Influence of pH on moisture-absorbing swelling cracks of red layer in central Sichuan and its micro-mechanism

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Abstract
In this study, the influence of pH on the moisture-absorbing swelling cracks of red mudstone in southwest China was studied and its microscopic mechanism was revealed. A self-designed water absorption device combined with digital speckle correlation (DSCM), scanning electron microscope, XRD diffraction experiment, mercury injection experiment and other means were used. The results indicated that compared with an alkaline environment, an acidic environment resulted in the self-absorption and cracking of mudstone. The maximum water absorption rate of mudstone and crack rate in a pH of 3 were determined as 15.77 and 18.91%, respectively; whereas for pH = 11, they were 11.71 and 7.11%, respectively. In the acidic environment, the maximum combined displacement value and maximum principal strain value of mudstone self-priming and swelling evolution were both greater than in an alkaline environment. Simultaneously, in the former, the moisture absorption failure characteristics of mudstone exhibited increased swelling strain zones and swelling cores. The three possible mechanisms by which pH affects the expansion of mudstone hygroscopic cracks were proposed: hydration-expansion softening, adsorption-wedge failure, and humidity stress field. However, it was found that the solutions with different pH values may affect these three microscopic mechanisms through the following four physical or chemical processes: mineral dissolution, ion absorption and exchange, particle association, and pore change. The results of this study are expected to be of significance and aid in roadbed design, tunnel support, slope treatment, and other projects in the southwest region.

Keywords Expansion of mudstone hygroscopic cracks · Digital speckle correlation method · Various pH conditions · Displacement field and strain field · Expansion mechanism · Red layer

Introduction
The total area of the red layer in China is approximately 820,000 km². With the red layer in Southwest China accounting for 33% of the country’s total area, which is the region with maximum presence of the red layer (Huang et al. 2005; Guo et al. 2007). A red layer is a type of clastic rock strata deposited under the effect of high continental temperature following oxidation owing to the environment with red as the primary colour, and mainly belonged to the Jurassic and Cretaceous (Zhong et al. 2019; Dai et al. 2020). The red beds are primarily composed of mudstone, sandy mudstone, and sandstone. Among these, mudstone exhibits low engineering properties, such as low strength, brittle nature, and easily softens, disintegrates, and weathers away when in contact with water. Further, it exhibits expansibility and significant rheology (Yang et al. 2006; Chen et al. 2009). In this study mudstone acquired from Sichuan Province, Neijiang City, Weiyuan County, and belonging to the Middle Jurassic Xintiangou Formation was studied. The red mudstone can absorb moisture and expand, resulting in the generation, expansion, and penetration of cracks. Consequently, it has resulted in several engineering disasters, such as the deformation of the upper arch of the roadbed, rupture of the tunnel floor, and instability and collapse of the slope (Zhang et al. 2018a, b; Zeng et al. 2020; Li et al. 2019, 2021; Wen et al. 2020; Dai et al. 2021; Tandon et al. 2021).

In expansive rock (soil) engineering, cracks can seriously deteriorate the engineering properties of rock and soil (such as deformation, strength, seepage, stability), causing serious
damage to the engineering building and structure (Yin et al. 2012; Salimi et al. 2018; Zeng et al. 2020). Consequently, scholars have conducted numerous systematic studies on swelling rocks and soil cracks. Currently, there exist several research results on the crack development characteristics and quantitative description of expansive rock and soil (Mawlood and Hummadi 2019; Zhou et al. 2021). Lu et al. (2002) and Chen (2014) employed geotechnical CT–triaxial instrument to study the crack evolution of expansive soil. Yi et al. (1999) studied the fractal characteristics of the crack structure of expansive soil based on the fractal theory. Wang et al. (2010) proposed a quantitative description method for swelling rock cracks based on the numerical processing technology of image gray and binarisation. Many scholars have studied the influence of different conditions (number of dry and wet cycles, temperature, initial degree of damage) on the evolution of cracks in expensive soil, as well as the corresponding soil deformation and mechanical behavior (Wei et al. 2015; Tang et al. 2012a, b; Mao et al. 2018). Zhou et al. (2020) studied the macroscopic mechanical characteristics and microstructural characteristics of red layer soft rock under different heating methods, different temperatures and different immersion times. Moreover, there have been several studies examining the occurrence and propagation mechanism of cracks in swelling rock and soil using experimental, theoretical, and numerical models. Through experimental results, many scholars have summarized the laws of the generation and propagation of cracks in expansive soil, and established corresponding theoretical models (Konrad and Ayad 1997; Ma et al. 2007; Wu et al. 2012). Using both elastic theory and fracture mechanics, a mathematical expression of the depth of crack propagation is proposed (Yao et al. 2002). Zhou et al. (2021) used the expansion-softening mechanism and numerical analysis of expanding rocks to study the expansion-cracking mechanism of red layer mudstones during the expansion process. The corresponding calculation model is established by using the discrete element method (DEM). The purpose of the numerical simulation study in this paper is to explore the effects of minerals on the crack patterns and mechanical properties of red mudstone (Zhang et al. 2019). Zhang et al. (2022) presents an approach for capturing rock heterogeneity that combines peridynamic theory, digital image processing (DIP), and low-field nuclear magnetic resonance (NMR) imaging. The failure process of mudstone in an unconfined compression test is simulated. The studies mentioned have mainly focused on the shrinkage cracks of swelling rock and soil under the condition of water loss. However, under the condition of water absorption, expansive soil generally does not produce cracks, whereas expansive rock produces moisture-absorbing expansion cracks. Because the formation mechanism of the swelling rock moisture-absorbing swelling cracks is quite different from the above research results. Therefore, research on the quantitative analysis and formation mechanism of hygroscopic swelling cracks is still lacking.

Regarding the disintegration experiments of red-bed mudstone in different acidic or alkaline environments, there exist many research results. Studies have shown that under acidic conditions (pH < 7), with an increase in H⁺ concentration, the disintegration speeds up, whereas under alkaline conditions, with the increase in OH⁻ concentration, the disintegration speed slows down. Moreover, the disintegration speed of mudstone varies with mineral composition, soluble cement content, rock texture, grain pattern, porosity, granularity, and degree of weathering (Moon 1993; Gupta and Ahmed 2007; Yagiz 2010; Gobadi and Momeni 2011; Gautam and Shakoor 2013; Fereidooni and Khajevand 2018; Shen et al. 2020; Xin et al. 2022). Critelli et al. (2014) and Yuan et al. (2019a, b) demonstrated that hydrophysical and chemical reactions can result in the generation of secondary pores and changes in mineral composition, which affect the macro-mechanical properties of sandstones in acidic and alkaline solutions. Zhou et al. (2005) asserted that the role of H⁺ in soft rock softening is related to mineral dissolution. Spagnoli et al. (2012) believed that pH affected clay properties owing to its effect on the particle association of clay minerals. Zhao et al. (2018) explained the effect of pH on the disintegration of purple mudstone from the perspective of the release of K⁺, Na⁺, Ca⁡²⁺, and Mg⁡²⁺ cations. However, because the red beds in the southwestern region are very different from those in other regions (grain density, mineral composition, stratum lithology, porosity, weathering degree, etc.), they exist in different acid–base environments and consequently research regarding them is scarce. This is because the mudstone in this area exhibits characteristics such as high particle density, high clay content, strong hydrophilicity, and low resistance to metamorphism. Thus, the above research results cannot be extended to red-bed mudstones in southwestern China.

In this study, a self-designed water absorption device was employed and a CCD camera was used to record the deformation and destruction information of the sample during the water absorption process. Subsequently, the digital speckle correlation method was used to analyse the deformation field. Further, scanning electron microscopy, X-ray diffraction (XRD) experiments, mercury intrusion experiments, and other methods were combined to study the self-absorption cracking characteristics and micro-mechanisms of mudstone in the dry state of the southwestern region in different pH solutions. Consequently, three microscopic mechanisms explaining the development of moisture-absorbing swelling cracks in red layer mudstone and four effects of different pH solutions on the expansion of mudstone fractures were proposed. These complement the current research on the mechanism of moisture absorption and cracking of mudstone and
the effect of pH on the microscopic mechanism of mudstone cracking in red beds in central Sichuan. Furthermore, the results of this study is expected to be of significance and aid in roadbed design, tunnel support, slope treatment, and other projects in the southwest region.

**Experimental and analytical methods**

**Site description**

The samples used in this study were acquired from latitude 29° 62’ N, longitude 104° 73’ E, Zizhong County, Neijiang City, Sichuan Province, China. This is a subtropical humid climate zone with a mild climate and abundant rainfall. The highest temperature recorded is 39.9 °C, and the lowest is −4 °C, with the annual average temperature being 17.5 °C. The average annual rainfall received by this area is 972.7 mm, with 70% of the rainfall occurring in summer and autumn. The stratum lithology of this area is shown in Fig. 1. The red layer belongs to the Middle Jurassic Xintiangou Formation (geological age mark: J2x).

**Experimental program**

Considering the requirements for performing surface crack observation and the difficulty of sample preparation (Zhou et al. 2021), the sample was processed into a cylindrical shape (diameter 80 mm; height 20 mm). At the same time, electron microscopy scanning and mercury
intrusion porosimetry were carried out on mudstone samples to clarify the composition and pore structure of clay minerals. The SEM work was conducted on half cubes of 0.5 cm (thick) × 1 cm² (cross-sectional area). The sample was then ion milled by a Hitachi IM4000Plus Ion Milling System. After ion-milling, the samples were directly imaged with a Hitachi 4800 SEM. The MIP work was performed on the Micromeritics AutoPore IV 9500. The sample sizes were 1 cm³ and the pressures ranged from 0.5 to 33,000 psi (0.003–227.436 MPa) to obtain the volume of mercury intrusion at each pressure step. Subsequently, according to the test standard of ISRM (Fredlund and Hendry 1993), the natural density, natural water content, and initial porosity of the mudstone samples were measured, as shown in Table 1.

Further, to reduce the influence of the difference between samples on the experimental results, sample number (2, 5, 7, 8, and 13) with similar basic properties of mudstone samples were selected under different pH values (3, 5, 7, 9, 11).

### Sample materials and experimental procedures

The mudstone core of the test was excavated at the construction site, wrapped in plastic wrap and a plastic box to avoid moisture loss from the rock samples. The sample was acquired from the same intact rock at a depth of 30,000 mm, and the mineral composition of the mudstone was determined by XRD analysis. The XRD measurement data acquisition range was 2–65, and the scan rate was 0.02°/2. Mudstone is primarily composed of detrital (quartz, calcite, and hematite) and clay minerals (kaolinite, chlorite, illite, and montmorillonite), and the percentage content of each component is shown in Fig. 2.

The experimental device diagram is shown in Fig. 3, which comprises a CCD camera, precision electronic balance, data acquisition instrument, computer, connecting tubes, and other instruments. The different pH solutions used in the test were purchased from Xibiao Technology Co., Ltd. The experiment was performed by executing the following procedure: (1) five groups of samples were placed in an oven at 60 °C for drying (as shown in Fig. 4a). (2) The top surface of the rock sample was coated with the spot marking paint, and again placed in an oven at 60 °C for drying to volatilise the moisture in the spot marking paint. Thereafter, small black dots were drawn on the upper surface of the white with a black oily marker pen to create speckles (as shown in Fig. 4b). (3) Subsequently, the sample was placed on a permeable stone till the display on the electronic balance was stable, and the liquid levels in the two containers levelled. The camera position was adjusted to face the sample. During the experiment, the water absorption rate of the mudstone

![Fig. 2 Mineral composition of mudstone samples](image)

| Sample number | pH  | Natural density (g/cm³) | Natural moisture content(%) | Initial porosity(%) |
|---------------|-----|-------------------------|-----------------------------|---------------------|
| 1             | 2.61| 3.21                    | 4.7649                      |
| 2             | 2.55| 3.14                    | 4.8436                      |
| 3             | 2.61| 3.42                    | 4.9542                      |
| 4             | 2.58| 3.36                    | 5.0188                      |
| 5             | 2.56| 3.17                    | 4.8221                      |
| 6             | 2.53| 2.95                    | 4.6657                      |
| 7             | 2.56| 3.18                    | 4.8325                      |
| 8             | 2.59| 3.19                    | 4.8171                      |
| 9             | 2.62| 3.16                    | 4.9039                      |
| 10            | 2.55| 3.46                    | 5.0573                      |
| 11            | 2.62| 2.95                    | 4.5708                      |
| 12            | 2.53| 2.95                    | 4.7326                      |
| 13            | 2.56| 3.16                    | 4.8537                      |
| 14            | 2.59| 2.71                    | 4.6554                      |
| 15            | 2.62| 2.95                    | 4.6705                      |
was monitored by the number change of the electronic balance. (4) At the beginning of the test, the top surface of the permeable stone was submerged in water. The contact height between the water and the specimen was controlled to be less than 1 mm. (5) The readings of the electronic scale were recorded at regular intervals (0–10 min (recorded twice per minute); 10–30 min (recorded every minute); 30–60 min (recorded every three minutes); 60–120 min (recorded every 10 min); 120–600 min (recorded every thirty minutes)), and simultaneously, pictures of the upper surface of the rock sample were acquired. Finally, the experiment was ended after the readings on the electronic scale and the crack growth degree on the upper surface of the rock sample stabilised.

The digital speckle correlation method, also referred to as the digital image correlation method, is a non-contact measurement method that records the digital image of the deformation process, and in this study the measurement target was the deformation process of the object. The measurement range was according to the small deformation, vibration, and large deformation of the object, all of which were applicable, with the characteristics of high calculation accuracy and wide measurement range (Song et al. 2011; Mi 2013; Sun et al. 2019). The basic principle of the digital speckle correlation method involves the comparison of the points in the two speckle images. If two points in the correlation window possess the same gray value, they are considered to be the ‘same point’ before and after the deformation. Thus, by comparing the moving distance and moving direction of the point, the surface deformation of the object was calculated. This study is focussed on the influence of pH on mudstone hygroscopic expansion and displacement process evolution and maximum principal strain evolution.

The influence and significance of pH on swelling cracks of mudstone

The influence of pH on the moisture absorption characteristics of mudstone

The change in the water absorption rate of the mudstone sample over time is shown in Fig. 5. It can be concluded that the water absorption of each sample increased with time, and the trend of the water absorption curve of each sample was fundamentally the same; however, the final water absorption rate was different. The time-history curve of water absorption of mudstone samples exhibited two stages: a rapid growth stage and a slow growth stage. The rapid growth phase was completed within the first 30 min, and the water absorption rate accounted for approximately 90% of the total. In contrast, the duration of the slow growth phase was longer, and the water absorption rate was smaller. The self-absorption process of mudstone is primarily affected by various suction changes, mainly capillary suction and...
interlayer suction, both of which are collectively referred to as matrix suction (Fan et al. 2020; He et al. 2008). During the early stage of water absorption, the capillary force in the dry mudstone sample was much greater than the interlayer suction, and the water absorption rate increased rapidly with an increase in time. Consequently, the capillary suction in the sample gradually decreased. However, when the capillary suction was equal to the interlayer suction, the growth rate of water absorption decreased. Thereafter, with an increase in the water content, the capillary suction and interlayer suction gradually decreased, and finally when the two values decreased to zero, the capacity of water absorption also became zero and thus, the mudstone water absorption process was complete.

It is evident from the figure that when the pH of the solution is 3, 5, 7, 9, and 11, the final water absorption rates of mudstone are 15.77, 14.58, 13.67, 12.66, and 11.71%, respectively. Therefore, the acidic environment promoted the final water absorption rate of mudstone, whereas the alkaline environment had an inhibitory effect. The main factors affecting mudstone water absorption are the size of mudstone porosity, mineral content and type, and the occurrence of clay minerals (Zhang et al. 2018a, b; Li et al. 2022). In different acidic or alkaline environments, the clay minerals of the mudstone react with different pH solutions, such as mineral dissolution, ion exchange, and particle association (Su et al. 2002). On the one hand, clay minerals have different degrees of hydration expansion-cracking in different pH solutions. The higher the degree of hydration expansion and cracking, the more aqueous solution is required. On the other hand, mudstones have different pore structure changes in different pH solutions, and the larger the pore radius, providing space for accommodating more water. Therefore, it is believed in the manuscript that different pH solutions caused different degrees of hydration and expansion of mudstone clay minerals and changes in the pore structure of mudstones. The difference between these two parts leads to a difference in the final water absorption rate of the mudstone.

**The influence of pH on the swelling crack of mudstone**

Figure 6 shows the time-varying variation in crack propagation in mudstone under different pH values. The upper part of each picture is a physical picture acquired via a camera at different times, and the lower part of the picture is a picture that binarises the camera photo at the corresponding time. The surface crack distributions of the mudstone samples at different times were extracted. It is evident from the figure that the crack expansion of mudstone in the process of self-absorption primarily occurred in the rapid growth stage of self-absorption. The expansion of the mudstone surface cracks was observed to be stable when the self-priming time was 60 min. However, owing to no restriction on the side, microcracks exist on the side simultaneously when the mudstone sample is self-absorbed. Thus, the water migration rate on the side is faster than that in the middle part, and the side microcracks become the dominant channel for water migration in the self-absorption process. First, the moisture reaches the upper surface of the sample from the side. Simultaneously, owing to the uneven distribution of clay minerals and moisture, expansion stress is generated inside the sample. Because the side surface is unconstrained, compared to other parts of the mudstone sample, it is a weak structural surface, which is prone to stress concentration. Therefore, the crack generally begins to expand from the side, which upon reaching the upper surface of the sample, results in the formation of a crack along the center of the sample. This crack is a first-order crack developed by a crack on the upper surface.

It can be observed from Fig. 6 that a single crack is mostly curved, and the development and expansion of cracks do not expand at a certain angle, which contrasts with homogeneous materials such as metals. Mudstone is an inhomogeneous body, mainly owing to the uneven content and spatial distribution of clay minerals. However, it is evident from Figs. 6 and 7 that the initiation of child cracks generally develops perpendicular to the main cracks. This is because once the main crack is formed, the deformation restriction perpendicular to the direction of the main crack is released and the corresponding strain energy are released, which causes the strain energy parallel to the development direction of the main crack to continue to accumulate, thereby continually increasing the tensile stress field. However, when the tensile strength of the mudstone is exceeded, a
Fig. 6 Diagram of the expansion of mudstone cracks over time (a pH = 3, b pH = 5, c pH = 7, d pH = 9, e pH = 11)
new sub-level crack is formed perpendicular to the direction of the main crack (Tang et al. 2012a, b; 2018).

The primary geometric parameters of the commonly used cracks are as follows: the number of cracks, average width of the cracks, maximum width of the cracks, and surface crack rate. Because there exist many cracks in this study and their development is complicated, in this experiment the surface crack rate index was employed to quantitatively analyze the evolution process of the expansion cracks (Zhou et al. 2021; Liu et al. 2021). This indicator comprehensively considers the degree of crack development, and the calculation formula is as follows:

$$S_r = \frac{\sum_{i=1}^{N} S_i}{S_0},$$

(1)

where $S_r$ is the crack rate and $S_i$ is the area of each crack. Further, assuming that there are $N$ cracks in the sample, $S_0$ is the initial area of the upper surface of the sample.

It is evident from Fig. 8 that the trend of the change curve of the mudstone crack rate with time under different pH values is similar. The initial time for cracks to appear in mudstone samples increased with an increase in pH value. Further, the graph of crack rate exhibits a change with time, which can be roughly divided into two stages: the rapid development stage and the stable stage. At pH values of 3, 5, 7, 9, and 11, the final crack rates of mudstone are 18.91, 14.14, 12.34, 11.86, and 7.11%, respectively. The above results indicate that the increase in $H^+$ concentration results in an increase in the development of moisture-absorbing cracks in mudstone, and vice-versa. Moreover, considering the binarisation diagram of the mudstone sample in an acidic environment, it is evident that there are more and denser cracks in the mudstone sample than in an alkaline environment, and the development of the crack network is more complicated. Thus, this shows that the current increase in acid rain pollution in southwestern China may aggravate the expansion of red layer mudstone cracks in this area and increase the risk of engineering disasters such as subgrade arching and slope instability.

### Analysis of the effect of pH on the evolution of swelling deformation of mudstone

#### Influence of pH on swelling of mudstone and evolution of displacement field

In the whole process of hygroscopic expansion and cracking of mudstone, the total displacement change of moisture absorption expansion deformation of mudstone at different times was obtained, as shown in Fig. 9. It is evident that the total displacement on the outside of the specimen is greater than that on the inside. However, when the total displacement changes from the outside to the inside of the diameter, an irregular decreasing form of concentric circles is observed rather than a regular decreasing form. This confirms the differences in the total displacement of mudstone on the same radius circle. With an increase in the moisture absorption and expansion time of mudstone, the total displacement of mudstone expansion gradually increased from the outside to the inside, and the moisture absorption and expansion of mudstone exhibited differential expansion. In addition, the crack network was employed to divide the entire area into several small areas, and the total displacement value of the outer area was greater than that of the internal measurement area. Moreover, because of the existence of a deformation space in the outer area, it is more conducive to the generation and expansion of cracks.

Simultaneously, under different pH values, the maximum total displacement value of mudstone swelling due
Fig. 9 Moisture absorption and expansion and displacement changes of mudstone under different pH (a pH = 3; b pH = 5; c pH = 7; d pH = 9; e pH = 11)
Fig. 9 (continued)

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to moisture absorption decreased with increasing pH value, thereby demonstrating that an acidic environment promotes moisture swelling and deformation of mudstone. Moreover, as the pH value decreased, the mudstone speckle interference fringes became more turbulent and the fluctuation amplitude increased, which indicated that under an acidic environment, the moisture absorption and expansion of the mudstone surface produced more cracks, thereby resulting in the disappearance of certain scattered spots and discontinuity of displacement on both sides of the cracks. Therefore, there were more sudden changes in the combined displacement cloud image. Further, as the pH value increased, the absolute value of the total displacement on both sides of the crack decreased. This is because of the uneven distribution of mudstone clay minerals and the uneven spatial distribution of water during mudstone self-absorption (Zhang et al. 2018a, b; Zhou et al. 2021). When clay minerals encounter acidic solutions, they produce a greater swelling force and thus, the differential expansion of mudstone is more obvious.

The influence of pH on the evolution analysis of the maximum principal strain of mudstone hygroscopic swelling

During the entire process of mudstone swelling, the maximum principal strain cloud diagrams at different moments of mudstone swelling were obtained, as shown in Fig. 10. It is evident that the maximum principal strain around the crack is larger than that of other uncracked parts, which is consistent with the mechanism by which the moisture-absorbing swelling crack of mudstone generates and expands along the maximum principal strain (maximum principal stress). Simultaneously, in the process of moisture absorption and expansion of mudstone, the maximum principal strain does not develop in a certain direction in contrast to a homogeneous material and shows irregularity. This shows that mudstone is not a homogeneous body, its clay minerals are unevenly distributed in space, and it absorbs water unevenly. Further, the crack divides the mudstone surface area into several expansion strain zones. Moreover, in contrast to homogeneous materials, there is only one expansion core, but mudstone surfaces
Fig. 10  Variation of the maximum principal strain of mudstone swelling under different pH (a pH = 3; b pH = 5; c pH = 7; d pH = 9; e pH = 11)
Fig. 10 (continued)
Discussion on the micro-mechanism of pH influence

Three micro-mechanisms of hygroscopic crack propagation in red mudstone

The crack propagation mechanism of red mudstone primarily includes hydration-swelling and softening, adsorption-wedge failure, and humidity stress field. Hydration-swelling and softening are chemical processes of hydration, expansion, and exfoliation of clay minerals. Clay minerals in red mudstone, such as hydrophilic montmorillonite, easily absorb water, resulting in the expansion of the electric double layer (Chenevert 1970; Fairhurst and Hudson 1999). The clay particles then increase in size owing to crystal expansion and osmotic expansion (Miller and Low 1990; Fukue et al. 1999). Consequently, the resulting expansion pressure reduces the attractive force between the structural connections and the bonds between the particles are broken, leading to the development of mudstone cracks.

Adsorption-wedge failure (Fig. 11) is a mechanical process involving crack initiation, propagation, and coalescence (Terzaghi and Peck 1967). Mudstone absorbs water under...
the action of matric suction. Simultaneously, cracks and pores are conducive to water absorption and are the dominant channels for water migration, resulting in increased capillary pressure and gas pressure. In addition, both pressures tend to promote crack propagation and coalescence (Liu et al. 2020). Consequently, the bond between carbonate and clay minerals is broken by the two pressures, which causes the red mudstone to crack. Thus, water enters the pores and cracks and results in the formation of a strength damage zone with the contacted matrix (Fig. 11), which causes stress concentration at the junction of the strength damage zone and the intact bedrock. Subsequently, under the interaction of capillary pressure and gas pressure, the stress concentration area promotes the generation and propagation of cracks.

The theory of the humidity stress field was proposed by Professor Miao Xiexing (1993, 1995), who highlighted that the diffusion of water in a swelling rock mass is coupled with water content, water absorption, volume deformation, etc. The red-bed mudstone in central Sichuan is a heterogeneous body composed of different minerals. Thus, the expansion coefficients of various minerals are different under the influence of the humidity field, such that the deformation of various mineral particles is different after mudstone encounters water. Various mineral particles in the mudstone cannot freely deform according to their inherent expansion coefficient with the change in humidity. Therefore, there exist mutual constraints among clay mineral particles, and those with large deformations are compressed, while those with small deformations are stretched. Consequently, a type of humidity structural stress was formed in the mudstone. Moreover, maximum stress often occurs at the junction of the mineral particles, which upon reaching or exceeding the tensile strength of mudstone, results in the connection between the mineral particles being broken, thereby resulting in cracks (Ji 2009; Xu 2018).

When mudstone is self-absorbed, hydration expansion and softening reduce the strength of the mudstone itself, thereby rendering it easier for adsorption-wedge pressure and humidity stress to break the bond between mudstone particles and form cracks. Consequently, the appearance of cracks provides an advantageous channel for the migration of water and enhances the adsorption-wedge failure of mudstone and the humidity stress field effect. Moreover, in the process of mudstone self-absorption, the three mechanisms complement each other and work together to accelerate the crack of the connection between mudstone particles, as well as the generation, expansion, and penetration of cracks.

**Four influences of pH value on the propagation of mudstone cracks**

The influence of acidic and alkaline solutions on the crack expansion of red-bed mudstone primarily includes the following four aspects: mineral dissolution, ion absorption and exchange, particle association, and pore changes. The dissolution of minerals affects the chemical decomposition process of the red-bed mudstone in central Sichuan, which mainly manifests as dissolution and erosion. The dissolution equation of mudstone clay minerals in an acid–base environment is shown in Table 2. As shown in Table 2, clay minerals are more soluble in acidic environments, illite and montmorillonite are dissolved and transformed into kaolinite in an acidic environment, and mudstone contains kaolinite. Therefore, in acidic environments, the kaolinite content in mudstone is significantly greater than that in neutral and alkaline environments. Further, kaolinite exhibits high hygroscopicity, thereby promoting hydration swelling and softening (Yong et al. 1979; Cuadros et al. 2015; Su et al. 2020), which causes the final water absorption rate of mudstone in acidic environments to be higher than that in neutral and alkaline environments. In addition, H⁺ dissolves haematite and breaks the carbonate cementation in calcite (Zhang et al. 2018a, b), which promotes the generation, expansion, and penetration of cracks in acidic environments.

Ion exchange is an exchange process between ions and molecules adsorbed to mineral particles via physical and chemical forces and water (Kozaki et al. 2005). Owing to the large specific surface area of clay minerals, a large amount of colloidal substances are adsorbed on the surface (Ma 2016), and ion exchange with ions in water is easier. Further, when mudstone is self-absorbed in an acidic solution, H⁺ can be replaced by cations such as K⁺, Al³⁺, Ca²⁺, and Mg²⁺, which may cause the crystal lattice to separate from the water phase, which results in the dissolution of montmorillonite (Townsend 1984). In addition, in the acidic environment of mudstone, bond breaks are usually formed on the edges or non-cleavage surfaces of clay mineral particles in contact with water after the minerals are dissolved, and bond breaks increase with a decrease in clay minerals. As both sides of the broken bond are charged positively and negatively, this
effect promotes the ion exchange capacity. Consequently, the ion exchange adsorption results in the transformation of minerals in the mudstone self-absorption process, and thus the cementation between particles is destroyed, thereby promoting the formation of mudstone cracks.

The association of particles affects the chemical decomposition of clay minerals in the mudstone of the central Sichuan red layer when it comes in contact with water, thereby affecting the generation, expansion, and penetration of moisture-absorbing cracks in the mudstone. Figure 12 shows the formation of macroscopic cracks and the microscopic association pattern of clay particles in red layer mudstones at different pH. The combination of the two particles reflects the dominant interparticle force. There exist three common types of minimum energy particle flocculation: edge-to-face, edge-to-edge, and face-to-face (Olphen et al. 2010; Yuan et al. 2019a, b).

Combined with Table 3, it is evident that when pH = 3, the mudstone pore size-pore volume distribution curve has a peak when the pore size is 17.11 nm. Moreover, micropores and transitional pores contributed more to the total pore volume, with the values being 0.0942 and 0.1620 mL·g⁻¹, respectively, at a contribution rate of 46.29%. Simultaneously, the specific surface area curve of mudstone has a single peak at a pore size of 6.48 nm, where the micropores and transition pores contributed the most to the total surface area, with specific surface area values of 19.9116 and 11.6297 m²·g⁻¹, respectively, at a contribution rate of 99.7%. Further, when pH = 7, the mudstone pore size-pore volume distribution curve has a peak when the pore size is 17.11 nm. Moreover, micropores and transitional pores contributed more to the total pore volume, with the values being 0.0942 and 0.1620 mL·g⁻¹, respectively, at a contribution rate of 46.29%. 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Fig. 12  Clay particle association form under different pH conditions (red circle): a particle dissolution (modified from Su et al. 2020), b edge-to-edge flocculation, c edge-to-face flocculation, d face-to-face flocculation

Fig. 13  Mudstone pore size-pore volume distribution under the condition of pH = 3

Fig. 14  Mudstone pore size-area distribution under the condition of pH = 3
Furthermore, when pH = 11, the mudstone pore size-pore volume distribution curve has a peak when the pore size is 17.11 nm. Herein, the micropores and transitional pores contributed more to the total pore volume, with values of 0.1163 and 0.2222 mL·g⁻¹, and the contribution rate reached 61.88%. Simultaneously, the specific surface area curve of mudstone has a single peak at 6.03 nm pore size, with the micropores and transition pores contributing the most to the total surface area, with values of 20.9757 and 12.6972 m²·g⁻¹, respectively, at a contribution rate of 99.71%. Thus, the analysis showed that with a decrease in the pH value, the pore volume and the proportion of the pore volume of the micropores and transition pores in the mudstone gradually increased, which indicates that the acidic environment promotes the transformation of mudstone micropores and transitional pores into mesopores and macropores. Therefore, an acidic environment is conducive to the generation, expansion, and penetration of mudstone water and moisture absorption cracks.

Thus, the four processes of mineral dissolution, ion absorption and exchange, particle association, and pore change synergistically affect the chemical and physical decomposition of the red mudstone in central Sichuan through hydration, expansion, dissolution, expansion, and exfoliation. This results in three distinct mechanisms in different pH solutions having different effects. Therefore, the final moisture absorption rate and final crack rate of mudstone at different pH values are quite different.

### Conclusion

Through the self-absorption experimental device designed for the study, real-time monitoring of mudstone water absorption and crack rate under different pH values...
was realised. Thereafter, the digital speckle correlation method was used to analyse the evolution of water absorption deformation of mudstone in different pH solutions. Further, by combining scanning electron microscopy and mercury intrusion porosimetry, we analysed the microscopic changes of mudstone under different pH solutions. Thus, this experiment studied the moisture absorption and cracking characteristics of red mudstone in different pH solutions and their micro-mechanisms, and the main conclusions drawn are as follows:

(1) The acidic environment was found to promote the self-absorption of red-bed mudstone, whereas an alkaline environment inhibited it. When the pH value of the solution was 3, the final water absorption rate of the red-bed mudstone was the highest (15.77%), whereas it was lowest at the solution pH value of 11 (11.71%).

(2) Red layer mudstone experiences moisture-absorbing swelling cracks in different pH solutions, and the rate of crack development is mainly concentrated in the rapid water absorption stage. As the pH increased, the final crack rate of the red mudstone decreased. For the solution pH value of 3, the final crack rate of the red mudstone was the highest (18.91%), whereas it was lowest when the solution pH was 11 (7.11%).

(3) In an acidic environment, the color of the total displacement cloud map is close to a concentric circle; in the alkaline environment, the color of the total displacement cloud map has a specific directionality. The maximum combined displacement and maximum principal strain of mudstone in an acidic environment were larger than those in an alkaline environment. Moreover, with a decrease in the pH value, the speckle interference fringe cloud image of the swelling of mudstone became more turbulent and fluctuated. Simultaneously, the failure characteristics of the mudstone exhibited increased swelling strain areas and swelling cores.

(4) The moisture-absorbing swelling cracks of red layer mudstone were explained via three microscopic mechanisms: hydration-swelling and softening, adsorption-wedge failure, and humidity stress field. Further, solutions with different pH values were found to affect these three microscopic mechanisms through four physical/chemical processes: mineral dissolution, ion absorption and exchange, particle association, and pore changes.

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**Data availability** The experimental data used in our research may be available from the corresponding author by request.

**Declarations**

**Conflict of interest** The authors declare that they have no competing interests.

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