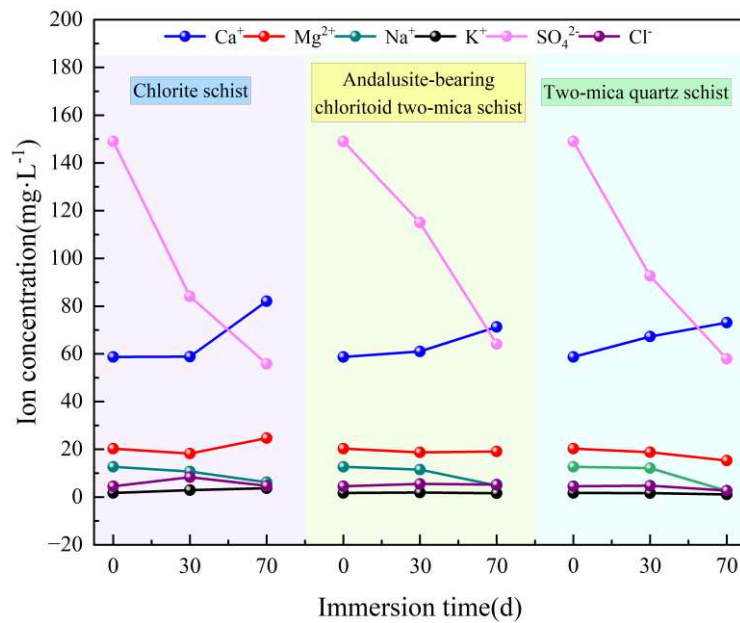


Figure 15. Changes in major-ion concentrations in the immersion solutions of the three schist types with immersion time.

In summary, the hydrochemical results demonstrated that immersion produced measurable changes in pH and major-ion concentrations and that the magnitude of these changes depended on lithology. The observed trends are consistent with coupled mineral dissolution, adsorption, ion exchange, and possible secondary precipitation during water–rock interaction. Chlorite schist showed the most pronounced aqueous geochemical response, whereas two-mica quartz schist exhibited comparatively limited changes. These hydrochemical observations complement the SEM evidence of particle separation and surface alteration, although additional mineral-saturation, alkalinity, and solid-phase analyses would be required to identify the individual reactions quantitatively.

4. Discussion of the Multiscale Mechanisms of Water-Induced Schist Softening

4.1 Physical Softening Mechanisms

The mechanical and SEM results presented in Sections 3.1 and 3.2 suggest that the physical component of schist softening involves hydration-induced swelling, separation of platy particles, enlargement of interparticle voids, and progressive loosening of the microfabric. These processes were most pronounced in chlorite schist and least evident in two-mica quartz schist.

(1) Hydration and Swelling of Clay Minerals

The crystal structure of montmorillonite and illite consists of two Si-O tetrahedral layers sandwiched by an Al- (O, OH) octahedral layer. In this structure, the interlayer is connected by van der Waals force and weak electrostatic attraction, and water molecules are easy to enter the interlayer. After the water molecules enter, they hydrate with the exchangeable cations (such as Na^+ and Ca^{2+}) between the layers to form hydrated cations, resulting in an increase in the unit cell spacing. At the same time, due to the replacement of the same crystal (such as Al^{3+} is replaced by Mg^{2+} and Fe^{2+}), the surface of the crystal layer is permanently negatively charged. In order to maintain the electrical neutrality, the cations adsorbed between the layers form a diffusion double layer, which further increases the particle spacing. Studies have shown that the volume of illite can be increased by 50% ~ 100% when it expands in water, and the volume of montmorillonite can be increased to 400% after water absorption[25].

In the SEM image (Fig.9,10), the edge of the flake particles became round and the interlayer cracks increased after the immersion of chlorite schist and two-mica schist. The pore spacing increased from 5.3 μm at drying to more than 6.8 μm after 70 days, and the maximum pore spacing in two-mica schist reached 13.2 μm , which directly confirms the occurrence of swelling. Among them, chlorite schist exhibits the greatest increase in porosity, approximately doubling from the dry state to 70 days of immersion, corresponding to its strongest expansion effect.

(2) Microstructural Disintegration

The water absorption and expansion of clay minerals are not uniform, and uneven stress is generated inside the rock, resulting in the destruction of the connection between particles and disintegration. At the same time, calcareous and argillaceous cements are diluted and dissolved in water, losing cementation. The connection between the particles is further lost, and a large number of micropores appear, which eventually leads to the fragmentation and disintegration of rock particles. The loose coarse particle skeleton-clay flocculation structure and the massive production of agglomerate particles in the SEM image of chlorite schist after 70 days of immersion are the direct microscopic evidence of disintegration. This physical damage not only directly reduces the macroscopic strength, but also increases the migration channels of water molecules and ions, creating favorable conditions for chemical dissolution.

Comparing the three schists, chlorite schist has the highest content of montmorillonite, the most significant expansion and disintegration, and the largest attenuation of macroscopic strength.

Two-mica schist takes second place ; the montmorillonite of two-mica quartz schist is only 1.1%, almost no expansion and disintegration, the structure is basically dense, and the strength is almost not decreased.

4.2 Chemical Softening Mechanisms

Hydrochemical analysis in Section 3.3 reveals the specific process of chemical softening, including cement dissolution, ion exchange and hydration.

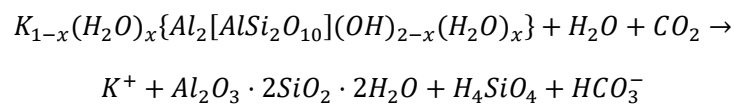
(1) Mineral Dissolution and Solid–Solution Redistribution

The hydrochemical analysis of the soaking solution (Fig. 15) shows that the concentration of Ca^{2+} in the chlorite schist increased from 58.7 to 82.1 mg / L with the soaking time, and the concentration of SO_4^{2-} decreased significantly from 149 to 55.8 mg / L. It shows that the calcareous and argillaceous cements such as calcite and gypsum in the rock dissolve in water, releasing Ca^{2+} and SO_4^{2-} . Cement dissolution weakens the inter-particle bonding, the expansion of pores and the decrease of mechanical strength. The release amount of Ca^{2+} in chlorite schist is the largest, which is consistent with the most serious strength attenuation (Section 3.1) and the most thorough microstructure damage (Section 3.2). The decrease of SO_4^{2-} may be related to the formation of insoluble sulfate precipitation.

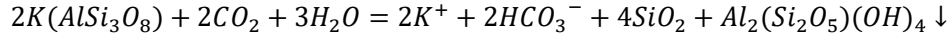
(2) Ion Exchange

The surface of clay minerals is permanently negatively charged and can adsorb cations in the solution. The order of adsorption capacity of different cations is : $\text{Fe}^{3+} > \text{Al}^{3+} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$. During the soaking process, the Mg^{2+} in the solution can replace the Al^{3+} in the mineral lattice, resulting in the initial adsorption of Mg^{2+} in the solution, resulting in a decrease in the concentration of Mg^{2+} in the solution, and the dissolution of montmorillonite and the release of Mg^{2+} in the later stage, resulting in a recovery of the concentration (Fig.15). The decrease of K^+ and Na^+ concentrations is attributed to the dissolution of feldspar and the adsorption of K^+ and Na^+ by clay minerals. The specific reaction is as follows:

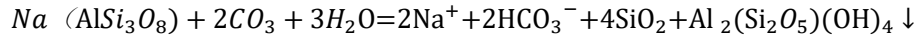
Illite dissolution reaction formula:



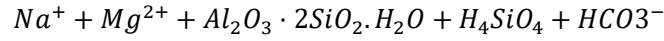
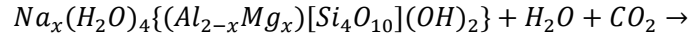
Potassium feldspar dissolution reaction formula:



Albite dissolution reaction formula:



Montmorillonite dissolution reaction formula:



(3) Hydration and pH Changes

Water molecules directly enter the mineral lattice and combine with cations, resulting in lattice expansion and reduced cohesion. The hydration of montmorillonite and illite is particularly significant. At the same time, the above reaction generates HCO_3^- , so that the pH of the soaking solution increases from the initial neutral 7.73 to the weak alkaline 8.33 after 30 days, and slightly drops to 8.15 after 70 days (Fig.14). The PH amplitude of chlorite schist and two-mica schist is larger, because of its loose structure and more pores, the water-rock reaction is more sufficient.

In summary, chemical damage and physical damage are intertwined : chemical dissolution weakens the connection between particles, increases pores and fissures, and in turn promotes water intrusion and physical expansion. This interaction will be integrated as a positive feedback loop in the next section.

4.3 Conceptual Model of Physicochemical Coupling

The aforementioned physical and chemical softening mechanisms are not independent and parallel, but are driven by the dynamic evolution of the fracture network and the specific surface area to form a self-reinforcing positive feedback loop (Fig. 16). In this section, based on the experimental evidence, the physical-chemical coupling conceptual model of schist softening in water is constructed.

4.3.1 Physicochemical Pathways within the Positive-Feedback Loop

Based on the microstructure evolution in Section 3.2 and the water-saving chemical dynamics in Section 3.3, the positive feedback cycle can be decomposed into the following four series steps (I → II → III → IV → I closed loop in Fig.16) :

Step I, water molecule invasion : water penetrates into the interior along the original cracks, bedding planes and pores at the edge of mineral particles. This stage is dominated by physical

infiltration, no significant chemical effect. For chlorite schist with initial fracture development (RQD = 33.5%), water is easier to enter and quickly reach the surface of montmorillonite particles.

Step II, physical expansion and disintegration : After montmorillonite and other 2:1 layered silicate minerals encounter water, water molecules enter the interlayer domain, and hydrate with exchangeable cations such as Na^+ and Ca^{2+} , resulting in an increase in the interlamellar spacing (the volume of montmorillonite can be expanded to several times of the original volume). At the same time, the diffusion electric double layer on the surface of the particles is thickened, the repulsion between the particles is increased, and the uneven expansion stress is generated inside the rock. In the SEM image, the edge of the particles becomes round and the pore spacing increases from $5.3 \sim 5.6 \mu\text{m}$ to $6.0 \sim 6.2 \mu\text{m}$ after 10 ~ 20 days of immersion, which is the direct microscopic evidence of expansion in this stage. With the continuous accumulation of uneven stress, the cementation between particles is destroyed, the rock skeleton is disintegrated, and the macroscopic strength is rapidly lost.

Step III, crack propagation and specific surface area increase : expansion and disintegration make the original crack further expand and generate a large number of microcracks. For chlorite schist, the maximum pore spacing has generally exceeded $6.8\mu\text{m}$ after 70 days of immersion, and a large area of lamellar spalling occurs, and the structure is loose coarse particle skeleton-clay flocculation. The new cracks and spalling surfaces significantly increase the specific surface area of the water-rock reaction, and also provide a smoother migration channel for water molecules.

Step IV, chemical dissolution acceleration : the increase of specific surface area makes the dissolution rate of cement (calcite, gypsum, etc.) and the interlayer ion exchange rate of clay minerals increase synchronously. The hydrochemical data confirmed that the concentration of Ca^{2+} increased from 58.7 mg / L to 82.1 mg / L , the concentration of SO_4^{2-} decreased significantly from 149 mg / L to 55.8 mg / L , and the pH increased from 7.73 to 8.33 (slightly decreased to 8.15 after 70 days), indicating that the dissolution of calcareous cements such as calcite and the hydrolysis of silicate minerals were significantly enhanced. The chemical dissolution further weakens the connection strength between particles, and the dissolved pores and enlarged cracks provide a new dominant channel for subsequent water infiltration.

Thus, loop back to step I to begin the next round of enhancements. In Fig.16, the clockwise cycle arrow and the gradient of the dotted line and the solid line are used to indicate the self-

strengthening characteristics of the cycle. After each cycle, the total amount of cracks and the specific surface area are increased compared with the previous cycle. Therefore, the physical expansion and chemical dissolution of the next cycle are amplified, forming an evolutionary trend of successive enhancement.

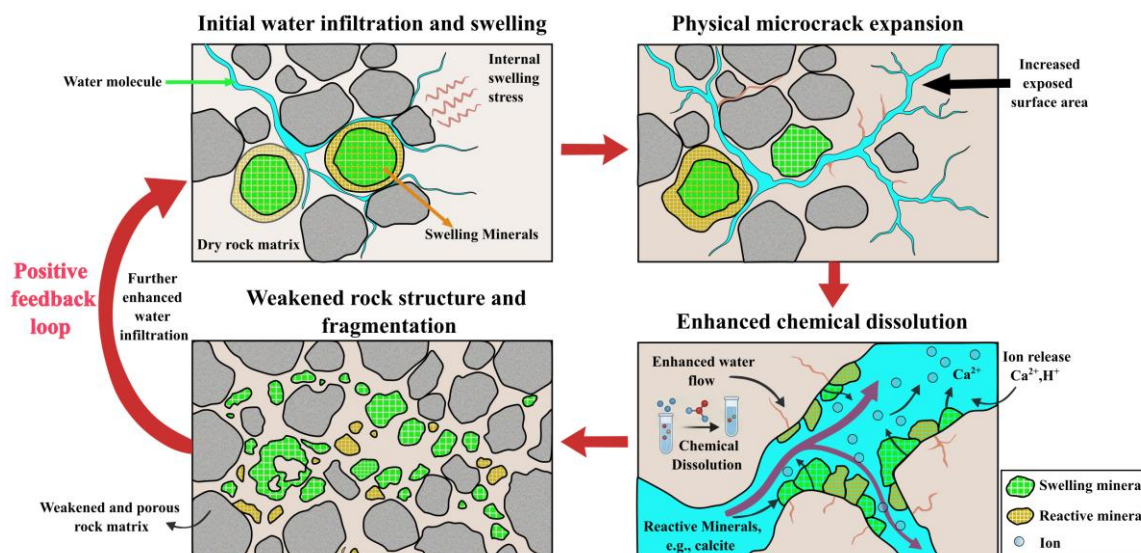


Figure 16. Conceptual model of the positive-feedback coupling between physical damage and chemical alteration during water-induced schist softening.

4.3.2 Time-Dependent Stages of Softening

The intensity of the positive feedback loop is not constant, but shows obvious time compliance. Combined with the strength decay curve in Fig.2, the microstructure evolution in Figs.9-11 and the chemical changes of water in Figs.14-15, the softening process can be divided into two stages:

0 ~ 20d is the rapid deterioration period, and the positive feedback cycle is highly active. At this stage, montmorillonite swelled rapidly, and the microstructure was drastically adjusted (the pore spacing of chlorite schist increased from 5.3 ~ 5.6 μm at dry to 6.0 ~ 6.2 μm at 10 ~ 20 days). At the same time, the cement dissolved rapidly (the concentration of Ca^{2+} increased significantly), and the two formed a strong positive feedback. The intensity attenuation accounts for more than 70% of the total decrease in 70 days. In this stage, the coupling effect is first driven by physical expansion, and the chemical dissolution is then accelerated.

20 ~ 70d is a slow stabilization period, and the positive feedback cycle enters the attenuation stage. Physical expansion tends to be saturated (interlayer hydration is basically completed, and the remaining expandable space is limited), the crack propagation rate slows down, and the chemical

dissolution is gradually approaching equilibrium (the change range of PH and ion concentration is significantly reduced). The strength attenuation curve tends to be gentle, and the deterioration is close to the asymptotic stable value. At this stage, chemical erosion is the dominant continuous damage factor, but its ability to drive fracture propagation has been greatly weakened.

The above stage characteristics indicate that the early stage of water-rock interaction (the first 20 days) is the key window period to control the long-term strength deterioration of schist.

4.3.3 Lithology-Dependent Expression of the Coupling Mechanism

A unified interpretation framework can be obtained by applying the coupling model to three kinds of schist :

Chlorite schist (montmorillonite 15.6%, RQD = 33.5%) : initial crack development, water infiltration channel is smooth ; the high montmorillonite content provides a strong physical expansion driving force ; the crack propagation exposes a large number of fresh surfaces ; chlorite dissolution and interlayer cation exchange are active (Ca^{2+} , K^{+} , Mg^{2+} concentration changes most significantly, SO_4^{2-} consumption is the largest) ; the positive feedback is the strongest, and the 70 d uniaxial compressive strength is reduced from about 20 MPa to about 8 MPa, and the deterioration is about 34.7%. Among the three, the softening is the most serious.

Two-mica schist (montmorillonite 6.6%, RQD = 41.3%) : initial fractures are moderately developed ; the content of montmorillonite is medium, and the degree of expansion and disintegration is limited ; the hydrochemical changes are in the middle (the increase of pH and the change of ions are less than that of chlorite schist) ; the coupling effect is general ; the 70 d strength decreased from about 13 MPa to about 10 MPa, and the deterioration was about 26.6%. The degree of softening is moderate.

Two-mica quartz schist (montmorillonite 1.1%, RQD = 43.0%) : dense structure, initial cracks are not developed ; montmorillonite content is very low, almost no physical expansion ; the contact area of water and rock is small, and the chemical dissolution is weak (the change of ion concentration is the smallest). Positive feedback almost does not start ; the 70 d strength decreased from about 32 MPa to about 28 MPa, and the deterioration was only about 19.9%. Softening is the slightest.

The strength deterioration degree of the three schists is positively correlated with the content of montmorillonite (chlorite schist 60% > two-mica schist 23% > two-mica quartz schist 13%),

which is completely corresponding to the degree of microstructure damage and the amplitude of hydrochemical change, which fully verifies the rationality of the above coupling model.

The proposed model provides three principal insights. First, water-induced schist softening results from reciprocal interactions between physical damage and chemical alteration rather than from the simple addition of independent mechanisms. Second, montmorillonite abundance represents an important intrinsic mineralogical control on hydration sensitivity, but its effect is moderated by initial fabric and water accessibility. Third, the feedback process is strongly time-dependent, with the initial immersion period representing the most rapid stage of mechanical degradation. These insights provide a unified framework for interpreting the contrasting water sensitivities of the three schist types.

4.4 Engineering and Sustainability Implications

Based on the test results in Chapter 3 and the above mechanism analysis, the following softening rules can be summarized :

First, the softening coefficient is positively correlated with RQD. The lower the RQD, the more broken the rock, the higher the degree of fracture development, the larger the specific surface area of water-rock interaction, and the more significant the softening. The linear fitting determination coefficient R^2 of the softening coefficient and RQD of chlorite schist and two-mica schist reached 0.933 and 0.968, respectively (Fig.4).

Second, the softening coefficient is positively correlated with the degree of weathering. The softening coefficient of schist in the fully strong weathering layer is significantly smaller than that in the medium-micro weathering layer. The most significant depth of softening is about 20 to 30 meters at the bottom of the fully-strongly weathered layer (Fig.6). This layer is the active zone of groundwater, and the water-rock interaction time is the longest and the most sufficient.

Thirdly, there is no obvious correlation between softening coefficient and burial depth. Although the increase of buried depth increases the confining pressure and drying strength, the degree of softening does not decrease, because the main controlling factors of softening are mineral composition and fracture development degree, rather than overlying pressure. Deep schist also has softening risk.

Fourthly, montmorillonite content is a key mineral factor controlling softening, which is

significantly negatively linearly correlated with softening coefficient, and R^2 is 0.9434 (Fig.5). When the montmorillonite content exceeds 5%, the softening risk increases significantly.。

Based on the above rules, the following engineering suggestions are put forward : in the investigation stage, the montmorillonite content $> 5\%$ should be taken as the high softening risk threshold. At the same time, the rock mass quality classification is carried out in combination with RQD, and the sections with low RQD and high montmorillonite content are focused on. In the design stage, drainage holes or cutoff curtains should be set at the interface between the fully-strongly weathered layer and the moderately weathered layer to reduce the long-term retention of groundwater at the interface. For deep schist, even if the buried depth is large, its softening potential should be considered, and it is not appropriate to rely solely on confining pressure to improve the safety factor. In the final construction and monitoring stage, the point load test can be used to quickly determine the softening coefficient, and the RQD can be used to guide the support design. Strengthen the deformation monitoring of the fully-strong weathered layer exposed slope before and after the rainy season.

From the perspective of sustainable mining development, these practical recommendations not only enhance slope safety but also confer long-term environmental and economic benefits. Proactive drainage and targeted support design reduce the frequency of landslide-induced production stoppages and emergency repairs, thereby lowering overall energy consumption and material waste. The proposed rapid-assessment framework (point load test combined with RQD and montmorillonite content) enables cost-effective risk screening, which is particularly valuable for small- to medium-sized mines with limited budgets. Furthermore, preserving the integrity of schist slopes through timely intervention extends the mine's operational life and reduces post-closure rehabilitation burdens, aligning with the principles of resource efficiency and environmental stewardship. By translating mechanistic understanding into actionable engineering measures, this study contributes to the broader goal of balancing mineral extraction with ecological and social sustainability.

5. Conclusions

This study investigated the water-induced degradation of chlorite schist, two-mica schist, and two-mica quartz schist collected from the eastern slope of an open-pit mine in southeastern Yunnan

Province, China. A total of 420 specimens were included in the dry and water-saturated point-load tests. A 70-day laboratory immersion experiment, X-ray diffraction (XRD), scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS), and hydrochemical analyses were further conducted to characterize strength degradation, mineralogical differences, microstructural evolution, and changes in solution chemistry. Based on the combined experimental evidence, a multiscale physicochemical coupling framework was proposed to explain the lithology-dependent softening of schist under water-rock interaction. The main conclusions are as follows:

(1) The severity of water-induced softening followed the order chlorite schist > two-mica schist > two-mica quartz schist. For chlorite schist and two-mica schist, the softening coefficient was positively associated with rock quality designation (RQD), whereas no clear relationship was observed for two-mica quartz schist. Lower softening coefficients were generally observed in more strongly weathered rock masses, while no systematic relationship with burial depth was identified. These results suggest that mineralogical composition and initial fracture conditions exerted greater control on water-induced softening than burial depth within the investigated dataset.

(2) Montmorillonite content was identified as an important mineralogical indicator of softening susceptibility. Its initial content was 15.6% in chlorite schist, 6.6% in two-mica schist, and 1.1% in two-mica quartz schist. Higher montmorillonite contents were associated with lower softening coefficients and more pronounced strength degradation. For the investigated site, a montmorillonite content of approximately 5% may serve as a preliminary screening criterion for elevated softening susceptibility; however, this value should be validated using additional lithologies and field datasets before broader engineering application.

(3) The estimated uniaxial compressive strength derived from point-load testing decreased nonlinearly with immersion time. The most rapid strength loss occurred during the first 20 d of immersion, after which the degradation rate gradually decreased. This temporal pattern coincided with pronounced pore enlargement and particle separation observed by SEM, as well as relatively rapid changes in the chemistry of the immersion solutions. The combined results support the interpretation that physicochemical interactions were most active during the initial stage of immersion and gradually approached a slower, quasi-stable state thereafter.

(4) The experimental observations support a coupled degradation mechanism involving physical hydration and chemical alteration. Hydration and swelling of clay minerals, together with

expansion of the electrical double layer, promoted particle separation, pore enlargement, and structural disintegration. Meanwhile, dissolution of mineral cementing phases and interlayer ion exchange weakened interparticle bonding. Physical damage increased the reactive surface area and fluid-accessible pathways, thereby facilitating chemical reactions, whereas chemical weakening promoted further water infiltration and microcrack development. This self-reinforcing feedback was most pronounced during the initial immersion stage and weakened as hydration and solution chemistry approached quasi-equilibrium. The process was strongest in chlorite schist and weakest in two-mica quartz schist, consistent with their contrasting montmorillonite contents and microstructural responses.

(5) For slope-risk management at the investigated mine, mineralogical screening should be combined with RQD measurements and rapid point-load testing to identify water-sensitive schist zones. Drainage and groundwater-control measures should be prioritized near transitions between strongly and moderately weathered rock masses, particularly where low RQD values coincide with high contents of expansive clay minerals. The softening potential of deeply buried schist should also be considered because burial depth alone did not eliminate water sensitivity. Integrating early identification, targeted drainage, and deformation monitoring may reduce slope-failure-related production interruptions, emergency remediation, material consumption, and energy use. These preventive measures can therefore contribute to safer, more resource-efficient, and more sustainable open-pit mining.

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