

Fracturing and Damage to Sandstone Under Coupling Effects of Chemical Corrosion and Freeze–Thaw Cycles

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Abstract Rapid freeze–thaw (FT) cycles were adopted to explore the damage deterioration mechanism and mechanical properties of sandstone specimens under the coupling effects of different chemical solutions and FT cycles. The variation regularities of the FT cycles and physical and mechanical properties of sandstone specimens immersed in different chemical solutions were analyzed by using sandstone sampled from a Chinese riverbank slope. The damage variable based on porosity variation was used in the quantitative analysis of the damage to the sandstone under the coupling effects of chemical corrosion and FT cycles. Experimental results showed that the sandstone specimens weakened substantially under those effects. Their fracture toughness K_{IC} , splitting tensile strength, and compressive strength showed a similar deteriorating trend with various numbers of FT cycles. However, a difference exists in the deterioration degree of their mechanical parameters, i.e., the deterioration degree of their fracture toughness K_{IC} is the greatest followed by that of splitting tensile strength, and that of compressive strength is relatively small. Strong acid solutions may aggravate the deterioration of FT damage in sandstones, but at the early stage of the experiment, strong alkaline solutions inhibited sandstone damage deterioration. However, the inhibiting effect disappeared when the number of FT cycles exceeded

25. The different chemical solutions had a different effect on the FT damage degree of the sandstone specimens; for example, SO_4^{2-} ions had a greater effect on FT damage than did HCO_3^- ions. Water–chemical solutions and FT cycles promote each other in deteriorating rocks and simultaneously affect the damage deterioration degree of sandstones.

Keywords Chemical erosion · Correlation · Coupling effect · Damage variable · Fracture toughness · Freezing and thawing cycles · Mechanical characteristics · Sandstone

1 Introduction

Rock, as a type of natural aggregate formed in a geologic process, is composed of mineral particles, pores, and cementing materials. Microcracks, crevices, and flaws of different types are inevitably scattered inside rocks, leading to mechanical properties that are nonlinear, anisotropic, time related, and destructive. Rock deformation and failure processes involve internal randomly distributed flaws that appear, propagate, converge, and cut through the rock. Rock failure is closely related to rock fracture. Several scholars have applied fracture toughness to the quantitative evaluation of rock engineering stability and safety and have done numerous experimental studies. Ciccotti et al. (2000) and Saadaoui et al. (2000) used the double torsion method to experimentally study the static fracture toughness of rocks. Cui et al. (2010) comparatively analyzed two test methods for the fracture toughness of chevron-notched rocks. Ayatollahi and Aliha (2007) conducted an experimental study of the fracture toughness of brittle rocks under I/II mixed-load modes. Chen and Zhang (2004)

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analyzed by a laboratory test the fracture toughness of rocks sampled from deep strata. Erarslan and Williams (2012) explored the relation between the fatigue failure mechanism and the fracture toughness of rocks. Wang et al. (2011) studied the fracture toughnesses of type I and II rocks under dynamic conditions.

Rocks exist in a complicated natural environment and are often subjected to varying influences. Water, as one of the most active elements in geologic activities, often contributes to the deformation and failure processes of rocks. The interaction between water and rocks has become a key influence on rock mass engineering safety and stability. In recent years, the study of water–rock interactions has become a cutting-edge topic drawing extensive concern from scholars worldwide, with much research success. Colback and Wiid (1965) and Dunning et al. (1994) explored the strength of water-bearing rocks in their studies. Logan and Blackwell (1983), Dieterich and Conrad (1984), and Feucht and Logan (1990) investigated the effect of water–chemical solutions on the elastic modulus and friction deformation of rocks. Lajtai et al. (1987) studied the influence of water on the mechanical features and failure of granites. Feng et al. (2001) systematically studied the effects of different water–chemical solutions on rock mechanical features and built a water–chemical corrosion constitutive model incorporating damage variables. Li et al. (2003) established a chemical damage strength model for acid solutions that accounted for their corrosive effects on the cementing materials of sandstones. Dunning et al. (1994) explored the effect of a chemical environment on rock fracture toughness value and crack propagation rate. Feucht and Logan (1990) analyzed the effects of chemical solutions on the friction coefficient and strength of crack planes in an experimental study of the influence of different chemical solutions on precracked sandstone specimens; Dieterich and Conrad (1984) made similar studies. Nara et al. (2012) experimentally studied the effect of humidity, and Karfakis and Askram (1993) of water–chemical solutions, on rock fracture toughness. Reinhardt and Mielich (2014) explored the effects of alkaline chemical solutions on rock fracture toughness. Bruno and Nakagawa (1991) found in a field test that an increase in hydraulic pressure at the pores on the tips of cracks could promote crack propagation and that an increase in the hydraulic pressure gradient at the pores might inhibit crack growth. In summary, water–rock interaction may significantly weaken fracture mechanical features of rocks.

In addition to the severe effect of the hydrochemical environment on rock deformation and failure, temperature changes are also key influences of those factors; particularly, the diurnal variations and seasonal changes in the

temperatures of cold regions may lead to the deterioration of the physical and mechanical properties of rocks from freezing and thawing (FT) cycles. Studies on the effects of FT cycles on the deterioration of rocks have been conducted by scholars both in China and abroad. Nicholson et al. (2000) studied FT cycles for a variety of sedimentary rocks and analyzed their mass loss. In addition, they proposed four rock deterioration models to explain the effect of existing internal flaws on rocks. The results they achieved via experiments could be used for the selection of rock specimens for rock durability tests, particularly for high-strength hard rocks. Argandona et al. (1999) used computed tomography to scan a dolomite under FT cycles, and analyzed the pore evolution of the rock. They found that the rock broke partially and debris fell off after it was subjected to seven FT cycles, leading to the severe FT loss of the rock. After the number of FT cycles exceeded 12, a crack cut through the rock and resulted in rock failure. Mutlutürk et al. (2004) described the loss of rock integrity in a mathematical model, which provided useful parameters for the integrity of rocks; the model was validated by an experimental study on different rock specimens under FT cycles. In DelRoa et al. (2005), conducted an experimental study on the FT cycle of a variety of granite rocks at temperatures of -12 to 20 °C, and also conducted acoustic detection. They concluded that the wave velocity of rock specimens differed among different varieties and might change with various numbers of FT cycles; that is, the velocity decreased with increasing FT cycles, because the cycles aggravated internal damage in the rocks. Tan et al. (2011) conducted an experimental study on FT cycles of granite at temperatures of -40 to 40 °C and concluded that the compressive strength of the rocks decreased with an increasing number of FT cycles.

As mentioned earlier, rocks exist in a complicated environment, and in most instances are simultaneously subjected to chemical corrosion and FT cycles. The deterioration from FT of rocks, especially fissured rocks, in different hydrochemical environments should draw wide attention from scholars. However, studies on this topic are rare.

This study conducted three-point bending, uniaxial compression, and tensile splitting strength tests on mode-I cracked sandstone specimens under the coupling effects of different chemical corrosion and FT cycles. The variation regularities in physical and mechanical properties, for example P wave velocity, mass loss, porosity, fracture toughness K_{IC} , compressive strength, and splitting tensile strength, of rocks damaged by chemical solutions, and FT cycles were analyzed. This study can serve as a reference for the engineering of rock masses in cold regions.

2 Introduction of Tests

2.1 Specimen Preparation and Test Method

The sandstones used in the tests were sampled from a typical riverbank slope in the Three Gorges Reservoir region of the Yangtze River, China, where the sandstones had high homogeneity and integrity. The minerals were identified as medium and fine calcareous quartz sandstones with porous calcareous cement. As required by the Chinese standard rock test procedures for Water Resources and Hydropower Engineering (2007), rectangular specimens with straight incisions were selected, and the three-point bending method was adopted to measure the fracture toughness K_{IC} of the rocks. Figure 1 is a schematic of the loading setting. The specimens were 50 mm × 50 mm in cross section, the lengths were between 250 mm and 260 mm, and the straight incisions were between 21 mm and 23 mm deep and 1.0 mm wide. After processing the specimens, we measured their P wave velocity. The discrete-type specimens were screened out. A total of 68 sandstone specimens were selected and divided into 17 groups, 1 of which was used to measure fracture toughness and other related mechanical characteristics of the sandstones under natural conditions. The measurements were used as initial values for comparative analysis. The remaining 16 groups were used to study the coupling effect of chemical corrosion and FT cycles.

Before the test, the sandstone specimens were dried at 105 °C to maintain a constant weight and then cooled for mass measuring. Later, the vacuumization method was adopted to saturate the specimens with 0.1 mol/L of Na₂SO₄ (pH 3.0) solution, 0.1 mol/L of NaOH (pH 12.0) solution, 0.1 mol/L of NaHCO₃ (pH 3.0) solution, and pH 7.0 distilled water. The specimens and solutions were then placed into a FT test machine. The depth of the chemical solutions used to immerse the specimens exceeded the height of the specimens by 5 cm. The specimens were then subjected to FT cycles. Each cycle lasted approximately 4 h. The specimens were taken out every 25 cycles to measure the P wave velocity and test the fracture toughness. The numbers of FT cycles were set to 0, 10, 25, 50,

75, and 100, and four tests were conducted in parallel for each chemical solution under each test cycle.

We needed to study the relation between the fracture toughness of specimens and their compressive strength or splitting tensile strength and reduce the errors arising out of specimen heterogeneity, which improve the comparability between the fracture toughness of specimens and their compressive or splitting tensile strength under the same conditions. To do this, we cut one of the two segments of the fractured specimen into a 100-mm rectangular specimen for the uniaxial compression test, and the other segment into a cylindrical specimen with a diameter of 50 mm and a length of 30–35 mm for the splitting tensile strength test. The physical and mechanical parameters of the specimens were then tested in saturation to further explore the variations in regularity. The temperature curve for the FT cycles is shown in Fig. 2.

2.2 Test Apparatus

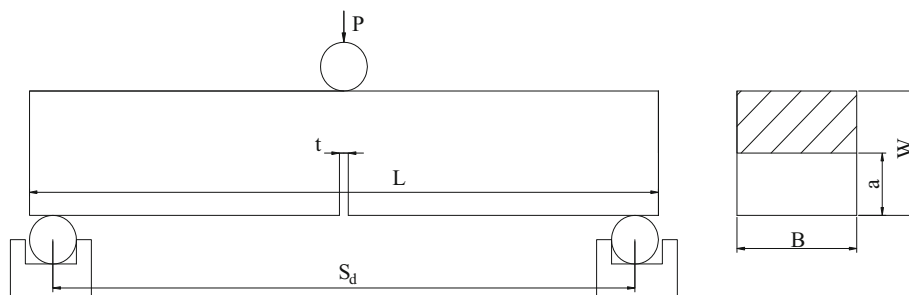
A CABR-HDK9A rapid FT test machine was used in the tests; its FT temperatures ranged from −20 to 20 °C. The uniaxial and triaxial compression tests were conducted in a WDT-1500 large-scale multifunctional reactive material testing machine. Displacement loading was adopted in the entire process of the tests. The velocity was 0.1 mm/s, the maximum axial load was 1500 kN, the maximum confining pressure was 80 MPa, and the measurement ranges of axial and radial displacements were 0–10 and 0–5 mm, respectively. The P wave velocity was measured with an RSM-SY5 acoustic detector.

3 Test Results and Analysis

3.1 Mass Variation Regularity

The saturated mass of the sandstone specimens was measured every 25 FT cycles. The mass loss rate, determined by the mass, was equal to the initial dry mass minus the saturated mass after a certain number of FT cycles, all divided by the initial dry mass. The relation between mass

Fig. 1 Loading sketch of the three-point bending specimens. P is load leading to the fracture, $t = 1$ mm, $L = 25$ –26 cm, $S_d = 16.6$ cm, $B = 5$ cm, $a = 22$ –23 mm, $W = 5$ cm



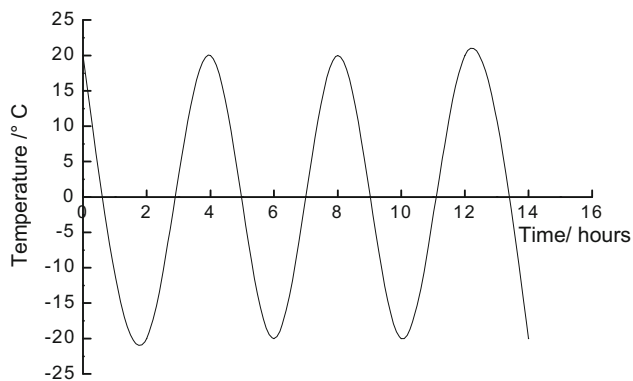


Fig. 2 Temperature curve for the freeze–thaw cycles

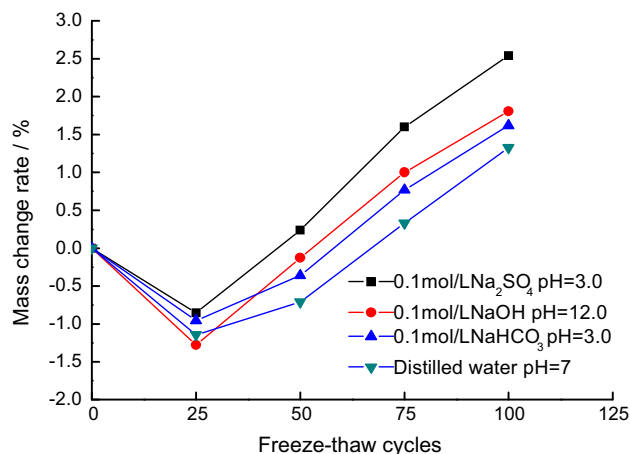


Fig. 3 Relation between the mass change rate of the sandstone specimens and FT cycles under the coupling effects of different chemical solutions and FT cycles

change rate and freeze–thaw cycles under the coupling effects of chemical solutions and FT cycles is shown in Fig. 3.

Figure 3 indicates that the mass change rate of the sandstone specimens varied in the same manner when they were under the coupling effects of different chemical solutions and FT cycles. Those rates showed an initial increasing trend and a subsequent decreasing trend. Furthermore, the mass loss degree of specimens increased with an increasing number of FT cycles. However, the mass of the sandstones immersed in different chemical solutions decreased in different degrees after they were affected by FT cycles. Different chemical solutions had different deterioration effects on the sandstone, so FT cycles may have different effects on the deterioration of sandstone, which may show mass change.

At the early stage of the test (0–25 FT cycles), the sandstone specimens under different states might have shown an increase in mass because the specimens imbibed water. Nonetheless, the increased degree in the mass of the

specimens differed in different chemical solutions. The increased degree in the mass of the specimens in the acid 0.1 mol/L Na_2SO_4 (pH 3) solution was the lowest, that in the alkaline 0.1 mol/L NaOH (pH 12.0) solution was the highest, and that in the neutral distilled water was ranked in the middle. After the number of FT cycles exceeded 25, the specimens showed a gradually decreasing trend in mass as the number of the FT cycles increased. The mass loss degree of the specimens in the 0.1 mol/L Na_2SO_4 (pH 3.0) solution was the highest and that in the neutral distilled water was the lowest. The damage degree of the sandstone specimens in the 0.1 mol/L Na_2SO_4 (pH 3.0) solution was higher than that in the 0.1 mol/L NaHCO_3 (pH 3.0) solution when the solution concentration, pH value, and number of FT cycles remained unchanged.

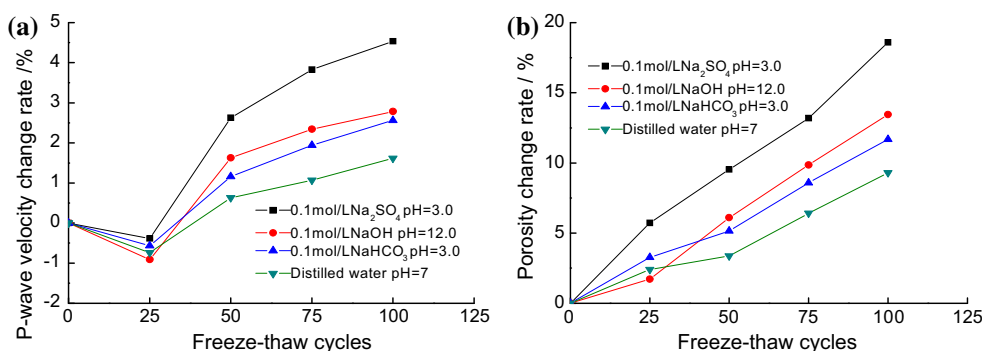
3.2 Variation Regularity in Porosity and *P* Wave Velocity

To identify the effects of the different chemical solutions and the FT cycles on the physical properties of the specimens, two physical variables that indicated the status of the sandstone specimens were defined; that is, the porosity change rate was equal to the porosity after the FT cycles minus the initial porosity, all divided by the initial porosity. The *P* wave velocity change rate was equal to the *P* wave velocity at the initial drying minus the *P* wave velocity after FT cycles, all divided by the *P* wave velocity at the initial drying. The relationships among the porosity change rate, the *P* wave velocity change rate, and the FT cycles under the coupling effects of chemical solutions and FT cycles are shown in Fig. 4.

Figure 4 implies that the physical properties of the sandstone specimens showed the same variation trend under the coupling effects of different chemical solutions and FT cycles. With an increasing number of FT cycles, the porosity of the sandstone specimens gradually increased, whereas the *P* wave velocity first increased and then decreased. Both the porosity change rate and the *P* wave velocity change rate of the specimens increased as the number of FT cycles increased.

During the first 25 FT cycles, the porosity of the FT specimens increased. At the same time, the internal flaws of the sandstone were filled with chemical solutions because of the water–rock interaction and FT effect. As a result, the homogeneity of the specimens improved and the *P* wave velocity increased. The distribution homogeneity of the chemical solution concentration inside the specimens might have been improved because of the specimens' high porosity, which could cause the *P* wave velocity to significantly increase. Thereafter, with the increasing number of FT cycles, the porosity change rate and *P* wave velocity change rate of the specimens increased; that is, the porosity

Fig. 4 Relationships among the *P* wave velocity change rate, the porosity of the sandstone specimens, and the FT cycles under the coupling effect of different chemical solutions and FT cycles. **a** *P* wave velocity change rate ~ FT cycles. **b** Porosity change rate ~ FT cycles



increased with the increasing number of FT cycles. The *P* wave velocity showed the opposite trend.

Differences existed in the porosity and *P* wave velocity of the sandstone specimens under the coupling effect of different chemical solutions and FT cycles. During the first 25 FT cycles, the porosity change rate and *P* wave velocity change rate were the highest when the specimens were immersed in the acid 0.1 mol/L Na₂SO₄ (pH 3.0) solution, the lowest in the strong alkaline 0.1 mol/L NaOH (pH 12.0) solution, and ranked in the middle in distilled water. After the number of FT cycles exceeded 25, the porosity change rate and *P* wave velocity change rate showed a gradually increasing trend with an increasing number of FT cycles. The increased rates of the specimens in 0.1 mol/L Na₂SO₄ (pH 3.0) were the highest, and in the pH 7.0 neutral distilled water, the lowest. Hence, the acid solution aggravated the FT damage deterioration of the sandstone specimens. At the early stage of the test, the strong alkaline solution had a certain inhibiting effect on the FT damage of the specimens. However, the inhibiting effect decreased and finally disappeared as the number of FT cycles increased. This signified that 25 FT cycles were a threshold value for the porosity and *P* wave velocity of the sandstone specimens to change in the 0.1 mol/L NaOH solution.

As shown in Fig. 4, different chemical compositions might have different effects on the FT damage to the specimens. The effect of the 0.1 mol/L Na₂SO₄ (pH 3.0) on the porosity and the *P* wave velocity of the sandstone specimens was greater than that of the 0.1 mol/L NaHCO₃ (pH 3.0) when other conditions remained the same, signifying that SO₄²⁻ ions aggravated the FT damage in the specimens.

Figure 5 shows the relation between the porosity and *P* wave velocity of the sandstone specimens under the coupling effects of different chemical solutions and FT cycles. The figure illustrates that the porosity increased under the coupling effects of different chemical solutions and FT cycles, whereas the *P* wave velocity showed a gradually decreasing trend. Therefore, the consistency of both properties was substantial, indicating that the *P* wave

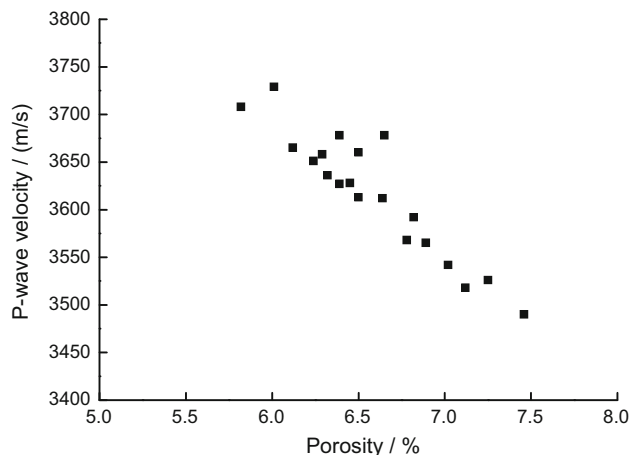


Fig. 5 Relation between the porosity and the *P* wave velocity of the sandstone specimens under the coupling effects of different chemical solutions and FT cycles

velocity of sandstone specimens after chemical corrosion and freeze–thawing could be used to indirectly reflect the porosity change rate.

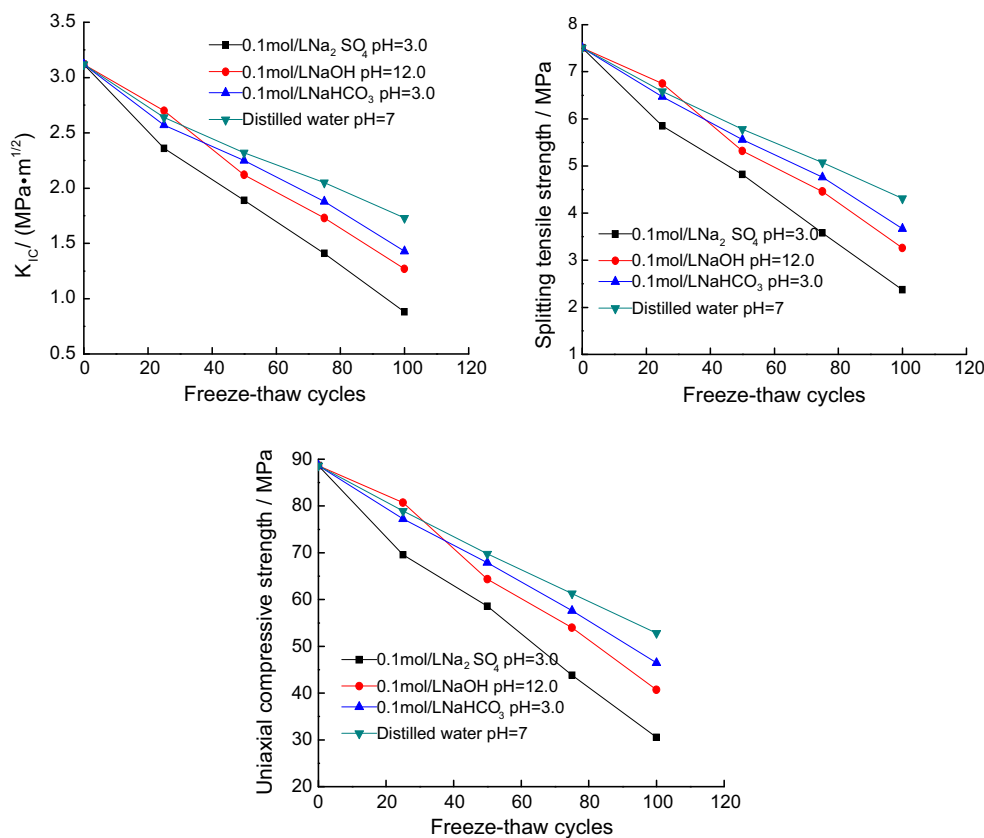
3.3 Analysis of the Fracture Toughness *K*_{IC}, Tensile Strength, and Uniaxial Compressive Strength

The fracture toughness of the sandstone specimens under different conditions was calculated based on the *K*_{IC} computational formula specified in the Chinese standard rock test procedure for Water Resources and Hydropower Engineering (2007). Figure 6 shows the relation between the *K*_{IC} and the FT cycles identified under the coupling effects of different chemical solutions and FT cycles. The computational formula of fracture toughness *K*_{IC} is expressed as follows:

$$K_{IC} = 0.25 \frac{S_d P_{max}}{B B^{1.5}} y \left(\frac{a}{B} \right) \tag{1}$$

$$y \left(\frac{a}{B} \right) = \frac{12.75 \left(\frac{a}{B} \right)^{0.5} \left[1 + 19.65 \left(\frac{a}{B} \right)^{4.5} \right]^{0.5}}{\left(1 - \frac{a}{B} \right)^{0.25}} \tag{2}$$

Fig. 6 Relationships among the fracture toughness (K_{IC}), tensile strength, uniaxial compressive strength, and FT cycles under the coupling effects of different chemical solutions and FT cycles



where K_{IC} refers to the fracture toughness (MPa $m^{1/2}$); B is the specimen width (cm), which is equal to the specimen height W (cm); S_d is the distance between two supporting points (cm); P_{max} is the load leading to the fracture failure (N); and a is the depth of the straight incision (cm). In this experiment, $S_d = 16.6$ cm, $W = B = 5$ cm, and $a = 21$ – 23 mm.

Figure 6 indicates that the fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength of specimens showed a basically identical trend as the number of FT cycles increased under the coupling effects of different chemical solutions and FT cycles. The fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength of the sandstone specimens had various degrees of deterioration after chemical solutions and FT cycles. As the number of FT cycles increased, the deterioration degree gradually increased. Nevertheless, the deterioration degree of fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength of the specimens differed when they were immersed in different chemical solutions.

During the first 25 FT cycles, the damage deterioration degree of the fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength was the highest in the 0.1 mol/L Na_2SO_4 (pH 3.0) solution, ranked at the middle in the distilled water, and was the lowest in the 0.1 mol/L NaOH (pH 12.0) solution. Thus, the alkaline environment

had a certain inhibiting effect on the FT damage of the mechanical properties. However, within 25–100 FT cycles, the inhibiting effect of the alkaline solution decreased as the number of FT cycles increased. If the other conditions remained unchanged, the FT deterioration degree of the fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength was the highest when in the acid 0.1 mol/L Na_2SO_4 (pH 3.0) solution, and the lowest in the pH 7.0 neutral distilled water. The strong acid environment aggravated the FT damage deterioration of the mechanical properties. However, during the first 25 FT cycles, the strong alkaline environment had a certain inhibiting effect on the FT deterioration of the mechanical properties. As the number of FT cycles increased, the inhibiting effect decreased in the 0.1 mol/L NaOH (pH 12.0) solution. The 25 FT cycles were the threshold value for specimen change in the mechanical properties of the sandstone in the 0.1 mol/L NaOH (pH 12.0) solution.

Figure 6 also implies that the solutions of different chemical compositions had different effects on the FT damage of the fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength, although the acid environment aggravated the FT damage deterioration of the mechanical properties. When the number of FT cycles remained unchanged, the deterioration degree of the

fracture toughness K_{IC} , tensile strength, and uniaxial compressive strength was lower in 0.1 mol/L NaHCO_3 (pH 3.0) than that in 0.1 mol/L Na_2SO_4 (pH 3.0). Hence, SO_4^{2-} ions had a greater effect on the FT damage of sandstone specimens than did HCO_3^- ions.

3.4 Analysis of Correlation of Mechanical Parameters

Previous studies have indicated that some relations existed between the strength parameters and fracture toughness of the rocks. The relations among the splitting tensile strength, uniaxial compressive strength, and fracture toughness K_{IC} were evaluated based on the summary of the test data in this study, as shown in Fig. 7. The diagram shows linear relations between splitting tensile strength and K_{IC} , and between uniaxial compressive strength and K_{IC} under the effects of chemical solutions and FT cycles. The relations could be expressed as follows:

$$K_{IC} = 0.4056\sigma_t + 0.0314 \quad (3)$$

$$K_{IC} = 0.0358\sigma - 0.11 \quad (4)$$

where σ is the uniaxial compressive strength of the sandstone specimens, and σ_t is the splitting tensile strength of the sandstone specimens.

To obtain a further understanding of the damage degrees of the fracture toughness, splitting tensile strength, and uniaxial compressive strength of the sandstone specimens under the coupling effects of chemical solutions and FT cycles, the chemically corroded and FT damage factor K_{cf} was defined as follows:

$$K_{cf} = \frac{f_0 - f_n}{f_0} \times 100\% \quad (5)$$

where f_0 is the mechanical characteristic value of the sandstone specimens under natural conditions, and f_n is the mechanical characteristic value of the sandstone specimens when they underwent N FT cycles. A high K_{cf} indicated a

large resistance capacity of the sandstone specimens to chemical corrosion and FT cycles.

The relations between the deterioration rate of mechanical characteristics and FT cycles identified based on Eq. (5) under the coupling effects of different chemical solutions and FT cycles are shown in Fig. 8.

Zhang (2002), Golshani et al. (2006, 2007), Deng et al. (2012), and many other scholars worldwide have shown a linear relation between fracture toughness K_{IC} and the tensile strength of rocks. Deng et al. (2012) created a formula explaining the relation between fracture toughness K_{IC} and tensile strength for mode-I cracked rocks:

$$r = \frac{1}{2\pi} \left(\frac{K_{IC}}{\sigma_t} \right)^2 \quad (6)$$

where r is the crack propagation length.

Research findings (Golshani et al. 2006, 2007; Deng et al. 2012) indicate that crack propagation lengths are great and small when rock strength is high and low, respectively. We analyzed crack propagation lengths of the sandstone specimens under the test conditions in this study to evaluate the effects of different chemical solutions and FT cycles on the lengths. The results are shown in Fig. 9.

Figure 9 illustrates that the crack propagation lengths of the sandstone specimens generally showed a gradually decreasing trend under the coupling effects of chemical solutions and FT cycles, which indirectly indicated that the strength properties of the sandstone specimens had an increasing deterioration tendency. The results were consistent with the analysis of the deterioration regularity in the splitting tensile strength and the compressive strength of the specimens. Equation (6) indicates that the deterioration degree of the specimen fracture toughness was significantly higher than that of the splitting tensile strength when the splitting tensile strengths and crack propagation lengths of the specimens decreased at the same time. That condition was a good explanation of the test phenomena in Fig. 8; that is, the deterioration degree of the specimen fracture toughness was the highest and that of compressive strength was the lowest.

Fig. 7 Relations among the splitting tensile strength, uniaxial compressive strength, and K_{IC} of the sandstone specimens. **a** Splitting tensile strength $\sim K_{IC}$. **b** Uniaxial compressive strength $\sim K_{IC}$

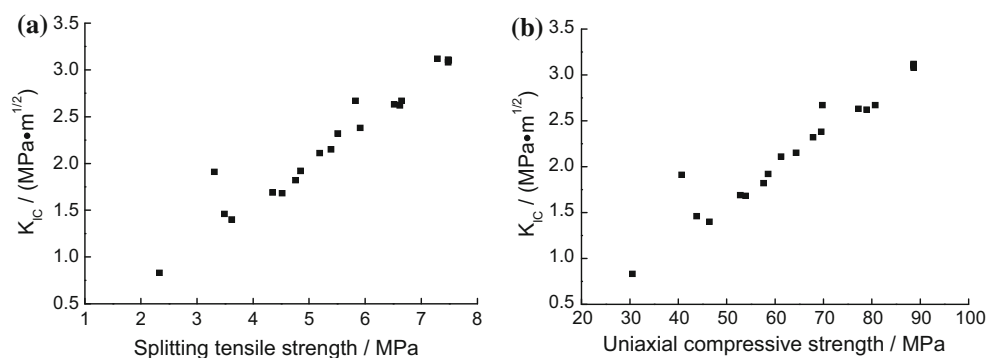


Fig. 8 Relationships between the deterioration rate of the mechanical characteristics and the FT cycles under the coupling effects of different chemical solutions and FT cycles. **a** 0.1 mol/L Na_2SO_4 pH 3.0. **b** 0.1 mol/L NaOH pH 12.0. **c** 0.1 mol/L NaHCO_3 pH 3.0. **d** Distilled water pH 7.0

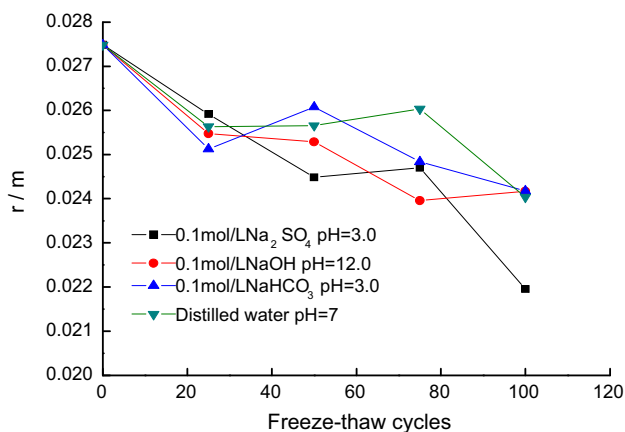
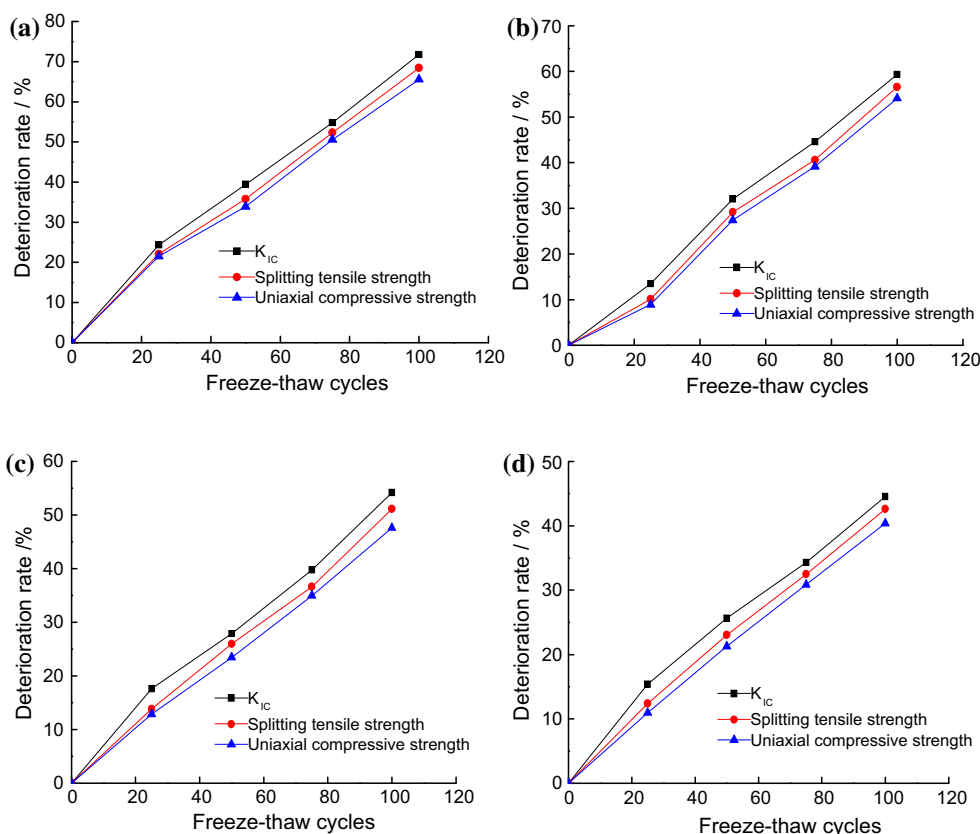


Fig. 9 Relations between the crack propagation lengths of the sandstone and the FT cycles under the coupling effects of different chemical solutions and FT cycles

4 Analysis of the Damage Variable Mechanism

4.1 Damage Variable

Based on the preceding analysis of the damage deterioration degree of the sandstone specimens under the coupling effects of chemical solutions and FT cycles, the damage

variable D was expressed according to the changes in the porosity of the specimens:

$$D = \frac{n_N - n_0}{1 - n_0}, \quad (7)$$

where n_0 is the porosity of the sandstone specimens at the initial state, and n_N is the porosity of the sandstone specimens after they underwent N FT cycles under the different chemical solutions.

The damage variable of the sandstone specimens was evaluated based on Eq. (7) for different numbers of FT cycles, as shown in Fig. 10. The diagram shows that as the number of FT cycles increased, the damage variable of the sandstone specimens would gradually increase under different chemical solutions. A certain distinction existed in the variation regularity of the damage variable in different chemical solutions.

During the first 25 FT cycles, the damage variable of the sandstone specimens was higher in the acid 0.1 mol/L Na_2SO_4 (pH 3.0) solution than in the alkaline 0.1 mol/L NaOH (pH 12.0) solution and in the pH 7.0 distilled water. The damage variable of the specimens in the alkaline 0.1 mol/L NaOH (pH 12.0) solution was the lowest of all; that is, $D_{\text{Na}_2\text{SO}_4} > D_{\text{Distilled water}} > D_{\text{NaOH}}$. After the number of FT cycles exceeded 25, the damage degree of the sandstone specimens increased as the number of FT cycles

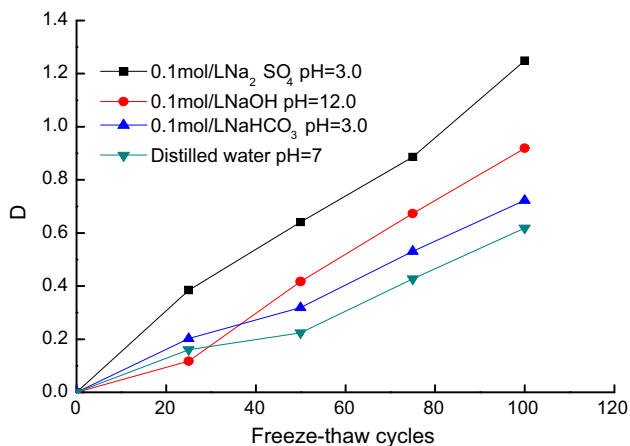


Fig. 10 Curves of the $D - FT$ cycles of the sandstone specimens under different chemical solutions

increased in the 0.1 mol/L NaOH (pH 12.0) solution; that is, $D_{Na_2SO_4} > D_{NaOH} > D_{Distilled\ water}$. Thus, the 0.1 mol/L Na_2SO_4 (pH 3.0) solution could aggravate the FT damage deterioration of the sandstones. By contrast, the NaOH solution had a certain inhibiting effect on the specimens, but that effect disappeared when the number of FT cycles exceeded 25.

When the concentrations and pH values of the solutions remained unchanged, the effect of the acid 0.1 mol/L Na_2SO_4 (pH 3.0) solution on the FT damage deterioration degree of the sandstone specimens was greater than that of the 0.1 mol/L $NaHCO_3$ (pH 3.0) solution. Therefore, the SO_4^{2-} ions aggravated the FT damage deterioration of the sandstone specimens.

4.2 Effect of Damage on the Mechanical Parameters

The damage variable was calculated based on Eq. (7) for the sandstone specimens that underwent different numbers of FT cycles under different chemical solutions. The relations between the damage variable and the mechanical parameters, including fracture toughness K_{IC} , splitting tensile strength, and compressive strength, are shown in Fig. 11.

Figure 11 shows that the fracture toughness K_{IC} , splitting tensile strengths, and compressive strengths of the sandstone specimens gradually deteriorated as the damage of the specimens became severer under the coupling effects of chemical solutions and FT cycles, implying that those factors led the specimens to deteriorate. As the number of FT cycles increased, the damage deterioration gradually increased. The accumulated damage might have resulted in the deterioration of the physical and mechanical features of the sandstones to different extents.

Linear regression was conducted for Fig. 11. The relation between the mechanical properties and damage variables of the sandstone specimens was obtained as follows:

$$K_{IC} = 3.1109e^{-0.9583D} \quad (8)$$

$$\sigma_t = -4.3038D + 7.2473 \quad (9)$$

$$\sigma = -48.827D + 86.025. \quad (10)$$

5 The Engineering Properties of Sandstone After Chemical Solutions and Freezing and Thawing

The engineering properties of a rock mass are described by the relevant quantitative physical and mechanical properties. Accordingly, these test data were validated by calculating two parameters, the saturated uniaxial compressive strength (R_c) and the weathering reduction factor of strength, respectively.

The degree of rock hardness is determined by the saturated uniaxial compressive strength of the rock. The hardness degree of our sandstone specimens under the coupling effects of chemical solutions and FT cycles was divided based on the standard specified in The Professional Standard Compilation Group of People's Republic of China (2014). The results show that the hardness degree of sandstone specimens subjected to various degrees of deterioration after chemical solution and FT cycles was less than that of natural sandstone. At the early stage of the test, the specimens were all in the hard rock category under different chemical solutions. However, as the number of FT cycles increased, the deterioration degree of the sandstone's hardness differed under different chemical solutions. The hardness degree of the specimens changed from hard rock to quite hard rock in the 0.1 mol/L Na_2SO_4 pH 3.0 and in other chemical solutions and finally changed to quite soft rock in the 0.1 mol/L Na_2SO_4 pH 3.0.

The weathering reduction factor of strength is equal to the strength of sandstone after chemical corrosion and FT cycles, divided by its initial natural strength. Statistical analysis of test results showed that the weathering degree of natural sandstone was weak weathering, but that of the sandstone specimens was aggravated after the coupling effects of chemical solutions and FT cycles. As the number of FT cycles increased, the weathering degree of sandstone gradually increased. Nevertheless, the weathering degree of the specimens differed when they were immersed in different chemical solutions, causing differing weathering degrees from FT cycles. The greater the influence of chemical solutions on the FT deterioration degree of sandstone, the earlier in the FT cycles change happened. The weathering degree of sandstone specimens converted from weak weathering to moderate weathering in the

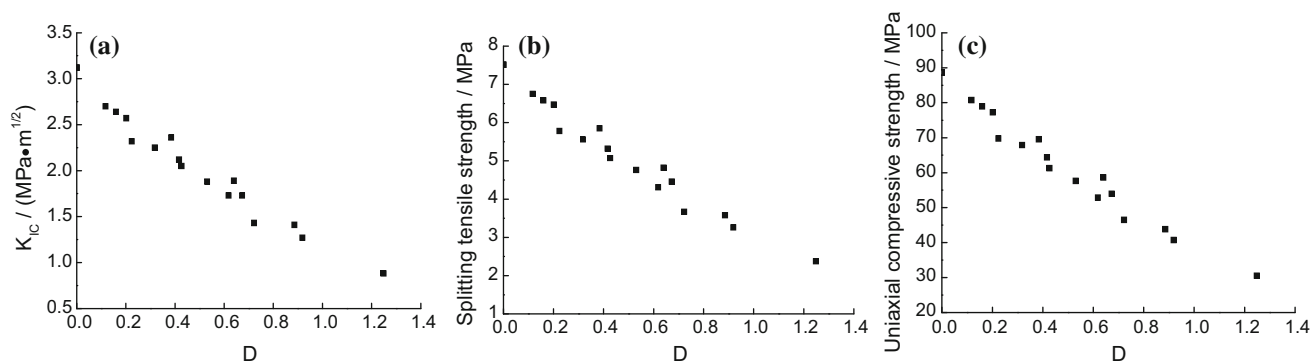


Fig. 11 Relation between physical and mechanical parameters and the damage variables of sandstone specimens. **a** $K_{IC} - D$. **b** Splitting tensile strength $\sim D$. **c** Uniaxial compressive strength $\sim D$

0.1 mol/L Na_2SO_4 (pH 3.0) and 0.1 mol/L NaOH (pH 12.0) solutions finally changed to strong weathering. Because the FT deterioration degree of sandstone was greater in the 0.1 mol/L Na_2SO_4 (pH 3.0) solution than that in the 0.1 mol/L NaOH (pH 12.0), strong weathering of sandstone in 0.1 mol/L Na_2SO_4 (pH 3.0) happened earlier in the 25 FT cycles than that in 0.1 mol/L NaOH (pH 12.0) solution. Moreover, the weathering degree of sandstone converted from weak weathering to moderate weathering only after immersion in other chemical solutions.

6 Conclusions

1. The mechanical properties of sandstone specimens showed a marked weakening trend under the coupling effects of different chemical solutions and FT cycles. However, a distinction existed in the deterioration degrees of the fracture toughness K_{IC} , splitting tensile strength, and compressive strength. The deterioration degree of the fracture toughness was the highest, followed by that of splitting tensile strength, and finally compressive strength.
2. Distinction existed in the effects of different chemical solutions on the FT damage degree of the specimens. The acid solution, 0.1 mol/L Na_2SO_4 (pH 3.0), aggravated the FT damage. By contrast, at the early stage of the test, the 0.1 mol/L NaOH (pH 12.0) solution had a certain inhibiting effect on the damage to the sandstone specimens. However, when the number of FT cycles exceeded 25, the inhibiting effect disappeared. SO_4^{2-} ions could aggravate the FT damage deterioration of the specimens.
3. A good linear relation existed among the fracture toughness K_{IC} , the splitting tensile strength, and the compressive strength as the sandstone underwent chemical corrosion and FT cycles. The crack propagation length generally showed a gradually decreasing

trend under the coupling effects of chemical solutions and FT cycles, thereby indirectly indicating that the strength characteristics of the sandstone specimens gradually deteriorated.

4. The damage variable was established based on the changes in the porosity of the sandstone. The damage variable gradually increased as the number of FT cycles increased. As the damage to the specimens became more severe, the mechanical properties gradually deteriorated. The relation between the fracture toughness K_{IC} and the damage variable was an exponential function, whereas the relations among the splitting tensile strength, the compressive strength, and the damage variable were linear.

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