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Study on the evolution of seepage characteristics of single-fractured limestone under water-rock interaction

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Abstract: Regarding the leakage of fractured limestone in the underground cavern of a hydropower station, the rock samples and reservoir water were collected on site, and two schemes of water-rock interaction tests which lasted 360 days were carried out. The scheme #1 regularly changed the soaking solution during the soaking process to simulate the long-term immersion and flow renewal phenomenon of groundwater, while the scheme #2 mainly simulates the long-term immersion process. Based on the micro-morphological characteristics of the fracture surface and the changes of ion concentration in soaking solution, the characteristics and mechanism of the seepage characteristics of fractured limestone under water-rock interactions were analyzed. The research results show that in the course of soaking, the permeability coefficient of the single-fractured limestone increases first sharply then gently. After 360 days of soaking, the permeability coefficients of the single-fractured limestone with 2.5 MPa, 3.0 MPa, 3.5 MPa, and 4.0 MPa confining stresses in the two schemes increased by 729.90%–384.17%、549.04%–297.45%, respectively. The smaller the confining stress is, the more obvious the permeability coefficient increases. Moreover, the growth trends of permeability coefficient stabilized after 120 days for scheme #1 and 90 days for scheme #2. In comparison, the permeability coefficient increase rate and amplitude of single-fractured limestone in scheme #1 are significantly higher, which is 1.34–2.07 times that of scheme #2. In scheme #1, the immersion reservoir water was periodically changed to maintain the disproportion of the immersion solution, which resulted in a large concentration gradient between the rock sample and the solution. This concentration gradient increased the reaction chemical potential, and accelerated the rate of mineral dissolution and erosion on fracture surface. In scheme #2, the long-term immersion facilitated the solution ion concentration to approach the equilibrium state gradually, leading to the dissolution and erosion rate of the minerals on fracture surface being significantly lower than that in the scheme #1. Long-term water-rock interaction weakens the roughness and fluctuation of fracture surface significantly accompanied with the progressively decrease of local slope and undulation, and the increase of overall erosion depth. Based on this, a seepage channel evolution model for single-fractured limestone under long-term water-rock interaction is established. The seepage channels of fractured rock samples gradually evolved to the direction of low anastomosis and large opening, which leads to significantly increases of equivalent hydraulic opening and permeability coefficient of fractured rock samples. The ideas and results of this study provide an excellent reference for the simulation of water-rock interaction in fractured rock masses.

Keywords: water-rock interaction; periodically change water; long-term immersion; seepage characteristic; microscopic morphological; seepage channel

1 Introduction

Joints and fissures in rock mass are the main seepage channels for groundwater. The process of groundwater flow induces the dissolution of soluble minerals in the fissure wall, which leads to gradual changes in the fracture seepage channels and the permeability characteristics of fractured rock mass, and thereby affecting the safety and stability of underground engineering[1]. Especially in karst areas, seepage and surface subsidence are easy to be triggered due to the long-term influence of water-rock interaction.

Water-rock interaction process shows obvious time effect[2]. On the one hand, many scholars have studied the change law of physical and mechanical properties of rock mass under water-rock interaction. Feng et al.[3], Wang et al.[4], Deng et al.[5], Tang et al.[6], Huang et al.[2], Zhou et al.[7], Fu et al.[8] and Yu et al.[9] carried out a series of short-term or long-term immersion tests on granite, sandstone, limestone and mudstone using water or chemical solution, and the mechanical properties and microstructure changes of various rocks under water-rock interaction were obtained, and the damage and degradation effects of various rocks were analyzed. On the other hand, many scholars have also studied the seepage characteristics of fractured rock mass under water-rock interaction. Brush[10] found that physical and chemical reactions in the immersion process

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facilitate the surface dissolution and precipitation of the fractured rock, leading to the change of seepage channels. Yasuhara et al.[11], Ogata et al.[12], Sheng et al.[13], Wang et al.[14] found that the fractures are highly eroded by chemical solution and the changes in permeability become more significant. Shen et al.[15], Jiang et al.[16] and Wu et al.[17] evaluated the influences of stress and chemical solution coupling effects on seepage characteristics of fractured rock mass.

These findings laid a good foundation for the analysis of physical and mechanical degradation rule of various rocks under water-rock interaction. However, the influence of long-term water-rock interaction on seepage characteristics of fractured rock mass has been rarely reported, and the influence of groundwater flow renewal has not been taken into account in relevant tests.

A hydropower project in Qingjiang field investigation revealed that an obvious leakage was encountered in the grouting adit of the underground powerhouse, which showed a trend of increase year by year. It was speculated that the main reason is during the operation process of the reservoir, the fractured rock mass around the grouting adit is in the flowing groundwater environment for a long time, and the permeability of fractured rock is therefore gradually enhanced due to water-rock interaction. In order to analyze the seepage inducement of the fractured rock in the grouting adit, the fractured limestone in the project was sampled and the long-term solution soaking test was designed. In order to simulate the flow renewal of groundwater, the immersion solution was replaced regularly to analyze the permeability change of the fractured limestone. The evolution mechanism of seepage characteristics was analyzed and explained by integrating the fracture surface morphology characteristics and the change law of ionic concentration of the immersion solution.

2 Sample preparation and test scheme

Since it is difficult to collect and prepare rock samples containing natural joints and fractures, artificial sample preparation method was adopted in this study to obtain rock samples with single joint. Limestone samples were collected from the Maokou Formation. According to the specification requirements[18] and the requirements of the seepage test equipment, cylindrical rock samples of 50 mm (diameter) ×50 mm (height) were prepared and the single fracture rock samples were split from the side center by using splitting method, as shown in Fig. 1.

(a) Before splitting (b) After splitting

Fig. 1 Typical rock sample photos

The mineral composition of the rock samples mainly consists of calcite and quartz, followed by illite, dolomite and pyrite, etc. The specific mineral composition and content (mass fraction) are list in Table 1.

Table 1 Rock sample mineral composition and content

Composition	Illite	Quartz	Calcite	Dolomite	Pyrite
content/ %	8	41	46	4	1

In order to accurately simulate the groundwater environmental conditions of fractured rock mass, the reservoir water collected on-site was transported back to the laboratory as the immersion solution, and the designed immersion time was 360 day. In order to capture the flow renewal of groundwater, the new reservoir water was replaced as the immersion solution at 10, 20, 30, 60, 90, 120 and 240 days, respectively. For comparative analysis, referring to previous experimental experience[5, 19], a group of long-term immersion tests without changing the immersion solution were carried out at the same time. For the convenience of description, the aforementioned soaking process of changing the immersion water regularly is called scheme 1, and the soaking process without changing the immersion solution is noted scheme 2.

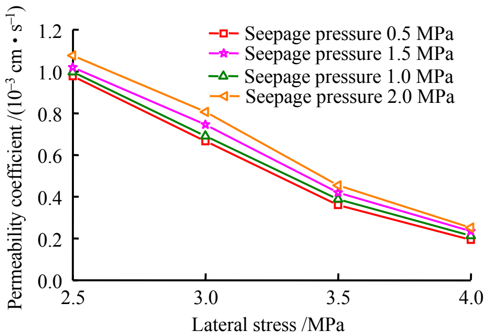
HYS-4 rock permeation analyzer was used to conduct seepage tests on fractured rock samples under different water-rock interaction periods. ST500 3D non-contact surface profiler was used to perform scanning analysis on the fracture surface, and the ionic concentration of immersion solution was analyzed by using GDYS-201M multi-parameters water quality analyzer. In the seepage test, the influences of overburden stress and seepage water pressure were considered. The lateral stress was designed as 2.5, 3.0, 3.5 and 4.0 MPa, and the seepage water pressure as 0.5, 1.0, 1.5 and 2.0 MPa, respectively.

During long-term water-rock interaction test, the discreteness of samples is an issue that deserves great care. If tests with different cycles are carried out on various samples at the same time, the fracture surface morphology characteristics of multiple samples cannot be guaranteed to be consistent, which may lead to great discreteness of test results. It is worth noting that during the test, the microscopic morphology scanning of the fracture surface is a nondestructive process; the lateral stress exerted by the seepage test is less than 10% of the rock sample compressive strength; the seepage water pressure is also relatively small, and the test time is relatively short for the soaking time. In general, the damage caused by test process to the rock sample is insignificant. Therefore, the "single specimen method" was adopted to conduct long-term immersion test. In other words, in the two experimental schemes, two rock samples were used respectively for the whole cycle tests, which can ensure the comparability of fracture surface morphology and permeability characteristics of rock samples in each cycle during the water-rock interaction tests.

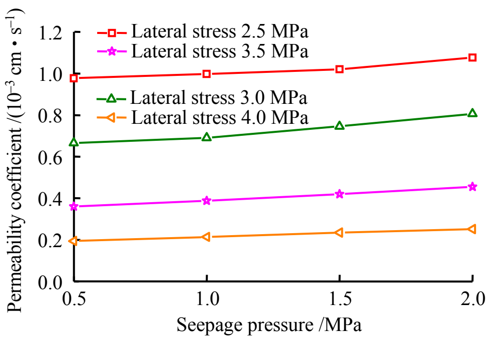
3 Seepage characteristics of single fracture limestone under water-rock interaction

According to the Cubic law and Darcy's law[20–22], the permeability coefficient of each rock sample with single fracture is obtained. The correlation curve between permeability coefficient and lateral stress of a typical rock sample in the initial state is plotted in Fig. 2.

As can be seen from Fig. 2, when the seepage water pressure remains constant and the lateral stress increases from 2.5 MPa to 4.0 MPa, the corresponding permeability coefficient decreases by 33.45%– 88.49%. When the lateral stress is constant and the seepage pressure gradually increases from 0.5 MPa to 2.0 MPa, the permeability coefficient varies within the same order of magnitude, indicating that the seepage pressure has little influence on the permeability coefficient of rock samples. This finding is in accordance with the research conclusion of Sun et al.[23]. For the convenience of comparison, in the following analysis, under the same lateral stress, the permeability coefficient is computed as the average value of permeability coefficients measured under different seepage pressures.



(a) Relationship between permeability coefficient and lateral stress



(b) Relationship between permeability coefficient and seepage pressure

Fig. 2 Permeability coefficient of single fracture limestone in the initial state

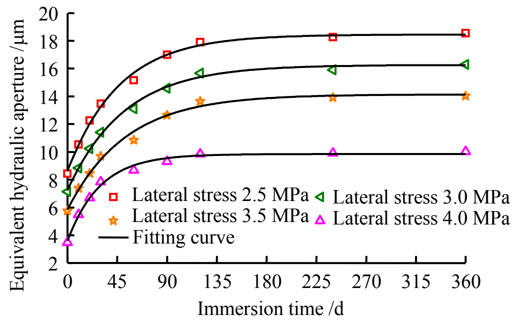
In order to analyze the permeability evolution rule of fractured rock samples after soaking, the curves of equivalent hydraulic aperture and permeability coefficient changing with the immersion time of a typical sample with single fracture in scheme 1 was shown in Fig. 3.

It can be seen from Fig. 3:

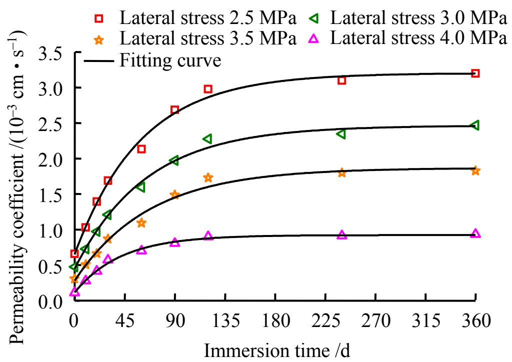
(1) With the increase of the immersion time, the equivalent hydraulic opening and permeability coefficient of the single fracture limestone experience the same trend, rising sharply and then gently. The increase of equivalent hydraulic opening and permeability coefficient in the first 120 days are faster, and then gradually slow down, which can be well fitted by using an exponential function.

(2) Compared with the initial state, after soaking for 10, 30, 60, 90, 120 and 360 days, the equivalent hydraulic opening for fractured rock samples under different lateral stresses increases by 24.89%–57.43%, 59.86%–125.16%, 79.70%–149.49%, 101.62%–167.42%, 112.32%–182.82%, 120.03%–187.72%, respectively. The variation of equivalent hydraulic opening in the first 120 days accounts for more than 90.00% of the total amplitude.

(3) Compared with the initial state, after soaking for 10, 30, 60, 90, 120 and 360 days, the permeability coefficient for fractured rock samples under different lateral stresses increases by 53.59%–147.84%, 155.57%–406.99%, 252.93%–522.48%, 306.51%–615.18%, 350.79%–698.79%, 384.17%–729.90%, respectively. The permeability coefficient in the first 120 days increases significantly. Comparatively, with the same immersion time, the smaller the lateral stress is, the more significant the increasing trend of permeability coefficient of fractured rock sample is.



(a) Variation of equivalent hydraulic aperture with immersion time



(b) Variation of permeability coefficient with immersion time

Fig. 3 Variation of seepage characteristics of single fracture limestone in scheme 1

In order to analyze the influence of regularly changed reservoir water on the water-rock interaction, the variation of permeability coefficient of the fractured rock sample in scheme 2 was statistically analyzed, as shown in Fig. 4.

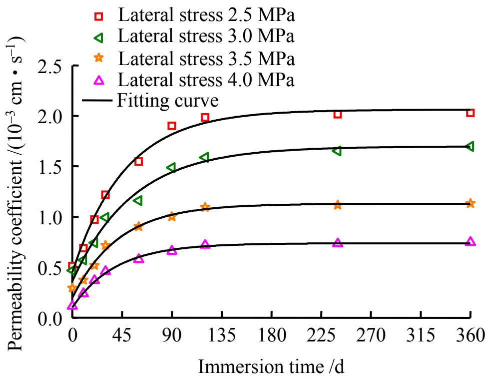


Fig. 4 Variation of permeability characteristics of single fracture limestone in scheme 2

According to the comprehensive comparison between Fig. 3 and Fig. 4, the growth trends of the permeability coefficients of single fracture limestone in the two schemes are similar, although the increase amplitude in scheme 2 is relatively small. For example, after soaking for 10, 30, 60, 90, 120 and 360 days, the permeability coefficient for fractured rock sample under different lateral stresses increases by 53.59%–147.84%, 155.57%–406.99%, 252.93%–522.48%, 306.51%–615.18%, 350.79%–698.79%, 384.17%–729.90%, respectively. In the first 90 days, there is an insignificant difference in the increase trend of the permeability coefficient for the two schemes; after 90 days, the difference between the results of the two schemes gradually increases and after 360 days, the difference reaches 86.72%–207.32%. On the whole, the increase trend of the permeability coefficient of fractured limestone in scheme 1 tends to be stable after 120 days, while that in scheme 2 rarely changes after 90 days. The main reason is that the evolution rule of the permeability coefficient of fractured limestone is closely related to the water-rock interaction. Without changing the immersion solution, the ion concentration in the solution tends to reach a equilibrium state, which leads to a slow water-rock interaction. When the immersion reservoir water is replaced periodically, new ions are added regularly to maintain the unbalanced ion concentration of the immersion solution and promote the water-rock interaction. The detailed analysis is combined with the statistics of immersion ion concentration and fracture surface morphology characteristics and will be presented follow.

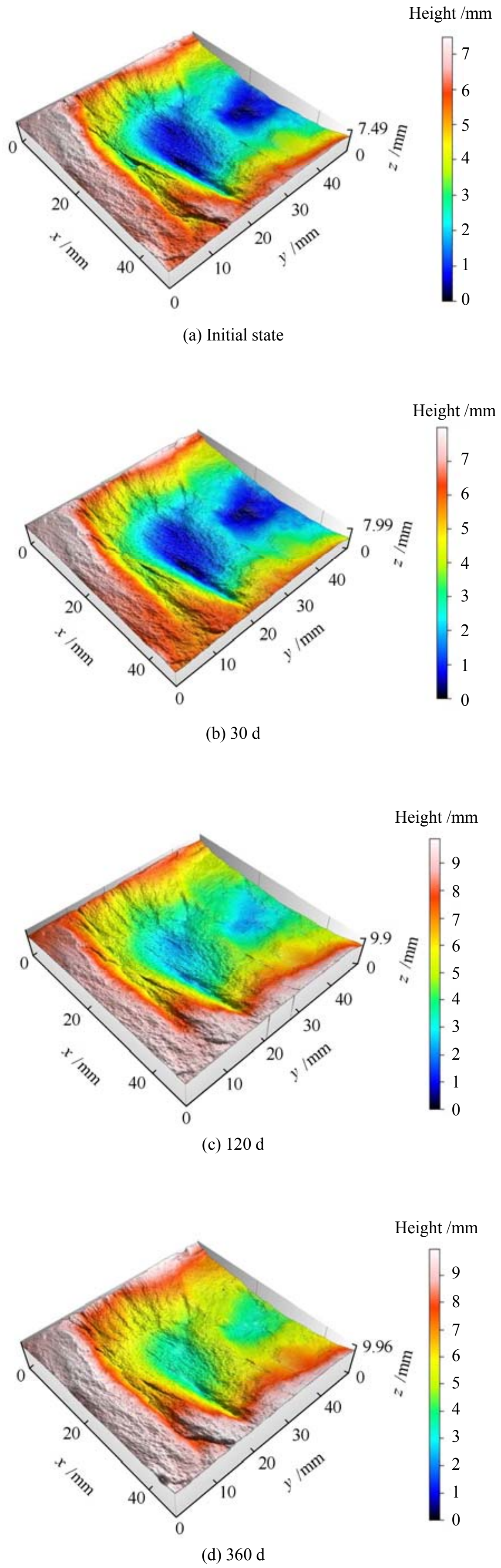
4 Fracture surface morphology of limestone under water-rock interaction

The change of fractured rock permeability is mainly related to the fracture surface morphology characteristics. Under the immersion of reservoir water, the uneven fracture surface is the key area of water-rock interaction[24–25]. For this reason, the sample fracture surface was scanned and analyzed at different immersion times. The fracture surface scanning photos of a typical sample are shown in Fig. 5. Due to the limited space of the paper, Figure 5 only gives some scanning results from scheme 1. Combined with previous research experiences[26–27], the height parameters and texture parameters of fracture surface were selected for statistical analysis. The height parameters include the maximum peak height of the surface, S_p, the maximum valley depth of the surface, S_v, the maximum height of the contour, S_z, the arithmetic mean deviation, S_a and the root mean square of the height, S_q; and the texture parameters include the slope root mean square, S_{dq} and the ratio of the spread interface area, S_{dr}. As shown in Fig. 6, height parameters and texture parameters were normalized for the convenience of comparative analysis of the variation amplitude of different morphology parameters.

It can be observed from Fig. 5 and Fig. 6:

(1) With the increase of the immersion time, the height parameters and texture parameters of the fracture surface decrease considerably at the initial stage, followed by a slow decline. In the first 120 days, the degradation amplitude of morphology parameters is obvious, accounting for more than 90.00% of the total amplitude. The changes of morphology parameters of the fracture surface tend to be stable after 120 days.

(2) Compared with the initial state, after soaking for 10 days, fracture surface height parameters, S_p, S_v, S_z, S_a, S_q reduce by 2.25%, 2.65%, 2.49%, 2.99% and 2.29%, respectively. After 120 days, these height parameters decrease by 19.30%, 18.21%, 18.63%, 18.77% and 14.78%, respectively. After soaking for 360 days, height parameters reduce by 20.87%, 19.44%, 19.99%, 20.26% and 15.83% respectively. Specifically, the height parameters, S_p, S_v and S_z are capable to reflect the maximum peak and valley height of the fracture surface. It can be seen from the variation of morphology characteristics that the water-rock interaction leads to the gradual decrease of the contour height of the fracture and therefore results in a smooth fracture surface. S_a can be used to reflect the roughness of the fracture surface and S_q indicates the discreteness and fluctuation of the microscopic morphology of the fracture surface. According to the change rules of S_a and S_q, it can be inferred that the roughness and fluctuation of the fracture surface significantly decrease under water-rock interaction.



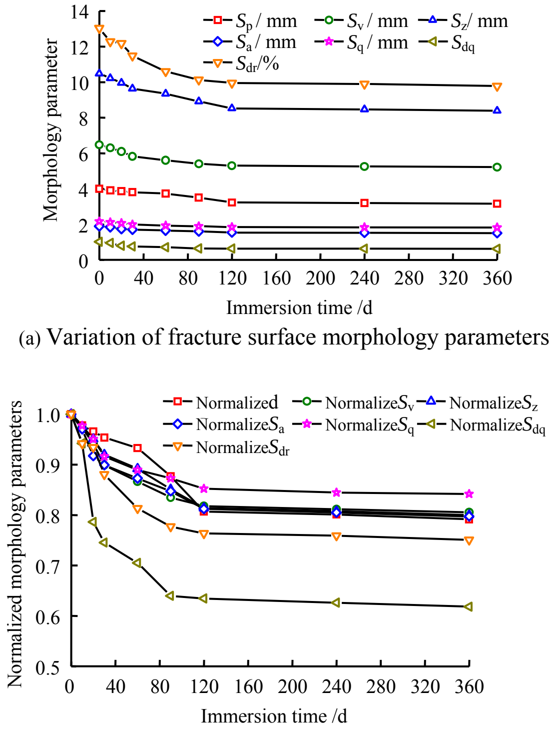
(a) Initial state

(b) 30 d

(c) 120 d

(d) 360 d

Fig. 5 Scanning images of fracture surface at different immersion times



(a) Variation of fracture surface morphology parameters

(b) Normalized fracture surface morphology parameters

Fig. 6 Change curves of morphological parameters of fracture surface under water-rock interaction

(3) Compared with the initial state, after soaking for 10 days, fracture surface texture parameters, S_{dq} and S_{dr} reduce by 5.79% and 5.82%, respectively. After soaking for 120 days, texture parameters decrease by 36.53% and 23.63%. And after 360 days, 38.17% and 24.93% of S_{dq} and S_{dr} are lost. Among the texture parameters, the contour shape and undulation state of the fracture surface can be well described by S_{dq}. Another texture parameter, S_{dr}, reflects the complexity of the fracture surface. When the theoretical value of S_{dr} is zero, the fracture surface is completely flat. The larger the S_{dr} is, the more complex the fracture surface will be. According to the variation of texture parameters, the local slope and undulation of the fracture surface induced by water-rock interaction gradually decrease.

In order to more intuitively display the influence of water-rock interaction on fracture surface morphology characteristics, the fracture surface profiles of rock samples with different immersion times are extracted for comparative analysis along the axial direction, as shown in Fig. 7.

Figure 7 illustrates that under the long-term immersion effect, the fracture surface morphology characteristics of rock samples have changed significantly:

(1) In the initial state, the fracture surface profile has sharp angles, clear edges and obvious changes in undulations. In addition, there are many small bumps on the profile line, and the corresponding profile trace length is 104.07 mm, which is more than 2 times the axial length of the rock sample.

(2) After immersion for 30 days, the amount of tiny bumps on the fracture surface gradually decrease with the edges and corners becoming smoother. The

main reason is that during the immersion process, the mineral particles on the fresh fracture surface are characterized by higher surface activation energy, and due to the large contact area between the bumps on the fracture surface and water molecules, mineral dissolution is prone to occur[28]. In the early stage of water-rock interaction, mineral particles on the fracture surface have more small bumps, and water-rock contact points are relatively dense, which leads to a faster chemical dissolution rate and a continuous corrosion of mineral particles on the surface. The results show that the surface corrosion depth is 0.21–0.35 mm, and the corresponding profile trace length is decreased by 4.04%.

(3) After immersion for 120 days, an obvious concentrated dissolution of minerals is encountered on the local undulations of the fracture surface[11]. With the increasing salinity and the decreasing solubility of the solution, regularly replaced water makes the solution with high salinity inside the rock diffuse to the outside. During diffusion, secondary formed minerals and ions are transported outward, leading to the continuous expansion of the dissolution range and depth of the fracture surface. Meanwhile, the fracture surface become more smooth, forming relatively smooth dissolution pits. The overall dissolution depth of the fracture surface is increased to 0.40–0.61 mm, and the corresponding profile trace length is decreased by 12.79%. Additionally, in the analysis of the fracture surface micro-morphology parameters, the maximum peak height S_p and maximum valley depth S_v also present similar changes, which decrease by 19.30% and 18.21%, respectively.

(4) After immersion for 360 days, the edges and corners of the profile line are gradually eroded to be smooth. The overall dissolution depth of the fracture surface increases to 0.49–0.65 mm, and the trace length of the profile line decreases by 13.19%

(5) In general, during solution immersion, water-rock interaction acts as the driving force of fracture surface morphology evolution. In the process of mineral dissolution, chemical potential (partial molar Gibbs free energy) determines the direction and limit of the physical-chemical reaction between water and rock under constant temperature and pressure. With regular replacing immersion solution, the chemical potential difference between limestone and immersion solution maintains at a higher gradient, which promotes the dissolution of fracture surface[30]. Driven by the chemical potential gradient, the rock reacts with the immersion solution. This process continuously consumes the cohesive energy of fractured limestone, and eventually reaches the lowest cohesive energy state in the rock[19]. At the same time, the dissolution gradually tends to be steady, and the dissolution depth of fracture surface, profile trace length and micro-morphology parameters gradually become stable.

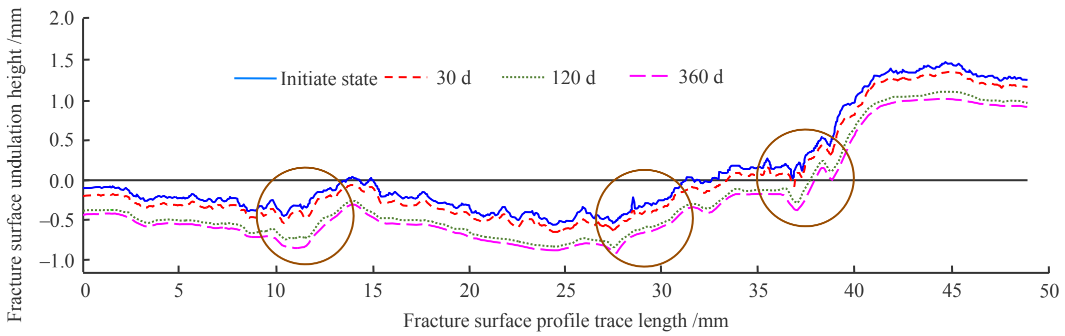


Fig. 7 Typical profile changes of fracture surface under water-rock interaction

5 Evolution mechanism and model of seepage characteristics of single fracture limestone under water-rock interaction

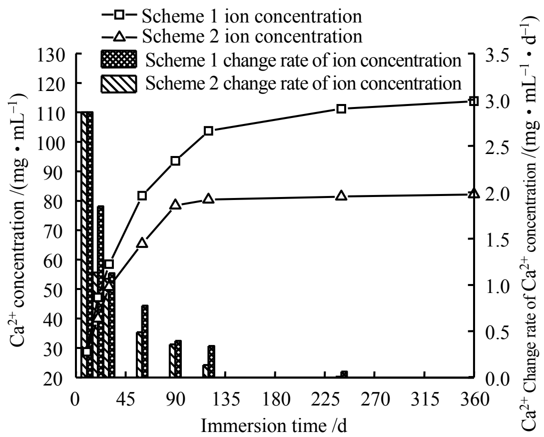
The above analysis indicates that the mineral composition of the rock sample is mainly calcite and quartz. In terms of the stability of chemical and physical properties, quartz is relatively stable and the physical-chemical reaction is therefore not obvious, whereas calcite tends to dissolve under the water-rock interaction. The rock sample is mainly composed of $CaCO_3$. Therefore, the Ca^{2+} and HCO_3^-, which have the largest concentration changes, are selected as the key objects to analyze the water-rock interaction during the immersion process. The relevant ion concentration change is plotted in Fig. 8. The curve shows the cumulative growth trend of ion concentration during the immersion, and the bar chart exhibits the rate of ion concentration change in each stage.

Some regularities are observed from Fig. 8 as follows: HCO_3^-

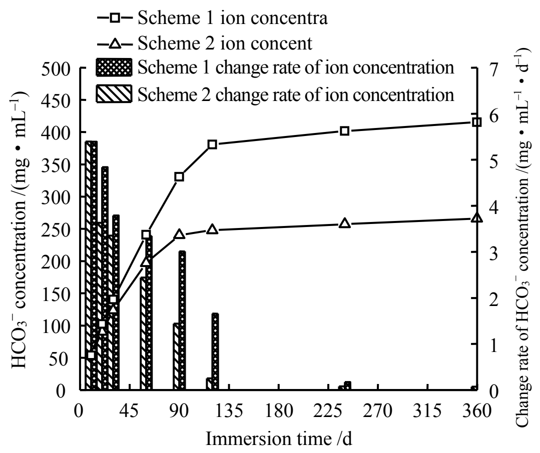
(1) During the immersion process, the concentrations of Ca^{2+} and HCO_3^- in the solution gradually increase, and the change of ion concentration curve is generally consistent under the two schemes. After immersion for 10, 30, 90, 120 and 360 days, the concentration of Ca^{2+} in scheme 1 cumulatively increases by 45.23%, 92.16%, 147.57%, 163.65% and 179.58%, respectively, and the concentration of HCO_3^- increases by 44.15%, 114.83%, 271.03%, 311.76% and 340.17%, respectively. In scheme 2, the concentration of Ca^{2+} cumulatively increases by 45.23%, 79.95%, 123.62%, 126.79% and 129.58%; and the concentration of HCO_3^- increased by 44.19%, 101.36%, 196.72%, 202.94% and 217.84%, respectively. This result is in accordance with the change of the permeability coefficient and fracture surface morphology parameters. The variation trend of ion concentration in immersion solution in the

two schemes tend to be stable at 120 days and 90 days, respectively.

(2) There is also significant difference in the range of ion concentration change between the two schemes. The main reason is that the dissolution rate of minerals is closely related to the equilibrium state of the corresponding ion concentration in the solution. In scheme 1, the reservoir water is periodically replaced, which is equivalent to updating the reactants in the solution. A large concentration gradient is naturally formed between the fracture surface and the immersion solution. The activity of water-rock chemical reaction is controlled by this concentration gradient. The increase of concentration gradient is favorable for the solution molecules to move towards the fracture surface in a high concentration state, accelerating the dissolution rate of minerals on the fracture surface. In scheme 2, the immersion solution is not replaced regularly, and the concentration gradient in the immersion solution gradually decreases and approaches the equilibrium state, leading to a slower dissolution rate of limestone. Therefore, starting from soaking for 30 days, the ion concentration growth rate in scheme 1 is significantly higher than that in scheme 2, which is 1.13–1.56 times of that in scheme 2.



(a) Variation of Ca^{2+} concentration



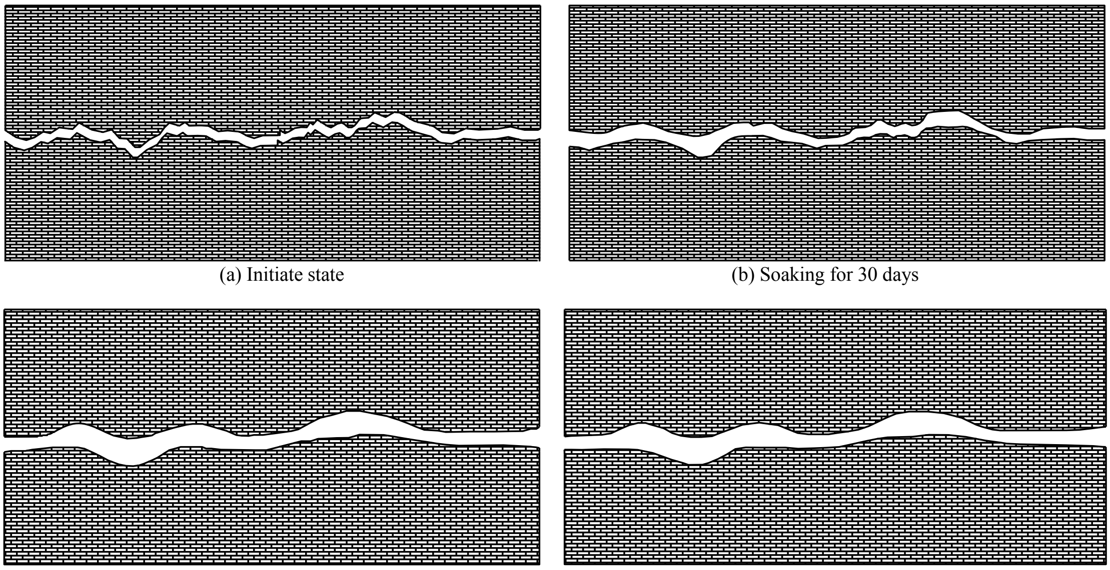
(b) Variation of HCO3– concentration

Fig. 8 Variations of typical ion concentrations in soaking solution under water-rock interaction

(3) The concentration of Ca^{2+} and HCO_3^- in the immersion solution in scheme 1 increase remarkably during the first 120 days, accounting for more than 90.00% of the total increment. After that, the concentration increase rates of Ca^{2+} and HCO_3^- decrease continuously. In scheme 2, during the first 90 days, the Ca^{2+} and HCO_3^- concentration in the solution increase significantly, and then the concentration rate stabilizes gradually. The main reason is that the water-rock chemical reaction mainly takes place on the water-rock contact interface. During the whole immersion period, the contact and reaction between the solution and the rock is a process of gradual expansion and inwards deepening. When the solution molecules first contact the fracture surface of limestone, there are more protruded mineral particles on the fracture surface. Furthermore, a larger water-rock interface and a faster dissolution rate lead to a high ion concentration growth rate in the solution. With the dissolution of mineral particles on the fracture surface, the protruded mineral particles on the surface gradually decrease. When the water-rock contact area shrinks, the hydro-chemical reaction also weakens, accompanied with the decrease of ions growth rates in the solution. With the diffusion of solution molecules into rocks along the micro-cracks and void space between mineral particles, the water-rock contact surface gradually decreases, the hydro-chemical reaction and ion formation rate tend to be stable gradually.

(4) During the soaking process, the mineral particles on fracture surface react with the solution, resulting in the dissolution of minerals. As the immersion time increases, the generated reaction materials are continuously brought into the immersion solution, which smoothens the undulated fracture surface, leading to the increase of hydraulic aperture [15]. The fracture space gradually evolves into a larger seepage channel, thus affecting the seepage characteristics of the single fractured limestone. On this basis, the evolution model of single fracture limestone seepage channel under water-rock interaction is established, as demonstrated in Fig. 9.

When seepage occurs in fractured rock, the fracture surface undulation and roughness have a significant influence on fracture surface fluid flow characteristics[31]. It can be seen from Fig. 9, in the initial state, the upper and lower fracture surfaces are completely matched with each other by sharp edges and corners, and clear irregular twists and undulations. The upper and lower fracture surfaces have a close anastomosis, corresponding to a narrow hydraulic aperture at this stage. After soaking for 30 days, the small bumps or irregular edges of mineral particles on the fracture surface tend to be smooth, and the fracture space gradually increases, corresponding to the increase of hydraulic aperture. After soaking for 120 days, the edges and corners on fracture surface are rounded. As the bumps on fracture surface decrease gradually, the dissolution pit becomes deeper, and a seepage channel with large space is formed between the upper and lower fracture surfaces. After being immersed for 360 days, the fracture surface tends to be flat, and the water-rock chemical reaction gradually weakens. In addition, the fracture space between the two fracture surfaces barely changes at this stage. Therefore, the permeability coefficient of fractured limestone tends to be stable.



(a) Initiate state (b) Soaking for 30 days

(c) Soaking for 120 days (d) Soaking for 360 days

Fig. 9 Evolution model of single-fracture limestone seepage channel under water-rock interaction

6 Conclusions

(1) Under long-term water-rock interaction, the permeability coefficient of limestone with single fracture increases sharply at first and then gently. After soaking for 360 days, the permeability coefficients of limestone subjected to different lateral stresses increase rapidly, which can be well fitted by an exponential function. When the immersion solution is updated regularly, the permeability coefficient increases at a faster rate, which is 1.34–2.07 times of that without immersion solution replacement. Moreover, the variation trend of rock fracture surface morphology in the soaking process is closely related to the water-rock interaction. The fracture surface height parameters and texture parameters show decreasing trends of “rapidly first and then slowly”.

(2) The seepage channel evolution model of single fracture limestone under water-rock interaction is established. Under long-term water-rock interaction, the seepage channel of fractured rock sample gradually evolves from a state with high matching degree to low matching degree and large aperture degree, which leads to the significant enlargement of equivalent hydraulic aperture and permeability coefficient.

(3) Compared with the long-term unchanged immersion, the regularly replaced reservoir water supplies new ions to the immersion solution, which maintains the unbalanced ions concentration and promotes the water-rock interaction. Therefore, when simulating and analyzing the influence of groundwater on the physical and mechanical properties of fractured rock, the environmental conditions of groundwater flow renewal should be simulated as far as possible.

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