Research Article

Mechanical Damage and Chemical Dissolution Kinetic Features of Limestone under Coupled Mechanical-Hydrological-Chemical Effects

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To address the mechanical damages of limestone under the coupled mechanical(M)-hydrological(H)-chemical(C) effects, we performed uniaxial compression experiments and dissolution kinetics experiments on limestone in flowing and static solutions for different lengths of time. Through experiments, the peak strengths of the limestone under coupled MHC effects for different time lengths and the major ion concentrations in solutions were obtained. By analyzing the strength damage and chemical dissolution kinetic characteristics, we achieved the strength damage equations and chemical dissolution kinetic equations. Results show that when the solution shifted from the static state to the flowing state, and as its acidity increased, the peak strength loss of the limestone rose as well. The solution mobility had a more significant impact on the peak strength loss than the solution pH value. The limestone dissolution in flowing water was higher than in static water, indicating that solution mobility would promote the limestone dissolution. Among the contributing factors to limestone dissolution, the solution pH value showed the strongest impact, followed by the common-ion effect and then the salt effect. The research result is expected to provide a theoretical basis for maintaining the stability of rocks in geotechnical engineering practice and protection of stone cultural relics.

1. Introduction

The coupled mechanical-hydrological-chemical (MHC) effects considerably affect the stability of rocks in geotechnical engineering, and studying the mechanical properties of rocks under the coupled MHC effects is of great importance [1].

Extensive studies have reported the impacts of chemical contents, pH value, and percolation of solutions on the mechanical properties of rocks under coupled MHC effects. Some research on the mechanical properties of limestone and sandstone after chemical corrosion found that acid solutions were most corrosive, followed by alkaline solutions, and neutral solutions had the weakest effect [2–6]. Zhang et al. [7] and Ding et al. [8] analyzed the physical and mechanical properties of limestone and sandstone under coupled effects of chemical corrosion and freeze-thaw cycles. They found

that alkaline solutions would degrade the mechanical properties of the sandstone most powerfully, followed by salt solutions and then acid solutions. These results revealed that the abundance of condensation nuclei and the solution pH value would determine the damage degree to the limestone. They established equations for limestone corrosion and damage under coupled effects of chemical corrosion and freezing-thaw cycles. Studies concerning the impacts of rainfalls on the stability of rock slopes revealed that infiltration of rainfall would reduce the strength of the rocks [9, 10]. Song et al. [11] studied the fracture of limestone under uniaxial compression of different osmotic pressures. They found that water seepage would induce fractures, causing damages to the rocks. Chen et al. [12] experimented how the acid rain corroded the limestone by leeching and static immersion. They analyzed the leeching corrosion mechanism of acid rain on limestone and revealed that the leaching corrosion by acid rain would

accelerate strength loss of the limestone. Huang et al. [13] analyzed the rock deterioration process along the hydrofluctuation belt on the slope of the Three Gorges Reservoir and explored the scouring corrosion effect of flowing water on the limestone.

These studies focus on the damage properties of rocks under different mechanical, hydrological, or chemical processes. However, the mechanical properties and chemical dissolution kinetic properties of rocks under coupled MHC effects remain to be explored.

The limestone from Longmen Mountain in Luoyang, Henan Province, China, was used as the research object. The stone cultural relics in Longmen Grottoes face geological calamities like acid rain and seepage, and the coupled MHC effects cause damages to the rocks there. Therefore, we conducted experiments to identify the mechanical characteristics of limestone under coupled MHC effects. Then, we compared the characteristics with those under coupled MC effects to find out the patterns of corrosion of limestone in different contexts. Moreover, the chemical dissolution kinetics method was employed to analyze the hydrochemical dissolution behaviors of the limestone. The research result is expected to extend the understanding of the damage mechanism of rocks in hydropower engineering projects and stone cultural relics.

2. Materials and Methods

2.1. Preparation of Test Pieces. The test pieces in this study are fresh limestone rocks from Longmen Mountain in Luoyang. The major mineral components of the rocks are calcite (CaCO_3) and a small quantity of dolomite ($\text{CaMg}[\text{CO}_3]_2$). The rocks were processed into cylindrical standard test pieces with a diameter of 50 mm and a length of 100 mm. To avoid anisotropy of the rocks and improve comparability of the test results, we extracted all test pieces from one same rock. The elastic wave velocity tests were performed on the prepared test pieces, and those with similar wave velocities were used as the final test pieces.

2.2. Preparation of Chemical Solutions. With industrial progress, the increasing discharge of exhaust gases, effluents, and liquid wastes from industrial and mining enterprises around Longmen Grottoes has led to an increase in the content of Cl^- and SO_2 -4 in the surface water and spring water of the Yihe River basin, and a rising content of CO_2 and H_2S in the air. Meanwhile, as the rain grew increasingly acidic, the content of Cl^- and SO_2 -4 in the rain increased [14]. According to the atmospheric and precipitation monitoring data of Luoyang, the areas around Longmen Grottoes are frequented by acid rain (with a pH value ranging from 4.38 to 7.80), which have strongly corroded the rocks [15]. Besides, the CO_2 generated by decomposition of fallen leaves exacerbates the corrosion effect of the rain. As a result, the stone relics in the Grottoes are particularly vulnerable to corrosion by rain during the flood season. We detected the pH value, chemical contents, and concentration of chemicals in the rain around the Grottoes. The results are shown in Table 1. The test solutions were prepared according to the precipitation, atmo-

TABLE 1: Specifics of water quality of rains in Longmen Grottoes.

Solution	Content of chemicals/(mmol/L)					pH
	Ca^{2+}	Mg^{2+}	Na^+	SO_4^{2-}	Cl^-	
Rain water	0.2378	0.0574	0.0212	<0.0100	0.5344	5.75

TABLE 2: Specifics of solutions used in this study.

Solution	Concentration/(mol/L)	pH	
NaCl solution	0.01	4	6
Na_2CO_3 solution	0.01	4	6
Na_2SO_4 solution	0.01	4	6
Distilled water	—	6.6	

spheric and geological conditions of the Grottoes (Table 2). As chemical processes often take long to show effects in real-world scenarios, the ion concentrations in the prepared solutions were increased to accelerate the processes and simulate the interaction between the chemical solutions and the rocks in a short time. The solutions used in the experiments were applied to test pieces, with a concentration of 0.01 mol/L and a pH value of 4 and 6. The results were compared with that of test pieces in natural conditions and distilled water.

2.3. Experiment Method. The prepared solutions (Table 2) were poured into the test vessels, and 500 mL solutions were applied to each test piece. The test pieces were dried in a drying oven at 105°C for 48 h till reaching a constant weight. The pieces were then cooled to room temperature before being soaked in the prepared solutions, and a micropump was employed to enable circulation of the solutions at a rate of 600 mL/h. The test pieces were soaked for 90 d, 150 d, and 210 d at room temperature. Experiments in static solutions were also performed for comparative analysis.

We performed uniaxial compression tests on test pieces soaked in solutions for varied lengths of time. Therefore, we could analyze the mechanical damages of the limestone in flowing and static solutions. The computer-controlled RMT-301 multipurpose electrohydraulic servo rock and concrete mechanical testing system developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences was employed for the uniaxial compression test, with the displacement control rate set at 0.002 mm/min.

Last, the concentrations of Ca^{2+} and $\text{Ca}^{2+}/\text{Mg}^{2+}$ in the solutions that had soaked the test pieces were measured as per the standards specified in GB/T 15452-2009 to analyze the chemical dissolution kinetic characteristics of limestone in flowing and static solutions.

3. Mechanical Damage Characteristics of Limestone under Coupled MHC Effects

3.1. Uniaxial Compression Test Results under Coupled MHC Effects. Table 3 shows the peak strength of the test pieces soaked in flowing solutions for different lengths of time in uniaxial compression tests, i.e., the peak strengths under coupled MHC effects. Table 4 shows the peak strengths of

TABLE 3: Peak strength of limestone under coupled MHC effects in uniaxial compression tests.

Solution	Peak strength (MPa)			Peak strength reduction rate (%)		
	90 d	150 d	210 d	90 d	150 d	210 d
0.01 mol/L NaCl (pH = 4)	123.12	110.26	100.33	23.49	31.48	37.65
0.01 mol/L NaCl (pH = 6)	133.30	119.46	110.12	17.16	25.76	31.56
0.01 mol/L Na ₂ CO ₃ (pH = 4)	135.67	126.31	118.79	15.69	21.50	26.18
0.01 mol/L Na ₂ CO ₃ (pH = 6)	138.23	128.67	122.46	14.09	20.04	23.90
0.01 mol/L Na ₂ SO ₄ (pH = 4)	127.62	116.38	105.58	20.69	27.67	34.39
0.01 mol/L Na ₂ SO ₄ (pH = 6)	132.47	122.82	113.47	17.67	23.67	29.48
Distilled water (pH = 6.6)	142.13	133.98	123.19	11.67	16.74	23.44

TABLE 4: Peak strength of limestone under coupled MC effects in uniaxial compression tests.

Solution	Peak strength (MPa)			Peak strength reduction rate (%)		
	90 d	150 d	210 d	90 d	150 d	210 d
0.01 mol/L NaCl (pH = 4)	133.68	123.01	116.23	16.92	23.55	27.77
0.01 mol/L NaCl (pH = 6)	139.07	132.84	125.02	13.57	17.44	22.30
0.01 mol/L Na ₂ CO ₃ (pH = 4)	142.36	134.18	126.78	11.53	16.61	21.21
0.01 mol/L Na ₂ CO ₃ (pH = 6)	144.44	137.38	129.85	10.24	14.62	19.30
0.01 mol/L Na ₂ SO ₄ (pH = 4)	136.46	127.69	121.58	15.19	20.65	24.44
0.01 mol/L Na ₂ SO ₄ (pH = 6)	141.56	133.17	125.69	12.03	17.24	21.89
Distilled water (pH = 6.6)	148.62	137.09	131.64	7.64	14.80	18.19

FIGURE 1: Changes in the peak strength of limestone under coupled MHC effects and coupled MC effects with time.

FIGURE 2: Change patterns of the peak strength of limestone under coupled MHC effects in solutions of different contents.

test pieces soaked in static solutions for different lengths of time in uniaxial compression tests, i.e., the peak strengths under coupled MC effects. The peak strength of the test piece under natural conditions was 160.91 MPa. Thus, the peak strength reduction rate in Tables 3 and 4 means the reduction rate in comparison with the peak strength in the natural state.

3.2. Change Patterns of Limestone Strength under Coupled MHC Effects. According to Tables 3 and 4, the peak strength of the limestone test pieces under coupled MHC effects and coupled MC effects decreased compared to that of limestone in the natural state. The longer the test piece stayed in the solution, the larger the decrease. Among the test groups, the test piece in the NaCl solution (0.01 mol/L, pH = 4) showed the most significant reduction in the peak strength: a reduction rate of 23.49%, 31.48%, and 37.65% after 90 d, 150 d, and 210 d in the solution, respectively. Under coupled MC effects, the test piece in the distilled water showed the least decrease in the peak strength, with a reduction rate at 7.64%, 14.80%, and 18.19% after 90 d, 150 d, and 210 d in the solution, respectively. The peak strength reduction of test pieces in other solutions was in between.

Figures 1(a)–1(d) present the changes in the limestone peak strength under coupled MHC effects and coupled MC effects in different solutions with time. As Figure 1 shows, in solutions of the same chemical contents and within the studied pH range, the peak strength of the test piece under the coupled MHC effects remains lower than that under the coupled MC effects regardless of the specific pH value, indicating that the coupled MHC effects cause more damages to the limestone than the coupled MC effects. In other words, the flowing solution damages the limestone more severely than the static solution, and the mobility of the solution has stronger impacts on the strength loss of the limestone than its pH value does. Thus, under the coupled MHC effects, the physical scouring, chemical corrosion, and stresses work together to accelerate the deterioration of mechanical properties of the limestone.

TABLE 5: Strength damage parameter and correlation coefficient of the limestone under coupled MHC effects.

Solution	<i>p</i> value	Correlation coefficient
0.01 mol/L NaCl (pH = 4)	0.0023	0.9759
0.01 mol/L NaCl (pH = 6)	0.0019	0.9918
0.01 mol/L Na ₂ CO ₃ (pH = 4)	0.0015	0.9771
0.01 mol/L Na ₂ CO ₃ (pH = 6)	0.0014	0.9762
0.01 mol/L Na ₂ SO ₄ (pH = 4)	0.0021	0.9824
0.01 mol/L Na ₂ SO ₄ (pH = 6)	0.0017	0.9802
Distilled water (pH = 6.6)	0.0013	0.9963

As Figures 1(a)–1(c) show, when the mobility state and chemical contents of the solution remain the same, the peak strength of test pieces in solutions with a pH value of 4 is smaller than that in solutions with a pH value of 6, which indicates that increased acidity (i.e., decreased pH) of the solution leads to a larger strength loss of the limestone.

Figure 2 shows the changes in the limestone's peak strength in solutions of different chemical contents under coupled MHC effects with time. As Figure 2 shows, when other parameters, i.e., the chemical concentration, pH value, and mobility state, of the solution remain the same, the test piece in the NaCl solution shows the largest peak strength loss under the coupled MHC effects, while the test piece in distilled water shows the least loss. As Table 4 shows, the same pattern is observed in test pieces under coupled MC effects. Therefore, under coupled MHC effects and coupled MC effects, the NaCl solution results in the largest peak strength loss of the limestone, followed by Na₂SO₄, then Na₂CO₃, and distilled water at last.

3.3. Strength Damage Equations of Limestone under Coupled MHC Effects. According to the uniaxial compression test results (Table 3), the relationship between the peak strength of the limestone under the coupled MHC effects and the

TABLE 6: Concentrations of Ca^{2+} and Mg^{2+} in flowing solutions.

Solutions	90 d		150 d		210 d	
	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)
0.01 mol/L NaCl (pH = 4)	0.001228	0.001573	0.001422	0.001777	0.001515	0.001976
0.01 mol/L NaCl (pH = 6)	0.001195	0.001435	0.001352	0.001703	0.001503	0.001839
0.01 mol/L Na_2CO_3 (pH = 4)	0.001317	0.001634	0.001502	0.001906	0.001594	0.002030
0.01 mol/L Na_2CO_3 (pH = 6)	0.000816	0.001008	0.000988	0.001268	0.001100	0.001412
0.01 mol/L Na_2SO_4 (pH = 4)	0.001298	0.001526	0.001498	0.001815	0.001582	0.001935
0.01 mol/L Na_2SO_4 (pH = 6)	0.001182	0.001481	0.001381	0.001758	0.001483	0.001895
Distilled water (pH = 6.6)	0.001108	0.001391	0.001288	0.001651	0.001418	0.001796

TABLE 7: Concentrations of Ca^{2+} and Mg^{2+} in static solutions.

Solutions	90 d		150 d		210 d	
	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)	Ca^{2+} (mol/L)	$\text{Ca}^{2+}\text{Mg}^{2+}$ (mol/L)
0.01 mol/L NaCl (pH = 4)	0.001154	0.001423	0.001324	0.001650	0.001432	0.001812
0.01 mol/L NaCl (pH = 6)	0.000986	0.001226	0.001151	0.001445	0.001256	0.001584
0.01 mol/L Na_2CO_3 (pH = 4)	0.001192	0.001494	0.001391	0.001775	0.001474	0.001885
0.01 mol/L Na_2CO_3 (pH = 6)	0.000603	0.000767	0.000779	0.001007	0.000872	0.001163
0.01 mol/L Na_2SO_4 (pH = 4)	0.001158	0.001450	0.001350	0.001728	0.001443	0.001852
0.01 mol/L Na_2SO_4 (pH = 6)	0.001062	0.001394	0.001241	0.001650	0.001343	0.001796
Distilled water (pH = 6.6)	0.000887	0.001103	0.001064	0.001312	0.001142	0.001432

corrosion time conforms to the following exponential function:

$$\sigma = \sigma_r + (\sigma_0 - \sigma_r)e^{-pt}, \quad (1)$$

where σ is the peak strength of the limestone under uniaxial compression and coupled MHC effects (MPa), and σ_0 is the residue strength of the limestone (MPa). As the experiment results show, the residue strength of the limestone under coupled MHC effects in all solutions stays largely the same at 4.0 MPa. t is the time of corrosion (d), and p is the strength damage parameter of the limestone under coupled MHC effects (d^{-1}). According to the experiment results and Equation (1), the value of the strength damage parameter (p) of the limestone under coupled MHC effects and the correlation coefficient were obtained, as shown in Table 5.

According to Equation (1), when the corrosion time (t) remains constant, the strength of the limestone under coupled MHC effects is determined by the strength damage parameter p . A larger p value indicates faster strength loss of the limestone, more reduction of the strength of the limestone after the same time of erosion, and a stronger damaging impact on the strength of the limestone.

4. Chemical Dissolution Kinetic Properties of Limestone under Coupled MHC Effects

4.1. Ion Concentrations of Solutions in Different Conditions. Tables 6 and 7 show the changes in the concentrations of Ca^{2+} and $\text{Ca}^{2+}/\text{Mg}^{2+}$ in flowing and static solutions that have been applied to the test pieces with the time.

4.2. Kinetic Equations for Dissolution of Limestone under Coupled MHC Effects. The dissolution of solids is a diffusion process of the solute and can be represented by the changes in the concentration of the solute in the solution per unit time. This process conforms to the Noyes-Whitney equation:

$$\frac{dC}{dt} = KS(C_s - C_t), \quad (2)$$

where dC/dt is the solute dissolution rate ($\text{mol}/(\text{d}\cdot\text{L})$), K is the dissolution rate constant of the solute in the dissolution media, a kinetic parameter that manifests the solute dissolution rate ($\text{d}^{-1}\cdot\text{mm}^{-2}$), S is the surface area of the solute (mm^2), C_s is the solubility of the solute in the dissolution media, which is a thermodynamic parameter that reflects the concentration of the solute at solubility equilibria (mol/L), and C_t is the concentration of the solute in the solution at the time point t (mol/L).

As per Equation (2), the following equation is obtained:

$$\frac{dC}{dt} = KSC_s - KSC_t, \quad (3)$$

where dC/dt is linearly correlated to C_t , the straight slope is KS , and the intercept is $KS \cdot C_s$. According to Tables 6 and 7, the Noyes-Whitney equations and correlation coefficients for calcite and dolomite, two major minerals in limestone, in different solutions, were obtained, as shown in Tables 8 and 9.

As Tables 8 and 9 show, the dissolution of calcite and dolomite in different solutions conforms to the Noyes-Whitney equation.

TABLE 8: Noyes-Whitney equations and correlation coefficients of calcite and dolomite in flowing solutions.

Solutions	Calcite	Dolomite
0.01 mol/L NaCl (pH = 4)	$y = -0.02490x + 0.00004494$ $R^2 = 0.9999$	$y = -0.02004x + 0.00004850$ $R^2 = 0.9530$
0.01 mol/L NaCl (pH = 6)	$y = -0.01985x + 0.00003662$ $R^2 = 0.9560$	$y = -0.01767x + 0.00004134$ $R^2 = 0.9993$
0.01 mol/L Na ₂ CO ₃ (pH = 4)	$y = -0.02529x + 0.00004796$ $R^2 = 0.9998$	$y = -0.02117x + 0.00005282$ $R^2 = 0.9976$
0.01 mol/L Na ₂ CO ₃ (pH = 6)	$y = -0.01353x + 0.00002006$ $R^2 = 0.9976$	$y = -0.01100x + 0.00002232$ $R^2 = 0.9987$
0.01 mol/L Na ₂ SO ₄ (pH = 4)	$y = -0.02386x + 0.00004548$ $R^2 = 0.9950$	$y = -0.01850x + 0.00004529$ $R^2 = 0.9920$
0.01 mol/L Na ₂ SO ₄ (pH = 6)	$y = -0.02008x + 0.00003689$ $R^2 = 0.9998$	$y = -0.01778x + 0.00004284$ $R^2 = 0.9986$
Distilled water (pH = 6.6)	$y = -0.01814x + 0.00003229$ $R^2 = 0.9899$	$y = -0.01705x + 0.00003917$ $R^2 = 0.9999$

TABLE 9: Noyes-Whitney equations and correlation coefficients of calcite and dolomite in static solutions.

Solutions	Calcite	Dolomite
0.01 mol/L NaCl (pH = 4)	$y = -0.02175x + 0.00003785$ $R^2 = 0.9963$	$y = -0.01860x + 0.00004211$ $R^2 = 0.9907$
0.01 mol/L NaCl (pH = 6)	$y = -0.01861x + 0.00002926$ $R^2 = 0.9968$	$y = -0.01712x + 0.00003455$ $R^2 = 0.9973$
0.01 mol/L Na ₂ CO ₃ (pH = 4)	$y = -0.02195x + 0.00003951$ $R^2 = 0.9929$	$y = -0.01899x + 0.00004511$ $R^2 = 0.9892$
0.01 mol/L Na ₂ CO ₃ (pH = 6)	$y = -0.00933x + 0.00001235$ $R^2 = 0.9952$	$y = -0.00753x + 0.00001429$ $R^2 = 0.9999$
0.01 mol/L Na ₂ SO ₄ (pH = 4)	$y = -0.02093x + 0.00003716$ $R^2 = 0.9989$	$y = -0.01787x + 0.00004212$ $R^2 = 0.9951$
0.01 mol/L Na ₂ SO ₄ (pH = 6)	$y = -0.01929x + 0.00003228$ $R^2 = 0.9996$	$y = -0.01726x + 0.00003953$ $R^2 = 0.9999$
Distilled water (pH = 6.6)	$y = -0.01706x + 0.00002505$ $R^2 = 0.9941$	$y = -0.01649x + 0.00003042$ $R^2 = 0.9998$

4.3. Limestone Dissolution Kinetics under Coupled MHC Effects. According to the Noyes-Whitney equations in Tables 8 and 9, the KS (straight slope) and C_s (solubility) of calcite and dolomite in different solutions can be obtained. In the experiments, it is assumed that $S = 19625 \text{ mm}^2$, and thus, the dissolution rate constant K and the solubility C_s are calculated (Tables 10 and 11).

Tables 10 and 11 have summarized the impacts of different solutions on the solubility and dissolution rate of calcite and dolomite.

When the solution contents remain the same, the solubility and dissolution rate of these two minerals in flowing solutions are higher than in static solutions, indicating that the

increased mobility of the solution will accelerate the dissolution of limestone.

When the contents and mobility of the solutions remain the same, the dissolution rate and solubility of the two minerals in a low-pH solution are higher than in a high-pH solution, which indicates a lower pH value of solution will facilitate dissolution of the limestone.

When the solution's mobility remains the same, the dissolution rate and solubility of the two minerals in NaCl and Na₂SO₄ solutions are higher than in distilled water, indicating a strong salt effect that facilitates dissolution of the solution limestone.

When the mobility of the solution remains the same, the dissolution rate and solubility of calcite and dolomite in the

TABLE 10: Values of K and C_s of calcite and dolomite in flowing solutions.

Solutions	Calcite		Dolomite	
	K ($\text{d}^{-1}\cdot\text{mm}^{-2}$)	C_s (mol/L)	K ($\text{d}^{-1}\cdot\text{mm}^{-2}$)	C_s (mol/L)
0.01 mol/L NaCl (pH = 4)	1.27×10^{-6}	0.001805	1.02×10^{-6}	0.002420
0.01 mol/L NaCl (pH = 6)	1.01×10^{-6}	0.001845	0.90×10^{-6}	0.002340
0.01 mol/L Na_2CO_3 (pH = 4)	1.29×10^{-6}	0.001896	1.08×10^{-6}	0.002495
0.01 mol/L Na_2CO_3 (pH = 6)	0.69×10^{-6}	0.001483	0.56×10^{-6}	0.002029
0.01 mol/L Na_2SO_4 (pH = 4)	1.22×10^{-6}	0.001906	0.94×10^{-6}	0.002448
0.01 mol/L Na_2SO_4 (pH = 6)	1.02×10^{-6}	0.001837	0.91×10^{-6}	0.002409
Distilled water (pH = 6.6)	0.92×10^{-6}	0.001780	0.87×10^{-6}	0.002297

TABLE 11: Values of K and C_s of calcite and dolomite in static solutions.

Solutions	Calcite		Dolomite	
	K ($\text{d}^{-1}\cdot\text{mm}^{-2}$)	C_s (mol/L)	K ($\text{d}^{-1}\cdot\text{mm}^{-2}$)	C_s (mol/L)
0.01 mol/L NaCl (pH = 4)	1.11×10^{-6}	0.001740	0.95×10^{-6}	0.002264
0.01 mol/L NaCl (pH = 6)	0.95×10^{-6}	0.001572	0.87×10^{-6}	0.002018
0.01 mol/L Na_2CO_3 (pH = 4)	1.12×10^{-6}	0.001800	0.97×10^{-6}	0.002375
0.01 mol/L Na_2CO_3 (pH = 6)	0.48×10^{-6}	0.001324	0.38×10^{-6}	0.001898
0.01 mol/L Na_2SO_4 (pH = 4)	1.07×10^{-6}	0.001775	0.91×10^{-6}	0.002357
0.01 mol/L Na_2SO_4 (pH = 6)	0.98×10^{-6}	0.001673	0.88×10^{-6}	0.002290
Distilled water (pH = 6.6)	0.87×10^{-6}	0.001468	0.84×10^{-6}	0.001845

Na_2CO_3 solution with a pH of 6 are lower than in distilled water, except that the solubility of the dolomite remains largely the same. It indicates that the ion effect plays a more significant role than the salt effect, and the common-ion effect reduces the dissolution of limestone. The dissolution rate and solubility of these two minerals in Na_2CO_3 solutions with a pH value of 4, however, are higher than in distilled water, which indicates that the pH value of the solution plays a more important role than the common-ion effect on the dissolution process, and a lower pH value of the solution leads to higher and faster dissolution of limestone.

5. Conclusions

The coupled MHC effects often undermine the stability of rocks in engineering practice. Despite the multitude of works that have been devoted to the damage characteristics of rocks, the mechanical and chemical dissolution kinetic characteristics of rocks under coupled MHC effects are rarely studied. In the present work, uniaxial compression and dissolution kinetics experiments were performed on limestone under coupled MHC effects to explore the limestone's mechanical damages and damage mechanism. The significant findings are as follows:

- (1) The coupled MHC and coupled MC effects lead to different degrees of damages to the peak strength of the limestone, and the longer the effects work, the larger the damage is. Within the studied range of

pH value, the coupled MHC effect causes more strength losses than the coupled MC effect, and the mobility of the solution has more substantial impacts on the strength loss than the pH value. In addition, the strength loss increases as the acidity of the solution increases. Among all the tested chemical contents of solutions, NaCl shows the most serious damages to the limestone strength, followed by Na_2SO_4 , then Na_2CO_3 , and, at last, distilled water

- (2) Based on analysis of the correlation between the peak strength and the corrosion time under the coupled MHC effects, the limestone strength damage equation under coupled MHC effects is obtained
- (3) Experiments have proved that the chemical dissolution kinetic behaviors of the limestone under coupled MHC effects conform to the Noyes-Whitney equation
- (4) Dissolution kinetic analysis of the limestone under coupled MHC effects has shown that the solution mobility improves the dissolution of limestone and a lower pH value leads to better dissolution. The salt effect and the common-ion effect show a considerable impact on the dissolution of limestone. The former increases the dissolution, while the latter reduces it. It is also found that the common-ion effect has a more substantial impact than the salt effect, while the pH value plays a more significant role than the common-ion effect

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

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