Research Article
Cut-Through Fractured Seepage Properties and Numerical Simulation of Sandstone after Different Temperature Treatments

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To explore the seepage characteristics of cut-through fractured rocks after different temperatures, sandstone in the Hunan area was selected as the research object. First, the influence degree of different temperatures on the permeability of fractured sandstone was studied, and the permeability variation of fractured sandstone with net confining pressure was revealed. The test data was nonlinearly fitted to prove that the relationship between permeability and net confining pressure conforms to the characteristics of the negative exponential function. Second, the macroscopic fractured state of sandstone after different temperature treatments was analyzed, and it is concluded that the inclination angle of the fracture surface decreases with the applied thermal temperature, the fracture surface gradually develops into a single shear failure surface, and the damage degree becomes more and more serious. Finally, the theoretical formula for the calculation of fractured seepage was introduced, and the FLAC3D embedded fish language was used to compile the seepage-stress coupling calculation program of the fractured sandstone after different temperature treatments. Numerical calculations were carried out based on samples with different fracture angles of fractured sandstone, and the calculated values were in good agreement with the test results. The research results can provide guiding significance for the research on the influence of high temperature in fire tunnel on the evolution of permeability of surrounding rock fissures.

1. Introduction

With the continuous construction of tunnels and deep mine projects, the subsequent emergence of deep rock mechanics has gradually become the research focus of many researchers, and the permeability characteristics of rocks under different working conditions have also become an important research topic [1–7]. For example, when a fire occurs in a tunnel, the surrounding broken rock mass will be affected by a high-temperature environment and the permeability will be changed [8–15]. Therefore, it is of great significance to carry out experiments on the seepage characteristics of fractured rocks after different temperature treatments and to study the changes in seepage characteristics of fractured rocks as the treatment temperature increases.

In recent years, many researchers have conducted in-depth research on rock permeability. At the same time, the law of rock permeability changes under the coupling action of rock osmotic pressure, and stress has also been further explored. Li et al. [16] took fractured sandstone as the research object and studied the relationship between confining pressure, pore water pressure, and permeability. Xu and Yang [17] tested the permeability of sandstone after compression in different time periods and analyzed the influence of confining pressure and seepage pressure on the strength and failure characteristics of sandstone. Feng et al. [18] employed a high-temperature and high-pressure rock mechanic testing machine to measure the permeability of granite under hydrostatic pressures of 25 MPa and 75 MPa. Shu et al. [19] used a single large-size granite crack (φ50 × 300 mm) to evaluate the evolution of hydraulic characteristics of the crack during long-term high-temperature flow. Morrow et al. [20] conducted experimental studies on the permeability of intact granite and a single fracture in granite at 150°C. The results show that the permeability of fractures gradually decreases with the increase of flow time.
Zoback and Byerlee [21] studied the influence of microfractures on permeability and found that the permeability of sandstone will slowly decrease after high-temperature exposure. He et al. [22] conducted a series of hydraulic tests for different inlet hydraulic pressures and increasing the confining pressure from 10 MPa to 30 MPa, and the change of the equivalent permeability of granite with temperature and confining pressure is analyzed. Yin et al. [23] studied the permeability changes of granite filled with fractures under high temperature and high pressure. Li et al. [24] studied the relationship between the seepage flow rate of rock fractures and temperature, and the results showed that the rock fracture opening and seepage flow rate gradually increased with the thermal temperature. Zhang et al. [25] found that the permeability of granite after losing its bearing capacity showed an exponential upward trend as the confining pressure decreased. Chen et al. [26] found that after heat treatment, the permeability of the rock sample under the triaxial loading process first decreases in the microcrack closure area, while it is almost constant in the elastic area, and then increases sharply in the crack propagation area.

In summary of the relevant literature, it is found that the permeability characteristics of rocks under different working conditions have become an important research topic. Most of the above studies have carried out rock permeability tests under stress-seepage coupling conditions and can better reflect the changing laws of permeability. However, there are few introductions to the permeability test of broken sandstone after high temperature. For engineering, such as geothermal mining and in the event of a fire in the tunnel, it will cause high-temperature environmental effects on the surrounding broken rock mass, causing its permeability to change. Thus, it is of great significance to carry out experiments on the seepage characteristics of fractured rocks after different temperature treatments and to study the changes in seepage characteristics of fractured rocks as the treatment temperature increases. The innovation of this paper is to study the permeability characteristics of fractured sandstone after different temperatures and use the FLAC3D self-editing calculation program of fractured rock permeability to analyze the influence of different temperature effects and seepage pressure on the permeability of fractured sandstone. The purpose of this research is to study the permeability characteristics of fractured sandstone after different temperature treatments, in order to study the influence of different temperature effects on the seepage characteristics of fractured rocks. The test results can provide a certain reference basis for the stability of the tunnel surrounding rock in the event of a fire and geothermal mining.

2. Materials and Methods

2.1. Description of Quartz Sandstone Samples. The sandstone used in this test is tight and the permeability and porosity of the original sandstone without temperature treatment and no fractures is \(12 \times 10^{-18} \text{ m}^2 \) and 5.6%, respectively. The sandstone specimens used in this experiment are taken from the sedimentary rock strata of the Guanyinyan Tunnel Project in Changsha, Hunan, and the overall rock was gray. Its geological period is between the Mesozoic and Cenozoic. Under the test procedures of the International Society for Rock Mechanics (ISRM), the same rock block was drilled, cored, and ground to obtain a standard cylindrical specimen with a size of \(50 \text{ mm} \times 100 \text{ mm}\) required for this test, and the end face flatness was \(\pm 0.02 \text{ mm}\). Remove the specimens that are macroscopically damaged or cracked and contain obvious cracks, as shown in Figure 1.

2.2. Test Instruments. The heating test of the specimen was carried out on the SX2-8-10 type high-temperature resistance furnace produced by Yantai Kaituo Technology Co., Ltd. The maximum power is 2.5 kW, the maximum working temperature is 1200°C, the long-term working temperature is 1000°C, and the temperature control accuracy is \(\pm 0.1^\circ \text{C}\).

The sandstone triaxial compression test and the sample fracture penetration test were carried out on the RLW-2000 multifield coupled rock triaxial instrument jointly developed by Dalian Maritime University and Changchun Chaoyang Testing Machine Factory. The maximum axial load of the equipment was 2000 kN. The measurement and control accuracy was controlled within 0.01%. The confining pressure can reach 80 MPa, and the osmotic pressure can reach 60 MPa. The maximum temperature was controlled by a microcomputer at 200°C, and the control accuracy was 2%. The heating equipment and seepage system are shown in Figures 2(a) and 2(b).

2.3. Test Principle. To study the change law of the permeability characteristics of fractured sandstone after different temperature treatments, it is assumed that the sample is a uniform continuum material, and the permeability characteristics are following Darcy’s law [27–29]. The expression used to test the permeability of the specimen is as follows.

\[
K = \frac{\mu L \Delta Q}{A \Delta P \Delta t},
\]

where \(K\) is the permeability of the sandstone sample in \(\Delta t\) time (m²), \(\mu\) is the fluid (water) viscosity coefficient, taken \(\mu = 1 \times 10^{-3}\text{Pa} \cdot \text{s}\) (water temperature 20°C), and \(\Delta Q\) is the volume of water flowing through the sandstone sample within \(\Delta t\) (m³). \(L\) is the seepage length of the water flow, that is, the height of the specimen in the test is 0.1 m. \(A\) is the cross-sectional area of the sample (m²). \(\Delta P\) is the osmotic pressure difference between the upper and lower ends of the sandstone sample (Pa). \(\Delta t\) is the time between recording points (s). The schematic diagram of the seepage test for fractured sandstone is shown in Figure 3.

2.4. Testing Procedures. Since this paper is to study the percolation characteristics of fractured sandstone after the action of different temperatures, different temperature treatments are chosen to be able to analyze the effects caused by different temperatures on the permeability of fractured sandstone. Meanwhile, the background of this paper is based on the fact that when a fire occurs in a tunnel, the high temperature changes the permeability characteristics of the surrounding fractured rock mass. Fires in tunnels are often caused by human-induced traffic accidents. And according to the
Figure 1: Sandstone specimens.

Figure 2: Test instruments. (a) High-temperature resistance box. (b) Multifunctional RLW-2000 rock triaxial instrument and seepage device.
research of Zhu et al. [10] and Martin and Michael [30], it is found that if a small car has an accident and a fire occurs, the maximum temperature can reach about 700°C. Meanwhile, in order to be able to distinguish the seepage pressure gradient and not exceed the confining pressure value, thus, the pore water pressure value of 1-4 MPa is selected for this test. This article refers to the relevant literature in which the in situ stress of the tunnel surrounding rock is about 2 MPa [31], so the axial pressure in the test is set to 2 MPa. Meanwhile, the main reason for maintaining the axial pressure of 2 MPa and not loading in this experiment is to test the relationship between the permeability characteristics of the specimens with cracks and the confining pressure. Thus, the sandstone specimens were heat treated at 200, 300, 400, 500, 600, and 700°C. Due to the discrete nature of the specimens, 3 specimens were selected for each group, and another group was selected without any heat treatments (normal temperature 20°C) as the control group, a total of 21 samples in 7 groups. After all the test pieces are heat treated, they are naturally cooled to room temperature 20°C. Then seal it with a heat-shrinkable tube and put the sample into the triaxial pressure chamber at one time. The permeable gasket was placed between the sample and the indenter to make the water evenly permeate the sample. During the triaxial compression test, the confining pressure value was fixed at 5 MPa, and one representative specimen was selected for each group, a total of 7 specimens were numbered by 20-5-1, 200-5-1, 300-5-1, 400-5-1, 500-5-1, 600-5-1, and 700-5-1, respectively. Taking 200-5-1 as an example, it means that the sandstone is subjected to a triaxial compression test at a confining pressure of 5 MPa after heating at 200°C.

(1) Triaxial compression test under fixed confining pressure
First, a triaxial compression test of sandstone under a fixed confining pressure of 5 MPa was carried out. During the test, the confining pressure \( \sigma_3 \) to 5 MPa was first loaded, the confining pressure loading was controlled by pressure, and the loading rate was 20 N/s. Later, the axial pressure \( \sigma_1 \) was loaded by displacement control, and the displacement load rate was 0.1 mm/min. Unload at the moment when the postpeak stage occurs and the strain increases and the strength decreases in a cliff-like manner.

(2) Fracture seepage test program
After the triaxial compression test was over, the sample will not be taken out temporarily, and the fracture seepage test will be carried out on the cut-through fractured sandstone sample in the triaxial pressure chamber. The upper end of the test piece is the water inlet, and the lower end is the water outlet (Figure 3). Later, the fracture seepage test under different water pressure conditions was carried out, the axial pressure was fixed at 2 MPa, the confining pressure was fixed at 5 MPa, and the water pressure was loaded step by step according to the test plan in Table 1. After loading according to the seepage water pressure gradient, the ruptured specimen was taken out for macroscopic damage observation and photographed to simulate the rupture mode.

After the heating is completed, both the 6 groups of samples and the control group samples repeat the above process (1) and (2). The control parameters and schemes of the cut-through fracture sandstone seepage test after different temperature treatments are shown in Table 1.

3. Experimental Results and Analysis

3.1. Stress-Strain Curve. The stress-strain curve of sandstone after different temperature treatments is shown in Figure 4. Among them, A-20-5 MPa represents the axial strain curve when the confining pressure is 5 MPa after 20°C treatment, and L-20-5 represents the radial strain curve when the confining pressure is 5 MPa after 20°C treatment. It can be seen from Figure 4 that the higher the applied temperature, the lower the peak intensity of the specimen.

3.2. Peak Strength of Sandstone. After different temperature treatments (20, 200, 300, 400, 500, 600, and 700°C), the average peak strength of sandstone under a fixed confining pressure of 5 MPa is 102.70, 90.95, 85.20, 72.17, 69.32, 66.8, and 60.89 MPa, respectively, as shown in Figure 5. According to Figure 5, it can be seen that the peak intensity of sandstone gradually decreases with the increase of temperature. The data in Figure 5 is fitted to get the correlation between peak intensity and temperature as

\[
\sigma_1 = -0.0637T + 102.659. \tag{2}
\]

3.3. Influence of Temperature on the Permeability of Fractured Sandstone. The permeability of fractured sandstone varies with seepage pressure after different temperature treatments, as shown in Figure 6. The permeability of the specimen (200-5-1) after the action of 200°C is 25.12° × 10^{-10}, 27.19° × 10^{-10}, 32.69° × 10^{-10}, 45.75° × 10^{-10}, 59.21° × 10^{-10}, 81.
26° × 10⁻¹⁸, and 109.89° × 10⁻¹⁸ m² at a pore water pressure of 1 MPa, 1.5 MPa, 2 MPa, 2.5 MPa, 3 MPa, and 4 MPa, respectively. It can be seen that the permeability of the specimen increases with the pore water pressure after a fixed temperature treatment.

At the same time, it is obtained from Figure 6 that when the same pore water pressure and confining pressure are applied, the permeability of the specimen increases with the applied temperature. It shows that the temperature will further enlarge the microcracks or pores in the rock sample, reduce the friction and cohesive force between the rock particles, and increase the cross-section of the seepage channel, which promotes the seepage of water and leads to an increase in permeability. This is due to the effect of the heat treatment process on the pore changes in the rock. And high temperature has a damaging effect on the crystal structure in the sandstone, and the sandstone composition undergoes a temperature response with the change of temperature. The thermal reaction caused by high temperature and the thermal expansion effect of minerals are the two main factors affecting the change of sandstone composition. On the one hand, during the gradual increase of temperature, the clay dehydroxylation in sandstone will form new minerals that are coarser and sparser than the original minerals [7], leading to the increase of the number of pores and the increase of pore space in the rock. On the other hand, when the core is heated, the minerals expand to different degrees, and their structure is disrupted, which leads to the expansion of the pores inside the rock or the formation of new pores to form a connected network, thus, changing the pore structure of the rock.

Meanwhile, in terms of micropore structure, the existence of pore water in sandstone seriously affects the permeability. With the increase of temperature, the water between the rock particles is evaporated, which will expand the fluid channel and facilitate the fluid flow. The content of clay minerals in tight sandstone is high, and it will form new minerals with the increase of temperature, which will increase the pore space and permeability. High temperature can destroy and change the original stable mineral structure in tight sandstone, such as the transformation from low-temperature...
quartz (α-quartz) to high-temperature quartz (β-quartz) [7, 32], which will further also increase the permeability. As for the thermal stress of rock, it will gradually increase with the temperature. When it increases to a certain critical value, the original stress state of the rock will be destroyed, and a new stress state will be formed, which will lead to the stress concentration of the rock, and the rock will have a strong thermal fracture. The width and density of microcracks increased sharply and eventually formed a network of interpenetrating fractures, which greatly increased the permeability.

3.4. The Influence of Net Confining Pressure on the Permeability of Fractured Sandstone. The permeability changes of fractured sandstone under different net confining pressures (the difference between confining pressure and pore water pressure) are shown in Figure 7. When the confining pressure is fixed at 5 MPa, the net confining pressure is 4, 3.5, 3, 2.5, 2, 1.5, and 1 MPa, corresponding to the pore water pressure of 1, 1.5, 2, 2.5, 3, 3.5, and 4 MPa, respectively. It can be seen from Figure 7 that when the net confining pressure is 4 MPa, the permeability of 20-5-1, 200-5-1, 300-5-1, 400-5-1, 600-5-1, and 700-5-1 is $20.08 \times 10^{-18}$, $25.12 \times 10^{-18}$, $31.08 \times 10^{-18}$, $36.49 \times 10^{-18}$, $1.21 \times 10^{-18}$, $43.85 \times 10^{-18}$, and $49.92 \times 10^{-18}$, respectively. After different temperature treatments, the permeability of fractured sandstone decreases exponentially with the increase of net confining pressure, and the permeability is related to the fracture mode of the fracture.

Therefore, in order to more specifically describe the effect of net confining pressure on the permeability of fractured sandstone after different temperature treatments. This paper assumes that the permeability fitting formula is shown in equation (3), and the test data is fitted to obtain the parameters $a$ and $b$, as shown in Table 2. The $R^2$ is the correlation coefficient of curve fitting, and $K$ is the permeability of fractured sandstone after different temperature treatments and different net confining pressure conditions. Among them, the correlation coefficient with curve fitting ($R^2 > 0.95$) indicates that the fitting equation can better represent the relationship between net confining pressure and permeability after different temperature treatments, and it can prove that its negative exponential function is reasonable.

$$K = a \exp \left[ -b \times \sigma_{net} \right],$$  \hspace{1cm} (3)

$$\sigma_{net} = \sigma_3 - \rho_{pw},$$  \hspace{1cm} (4)

where $\sigma_{net}$ is net confining pressure (Pa), $\sigma_3$ is confining pressure (Pa), $\rho_{pw}$ is pore water pressure (Pa), $a$ and $b$ are the fitting parameters, respectively.

3.5. Macroscopic Destruction. The macroscopic failure state and crack sketches of sandstone samples after different temperature treatments are shown in Figure 8. The sandstone sample without any heat treatment under a fixed confining pressure of 5 MPa has a vertical splitting failure that is basically parallel to the axial direction and caused by fracturing. This is because the temperature does not affect the internal structure of the sandstone. The fracture of the sample is a vertical “1” fracture along the fracture surface, and the fracture width is relatively narrow. With the increase of operating temperature and the accumulation of thermal stress, new cracks evolve at the same time, and finally, the cracks at the top and bottom of the sample are connected. The failure mode gradually changed from vertical splitting to shear failure with different crack angles, and the crack width gradually increased.

Due to the discreteness of rock specimens, the crack angle (the acute angle between the fracture surface and upper
surface of the specimen) of sandstone after room temperature treatment (20-5-1) can be approximately regarded as an angle of 90° (Figure 8(a)). With the increase of the applied temperature, the position of the fissure changes continuously when the specimen is broken. The surface of the sandstone specimen appeared to fall off of large mineral particles after 700°C treatment, which indicates that the high temperature has further enlarged the pores or cracks in the specimen, and the friction and bonding force between the rock particles are reduced. The crack angle gradually decreases with the increase of temperature, and the fracture surface gradually develops into a single shear failure surface, and the degree of crack angle becomes more and more serious (Figure 8(b)). Since the crack angle is the angle between the fracture surface and the upper surface of the sample. Therefore, the relationship between the crack angle ($\alpha$) and the internal friction angle ($\psi$) is

$$\alpha = 45° + \frac{\psi}{2}. \quad (5)$$

The internal friction angle will gradually decrease with the increase of temperature [33], so the crack angle will also decrease. Therefore, the fracture modes of sandstone after different temperature treatments appear as shown in Figure 8A(b). And according to formula (5), the relationship between the crack angle of the fractured sandstone and the operating temperature can be obtained, as shown in Figure 9. It can be found that the rupture angle has a negative relationship with the temperature, and the crack angle will also decrease. Therefore, the fracture modes of sandstone after different temperature treatments is simulated by the numerical method. According to Figure 8(b), it can be seen that the angle of shear strain rate shifts with the increase of operating temperature, and similar to the law in Figure 8(a). The failure angle gradually decreases, similar to the relationship in Figure 9. By comparing with the macroscopic failure mode in Figures 8 and 9, it can be found that the simulated failure results are closer to the actual results, indicating that the analysis of the failure mode with temperature in this paper is accurate.

4. Numerical Simulation Analysis and Discussions

In order to further reveal the seepage mechanism of sandstone fractures after different temperature treatments, a numerical model with different fracture angles was established to simulate and analyze the seepage mechanism according to the macroscopic failure of sandstone.

4.1. Overall Control Equation of Rock Seepage. The mathematical model of the three-dimensional rock mass seepage field in the seepage area is

$$\begin{align*}
\frac{\partial}{\partial x} \left( K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial H}{\partial z} \right) &= 0, \\
(x, y, z) &\in \Omega_1, \\
H(x, y, z) &= H_1(x, y, z)(x, y, z) \in \Gamma_1, \\
q(x, y, z) &= q_2(x, y, z)(x, y, z) \in \Gamma_2,
\end{align*} \quad (6)$$

where $\Omega_1$ is the seepage area of the fracture network, $H(x, y, z)$ is the head distribution function under the first type of boundary $\Gamma_1$, $q(x, y, z)$ is the flow function under the second type boundary $\Gamma_2$, $K_x$, $K_y$, and $K_z$ are the permeability coefficients in the main direction of permeability, which are determined by the crack width after different temperature treatments. $\Gamma_1$ and $\Gamma_2$ are the head distribution and flow distribution boundaries, respectively.

The three-dimensional stress field model of fractured rock mass after different temperature treatments is

$$\begin{align*}
\sigma_{ij} + f_i &= 0(x, y, z) \in \Omega, \\
e_{ij} &= 0.5 \times (u_{ij} + u_{ji})(x, y, z) \in \Omega, \\
\sigma_{ij} &= \lambda e_i \delta_{ij} + 2G e_{ij}(x, y, z) \in \Omega; \ i, j = 1, 2, 3, \\
\sigma_{ij} n_j &= t_i(H)(x, y, z) \in S_\alpha, \\
u_i &= \bar{u}_i(x, y, z) \in S_\alpha,
\end{align*} \quad (7)$$

### Table 2: Fitting parameters and $R^2$.

| Specimen numbers | a     | b     | $R^2$ |
|------------------|-------|-------|-------|
| 20-5-1           | 192.33| 0.62  | 0.99  |
| 200-5-1          | 190.78| 0.57  | 0.99  |
| 300-5-1          | 176.41| 0.47  | 0.99  |
| 400-5-1          | 184.79| 0.45  | 0.99  |
| 500-5-1          | 183.98| 0.42  | 0.98  |
| 600-5-1          | 209.83| 0.45  | 0.97  |
| 700-5-1          | 205.82| 0.41  | 0.97  |
where $\Omega$ is the entire rock mass area (including cracks), $\sigma_{ij}$ is the stress field tensor, $f_i$ is the body force, $\epsilon_{ij}$ is the strain field tensor, $u_{ij}$ and $u_{ji}$ are the displacement gradient, $\epsilon_v$ is the volumetric strain, $\lambda$ and $G$ are Lame constants. $n_i$ is the normal cosine of the boundary, and $t_i(H)$ is the known surface force acting on the boundary. $u_i$ is the known displacement on the boundary. $S_b$ is the known stress boundary, and $S_u$ is the known displacement boundary.

4.2. Calculation Formula for Seepage Flow in Cut-Through Fractured Sandstone. According to the assumption of a smooth parallel plate [31, 36], the relationship between the seepage flow rate and the average gap width of the sample containing cracks is

$$Q = kW = \frac{g\bar{c}^2}{12\mu}JW = \frac{gR\bar{c}^3\Delta H}{6\mu\Delta L}, \quad (8)$$

where $W$ is the cross-sectional area of the water (m$^2$), $J$ is the hydraulic gradient (dimensionless), $g$ is the acceleration of gravity ($g = 9.8$ m/s$^2$), $R$ is the radius of the sample section (m), $\bar{c}$ is the average gap width (m), $\mu$ is the dynamic viscosity of water (m$^2$/s), $\Delta L$ is the length of the seepage path (m), and $\Delta H$ is the length of the indenter at both ends of the sample (m).
The condition of this test is that the confining pressure of hydrostatic pressure is applied and the shear effect is ignored. The elastic constitutive relation of the crack increment of the broken specimen is

\[ d\sigma_n = \frac{\lambda + 2G}{V_m - u_n} du_n, \tag{9} \]

where \( \sigma_n \) is the normal stress, \( u_n \) is the normally closed deformation calculated by seepage, and \( V_m \) is the maximum closed deformation of the fracture.

According to formula (9), the normal closing deformation has a negative exponential relationship with normal stress, and we get

\[ u_n = V_m \left(1 - e^{-\sigma_n/\lambda + 2G}\right). \tag{10} \]

### 4.3. The Effect of High Temperature on the Width of Fractured Cracks

Cut-through cracks are affected by different temperatures; macroscopically, it is mainly manifested in the expansion of the surface structure of the cracks caused by temperature, thereby changing the equivalent gap width of the cracks. At the same time, the change of the fracture permeability coefficient is mainly due to the change \( \dot{\epsilon} \) of the fracture structure surface. Therefore, this paper takes into account the difference of crack opening, and in order to more intuitively compare the degree of influence of different temperatures on the width of through cracks, the average gap width change rate \( \rho \) is used to describe. The expression is as follows:

\[ \rho = \frac{\dot{\epsilon} - \dot{\epsilon}_0}{\dot{\epsilon}_0} \times 100\%. \tag{11} \]

According to the test results and formulas (8) and (11), the initial crack width \( \dot{\epsilon}_0 \) and the crack width \( \dot{\epsilon} \) after different temperatures are sorted out, and the difference between the temperature \( T \) and the change rate of equivalent gap width \( \rho \) under a fixed confining pressure of 5 MPa is obtained by the fitting curve. The fitting result is shown in Figure 10. And \( R^2 = 0.99 \), indicating a good degree of fit.

### 4.4. Calculation Method and Verification of Fracture Seepage

Based on the Flac3D platform [37, 38], a calculation example of the seepage-stress coupling of rock fractures was verified and compared with the test results. Numerical models of different fracture angles are established according to the macroscopic failure mode of the sample. The fracture and rock mass are set as permeable and impervious elastic solid elements, respectively. Since Flac3D does not provide a constitutive model of fractured seepage flow, the fish language, and time-step control method are used in this paper to compile the seepage stress coupling program and time-step iterative control to complete the numerical calculation process.

The numerical calculation process is to first close the seepage module, perform mechanical calculation iterations on the model, and calculate the deformation \( u_n \) and the crack width of the fracture element under stress according to equations (9) and (10). And then, the average gap width is calculated according to the lowest point, the middle point, and the highest point, and the permeability is calculated according to formula (8). Next, close the mechanic module and open the seepage module to simulate the flow of water along the fracture and the distribution of pore water pressure. Finally, repeat the simulation calculation of the seepage field and mechanical field until the model seepage flow stabilizes and stops.

### 4.5. Analysis and Discussions of Seepage Mechanism in Fractures

The crack width is relatively narrow in failure mode simulation (Figure 8(b)). This is because the original rock is in close agreement after failure, so a layer of grid is
Figure 11: Continued.
used to simulate the form of the crack. In the simulation calculation of seepage, the hydraulic opening is not simulated according to the grid size but according to the actual crack width. At this time, the crack width is calculated inversely from the experiment which is $\varepsilon$ in equation (11). Through the comparison of Figures 8(a), 8(b), and 9, it can be seen that the failure mode conforms to the rules, so this paper can fabricate the cracks in advance to carry out the simulation calculation of stress-seepage coupling after different temperature treatments. The process of establishing the numerical model is to first use the ANSYS 15.0 software to construct a cylindrical numerical model of the fractured sandstone after different temperatures according to the fracture mode in Figure 8. After that, the ANSYS numerical model is converted to the FLAC3D numerical model by model conversion, and finally, the fracture seepage simulation and calculation are carried out in FLAC3D. Among them, the size of the numerical model is the same as the size of the actual standard cylindrical specimen, both of which are 100 mm high and 50 mm in diameter. Formulas (6) and (7) in this paper express the constitutive relationship of the fracture model. Among them, formula (6) is the mathematical model of the three-dimensional rock mass seepage field in the seepage area, and formula (7) is the three-dimensional stress field model of the fractured rock mass under the influence of the seepage field. Equation (8) represents the relationship between permeability and fracture width under stress-seepage coupling after different temperature treatments. Meanwhile, perforated fissures are affected by temperature, which is mainly manifested macroscopically that rock particles will expand with increasing temperature and the internal stress will further increase, thereby changing the equivalent gap width of the fissures. Numerical simulations are carried out according to the test conditions, and the elastic modulus $E$ and Poisson’s ratio $\nu$ of sandstone after different temperature treatments can be obtained under the stress-strain curve. The calculation parameters are used as follows: The elastic modulus $E$ of the rock mass after different temperature treatments (20–700°C) is 36.73 GPa, 29.09 GPa, 23.91 GPa, 17.65 GPa, 16.34 GPa, 14.22 GPa, and 12.67 GPa, respectively. The initial elastic modulus of the crack is $E_2 = 25$ MPa, and the crack position and angle are determined by equation (5), Figures 8(b) and 9, respectively.

Figure 11 shows the pore water pressure distribution and the horizontal displacement cloud diagram of the fractured sandstone under the conditions of 5 MPa confining pressure and 1 MPa seepage pressure after different temperature treatments (20–700°C). It can be seen from Figure 11 that the fracture water pressure presents an inverted triangle or inverted T-shaped distribution, and the simulated fracture water pressure conforms to the law of conventional analysis. The crack deformation is basically in the vertical direction, and the upper part of the crack width is slightly wider than the lower part, which is caused by uneven seepage stress.

According to Figure 11, the horizontal displacement of the crack gradually increases from top to bottom. This is because the damage degree of the specimen gradually increases with the stress from top to bottom. At the same time, the pore water can flow along with the fractures, and the flow vector can conform to the regular analysis rules, indicating that the numerical model built in this paper can reflect the seepage law and characteristics of fractured sandstone. Due to the different forms of sandstone failure after different temperature treatments, the distribution of pore water pressure of fractured sandstone is also different during the numerical simulation.

The process of the permeability calculated by the simulation is that first, iterate the mechanical calculation according to the seepage-stress coupling program established in this paper. The fracture size is determined according to the iterative steps of mechanical calculation in the program, and the deformation $u_3$ and fracture width of the crack element are calculated according to formulas (9) and (10). Then calculate the permeability according to formula (8). Next, close the mechanic module and open the seepage module to simulate the distribution of water flow and pore water pressure along the fracture. Numerical analysis is carried out according to the above parameter conditions, and the calculated permeability of sandstone specimens under the confining pressure of 5 MPa and the water pressure of 1 MPa after different temperature treatments is compared with the experimental
values, as shown in Figure 12. By comparison, it is found that the test value is consistent with the calculated value, and the permeability range of sandstone after different temperatures is $10^{-18}$–$10^{-17}$ m$^2$. The simulation results show that the permeability of fractured sandstone gradually increases with the thermal temperature.

5. Conclusions

According to the triaxial stress-strain curve of the sample, the higher the applied temperature, the lower the peak strength of the specimen. Among them, the peak intensity of the sample after being applied at 700°C is 48.15% lower than the peak intensity after being applied at 20°C. The inclination angle of the fracture surface of the sample decreases with the increase of the temperature, from 90° after 20°C treatment to 62° after 700°C treatment. The damage degree was getting more and more serious, and the fracture surface gradually develops into a single shear failure surface.

The permeability of the specimen increases with the increase of pore water pressure after a fixed temperature treatment. When the same pore water pressure and confining pressure were applied, the permeability of the rock sample increases with the applied temperature. When the confining pressure was constant but the pore water pressure was different, the permeability of the fractured sandstone after different temperature treatments decreases exponentially with the increase of the net confining pressure, and the permeability was related to the fracture mode of the fracture.

According to the test data and the macroscopic failure state of sandstone, numerical models of different fracture angles were established. FLAC3D embedded fish language was used to compile the seepage-stress coupling calculation program of fractured sandstone after different temperature treatments to calculate the numerical model. The calculated value was in good agreement with the test value. The research results can provide a certain reference basis for the long-term stability analysis of deep rock mass engineering in the rich water area.

Data Availability

The data used in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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