Research Article

Numerical Study on Seepage of Chemical Grout Flow in Rock Fracture under Temperature Field

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Grouting technology is widely used to improve the mechanical properties and reduce the permeability of the rock in underground engineering. Fluidity is important to promote the grout to be injected into longer fractures, so chemical grouts with low viscosity and adjustable gel time are usually chosen to increase this property. However, the high temperature in some deep engineering leads to a faster hydration rate of the chemical grout than that in the room temperature environment, resulting in the decrease of fluidity. The heat exchange between the grout and the environment is usually ignored in the existing researches, so the aim of the numerical study is therefore to analyse the seepage process of chemical grout in the temperature field, where heat exchange between the grout and environment is considered. A sandstone model with a fracture is established in COMSOL, which is validated using laboratory experiments to confirm the accuracy of the results. The grouting time rises exponentially with the increasing of the flow distance in a single fracture, and a higher environmental temperature leads to a larger grouting time because the gap in the viscosity of the grout at different temperatures enlarges with the increasing hydration time. The effect of the temperature field on the grouting time becomes more significant when the temperature is higher and the hydration time is longer because the viscosity of the grout rises more slowly. The grouting time reduces dramatically when injection pressure is raised because an increasing pressure results in a larger aperture and less hydration time, which is one of the best ways to improve the efficiency of the grouting. The findings of this study can help for better understanding of the seepage process of chemical grout in fractures under high temperature and provide guidance for the selection of chemical grout in grouting engineering.

1. Introduction

As a means of reinforcement and seepage prevention, grouting technology was widely used to improve the mechanical properties and reduce the permeability of the rock in underground engineering [1–3]. The interior of the rock was developed generally with a large number of different sizes and forms of fractures, and it was of great importance to select an appropriate grout material to control the performance of different fractured rocks [4]. For the rock with deep fractures and micropores, chemical grout with low viscosity and adjustable gel time such as paste grout, silica solutions, hot asphalt grout, and polyurethane grout [5–7] was needed to increase the fluidity and ensure the compactness after grouting [8, 9]. The fluidity of fluids was not only related to the type of material but also varied with the pressure and temperature of the fluids [10–12]. Since pressure changes had little effect on the fluidity of grout material and could be generally negligible in the study, temperature was the primary factor affecting the fluidity of the grout. Therefore, the study on the fluidity changes of grout material at different temperatures is important in understanding the seepage process of grout flow in fractured rocks.

The development of deep engineering such as ultradepth drilling, deep laboratory, nuclear waste disposal, and deep resource mining had made temperature of rock increase...
from 30°C at a depth of 800 m to 50°C at a depth of 1500 m approximately [13–17]. In particular, the temperature of the rock had even exceeded 100°C in some high-temperature tunnels such as Sichuan-Tibet Railway and EGS-E tunnel [18, 19]. In the high-temperature environments, the temperature of the grout rose gradually, so its hydration rate was faster than that in the room temperature environment, leading to the decrease of its fluidity. The effect of temperature on the properties of different grouts had been studied. Xu et al. [15] analysed the effect of high temperature on cement, and a temperature-based model was developed to estimate the initial viscosity of cement grouting. Hao et al. [20] established a time-varying viscosity model, and the impact of the initial temperature on gel time was investigated. Li et al. [21] classified the reaction progress of cement-sodium silicate and polymer-modified cement grout and obtained the equations of time-dependent viscosity. Meanwhile, the seepage process of chemical grout at different temperatures in a rock sample had been analysed. Zhou et al. [4] and Yu et al. [22] set the temperature of the grout from 20°C to 80°C and studied the seepage process of different grout materials in the fracture. These researches mainly focused on the seepage of chemical grout with a fixed temperature in a short time, and the time for the heat exchange between the grout and the environment was ignored. However, the grout was prepared at a lower temperature in the high geothermal environment to ensure lower viscosity and adjustable gel time. Therefore, seepage and heat exchange process of chemical grout under temperature field continues to be an open problem.

Furthermore, the seepage of the grout in fractured rocks was a complex process, and purely theoretical analysis was difficult to obtain an accurate solution, so the current research on the seepage of the grout was usually studied from an experimental perspective. The conventional experimental methods for measuring permeability cannot describe the local characteristics of the fluids because of the invisibility of the rock, so transparent rock and imaging techniques were used widely. Cui et al. [23] and Liu et al. [24] used transparent rock material to obtain the relevant parameters reflecting rock properties and estimate the relative permeability curves, respectively. Wu et al. [25] and Chen et al. [26] used nuclear magnetic resonance (NMR) to analyse permeability coefficient in the sandstone sample and microstructures of Beishan granite after different temperature treatments, respectively. In actual rock engineering, the length of the fractures that need to be grouted may reach tens of meters [27], but the height of the sample used in the nuclear magnetic resonance test often does not exceed 50 mm, so it is not suitable to use it for the large-scale experiments. Moreover, an extensive amount of manpower and time to make the transparent rocks is needed to draw the comprehensive conclusion.

In this case, many researchers chose analytical and numerical modelling to study the seepage process of grouting, which could increase the efficiency of research and enhance the replicability of studies. Meanwhile, analytical and numerical modelling is suitable for some extreme conditions that could not be done in the experiments and various indexes such as viscosity, pressure, and temperature could be monitored at any moment and position. Abdelazim [28] used COMSOL model to simulate flow through rock fractures, and extreme conditions such as the high injection pressure were investigated. Wang et al. [29] studied the seepage process of grouting in microfractures under different grouting pressure and fracture aperture conditions by numerical simulation. Yan et al. [30] investigated the rheological properties of rocks in seepage field and obtained the relationship between the dynamic hydraulic force and the strain of rock specimen in seepage direction.

Therefore, an analytical and numerical study is conducted to analyse the seepage process of chemical grout in the fracture and the temperature field of the model is considered to reflect the change of viscosity and grouting time. Firstly, a sandstone model that could simulate the complex structure of real fracture is established firstly, where the fracture has a rough surface and a nonuniform aperture. Then, fluid field, temperature field, and mechanical field are established, respectively. Next, the reliability of the numerical simulation model is verified according to the related experimental data. Finally, four different lengths of fractures are studied considering that the properties of the grout are changed with the increase of hydration time. Based on the data from the study of the effect of fracture length on the grouting time, the effects of temperature field and injection pressure are investigated, respectively. The flowchart of the study is shown in Figure 1.

2. Model Concept and Governing Equations

The intention of this study is to model the chemical grout through the fracture and analyse the effect of different factors on the grouting time. In order to ensure the results of numerical simulation more accurate, the model should be established based on the actual situation. However, because of the complex geological structure of the fracture surface and its hidden and invisible characteristics, it is difficult to obtain the geometric distribution information of the fracture directly. In the traditional model, it is generally assumed that the fracture is a parallel flat model, but in fact, the surface of the natural rock fracture is rough and uneven, and the aperture is distributed nonuniformly. Previous studies have shown that the aperture can be described by truncated Gaussian distribution [31], and the distribution functions can be represented as

\[
F(d_f) = \begin{cases} 
\frac{1}{\sigma \sqrt{2\pi}} e^{\frac{(d_f - d_{fm})^2}{2\sigma^2}}, & d_f \geq 0, \\
0, & d_f < 0,
\end{cases}
\]  

(1)

where \(d_f\) is the fracture aperture; \(d_{fm}\) is the mean of the fracture aperture; \(\sigma\) is the average variance of the aperture.

The selection of grout materials should be based on the actual needs of rock mass engineering, and a great diversity of grouting materials have been studied. Cement grouts are the most widely used grouting materials to fill the fractures. Sulphoaluminate cement is often used as a grouting material.
because of its excellent properties such as early strength and high strength [32]. Cement-Metakaolin grout material can reduce the drying shrinkage and has great resistance to chloride ion and sulfate erosion in the fracture [33]. Since cement grout can hardly achieve a satisfactory diffusion range in the long fracture, different chemical grout materials are developed to enhance the performance of fractured rock mass. For example, waterborne epoxy resin is used to improve the toughness and adhesion of grouting materials [34]. Compared with other chemical grout, sodium silicate-ester grout has the advantages of controllable gel time, high strength, and low viscosity before the initial setting [4], so it is chosen as research object. The reaction mechanism of this grout is expressed as

\[
\text{CH}_3\text{COOCCH}_3\text{CH}_2\text{OOCCH}_3 + H_2O \rightarrow \text{HOCH}_2\text{CH}_2\text{OH} + 2\text{CH}_3\text{COOH}
\]  

(2)

\[
\text{Na}_2\cdot n\text{SiO}_2 + 2\text{CH}_3\text{COOH} \rightarrow n\text{SiO}_2^- + 2\text{CH}_3\text{COO}\text{Na} + H_2O
\]  

(3)

In order to increase the fluidity of the chemical grout and increase the gel time, the proportion of Na$_2$SiO$_2$, \(H_2O\), and C$_6$H$_{10}$O$_4$ is designed as 0.538 (kg): 1 (L): 0.175 (L). Experiment has shown that the initial gel time of the grout made with this ratio can reach 1540 min [4], which can meet the requirements of long-distance grouting.

The type of fluid determines the choice of fluid flow equation. Chemical grouts usually belong to Newtonian fluid, and the seepage law of the grout in the fracture can be obtained based on this assumption. Wei et al. [35] assumed that the grout was Newtonian fluid and studied the time-changed characteristics of the viscosity. Li et al. [36] considered the polymer grout as a self-expanding Newtonian fluid whose density decreased over time in the self-expansion phase. However, most of the clay grout and some chemical grout belong to Bingham fluids which cannot flow until the shear stress in the fluid is greater than its initial yield strength. Kim et al. [37] built a Bingham fluid model based on UDEC, and a series of numerical analyses were conducted to simulate the flow of viscous grout in a single rock joint with smooth parallel surfaces. Wang et al. [29] analysed the seepage process of grouting in undeveloped microfractures and a Bingham fluid seepage model was designed. In some cases, the characteristics of the fluid can even be transformed according to the proportion of each raw material. Yang et al. [38] confirmed that the cement grouts would experience a transformation from Bingham fluid to Newtonian fluid once the ratio of water to cement exceeded 1.25. Since the chemical grout chosen in this paper has properties of low initial viscosity and high gel time, the fluid governing equations are established based on Newtonian fluid.

The equation for time-dependent fluid flow in the fracture follows a modified form of Darcy’s law as

\[
\frac{\partial \rho}{\partial t} - \nabla\cdot (\rho d_i \mathbf{u}) = d_i Q_m,
\]  

(4)

\[
\mathbf{u} = -\frac{k_f}{\mu} \nabla p,
\]  

(5)

where \(\rho\) is the fluid’s pressure in the fracture (Pa); \(k_f\) is the fracture’s permeability (m$^2$); \(d_i\) is the fracture’s aperture (m); \(\rho\) is the fluid’s density (kg/m$^3$); \(\mu\) is fluid’s dynamic viscosity (Pa·s); and \(\mathbf{u}\) is the Darcy velocity of the fluid (m/s). Here, \(\nabla\) denotes the gradient operator restricted to the fracture’s tangential plane.

The effect of fluid inertial force is ignored in the model, and the cubic law refers to the fluid flow in the fracture. In order to consider the nonuniformity of the aperture, the
fractures are divided into a number of interconnected parallel flat grids with different apertures and the fluid flow in these parallel flats obeys the local cubic law as

\[ \kappa_f = \frac{d_f^2}{12f_f}, \]  

where \( f_f \) is the JRC of the fracture.

The heat transfer process can be described by the fluid heat transfer equation as Equations (7) and (8), where the Darcy velocity \( u \) is introduced to realize the temperature coupling.

\[ \rho C_p \frac{dT}{dt} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q, \]  

\[ q = -k \nabla T, \]  

where \( C_p \) is the constant pressure heat capacity (J/kg·K); \( T \) is the temperature of the grout (K); \( q \) is heat flux (W/m²), and \( k \) is thermal conductivity (W/m·K).

In the seepage process of the grout in the fractures, the grout absorbs the heat from the environment due to a certain temperature difference between the grout and the environment, which can be presented as

\[ -n \cdot q = h \cdot (T_{\text{ext}} - T), \]  

where \( h \) is the heat transfer coefficient (W/m²·K); \( T_{\text{ext}} \) is the environmental temperature (K).

### 3. Model Development

#### 3.1. COMSOL Multiphysics Package

COMSOL Multiphysics is an advanced numerical physics coupling simulation software; the advantage of which is the ability to describe the

| Classification       | Notation | Value  | Unit    | Description                |
|----------------------|----------|--------|---------|----------------------------|
| Grout material properties | \( \rho_g \) | 1230   | kg/m³   | Density                    |
|                      | \( \mu \) | \( \mu(T,t) \) | mPa·s   | Dynamic viscosity          |
| Sandstone properties | \( E \)  | 23.65  | GPa     | Elastic modulus            |
|                      | \( \nu \) | 0.17   | 1       | Poisson’s ratio            |
| Fracture properties  | \( f_f \) | 6      | 1       | JRC value                  |

**Table 1: Input parameters for the model.**
material properties, boundary conditions, and initial conditions using specified equations [28]. It is mainly based on finite element method as the main theoretical calculation, which can be used to simulate different physical phenomena by directly calculating and solving partial linear differential equations (single field) or a set of numerical functions of the partial linear differential equation (multifields) [39–41]. Since the coupling of three physics (solid structure, fluid flow, and fluid-heat transfer) is involved, the study selects COMSOL as the platform to analyse the chemical grout flow in the fracture. The governing fluid flow equations and fluid-heat transfer equations are derived from Darcy’s law and the thermal equation.

3.2. Basic Assumptions. The model in the study is developed based on the following assumptions.

(i) During the seepage process of the grout, the heat of the environment does not damage the sandstone itself and results in more microfractures. Previous researches suggested the temperatures usually needed to be above 400°C to study the thermal damage and failure mechanical behaviour of the rock [42, 43].

(ii) During the seepage process of the grout, the injection pressure of the grout does not cause physical damage or chemical reaction to sandstone mineral particles on the surface of the fracture.

(iii) The permeability of the sandstone itself is much smaller than that of the fracture, so the seepage process of chemical grout in the sandstone can be ignored in the numerical simulation.

(iv) The influence of environmental humidity on grouting time is ignored. Environmental humidity affects the evaporation rate of water in the grout material. In the dry environment, the water in the grout material evaporates quickly, and the initial gel time of the grout material is correspondingly short [44, 45].

(v) The preparation of chemical grout is carried out in one time, and the grout is injected into the fracture immediately once the preparation is finished. In this case, the hydration process of the grout is always in progress, even if some of the grout has not yet been injected into the fracture. Meanwhile, the grout has not reached the initial setting at the end of grouting.

(vi) The grout that has not yet been injected into the fracture is always kept at the set temperature by insulation; in other words, the temperature of the grout at the entrance of the fracture is constant at every moment.

(vii) The inside space of fractures does not contain any water before grouting.

3.3. Geometry, Boundary Conditions, and Input Parameters. Fractures with five different sizes are used to model flow behaviour in a fracture. The width and length of the fracture in the first model are 25 mm and 50 mm, respectively. The size of this model is same as that of the experimental model in Wu’s thesis [25], which is mainly used to verify the reliability of the numerical simulation model. Meanwhile, in order to analyse the effect of fracture length on the grouting time, four different lengths 25 m, 50 m, 75 m, and 100 m with the same width 5 m are designed. The fracture which is used to verify the feasibility of the model is an artificial fracture, and the fracture surface is flatter compared with natural fracture, so a parallel flat model is established. In the large-scale fracture model, MATLAB is used to generate aperture scatter points that are conformed to Gaussian distribution. The mean of the fracture aperture and the average variance are set to 0.1 mm and 0.05 mm, respectively. A rectangular mesh with 1 mm × 1 mm unit size is generated, and each mesh node is given a different random number. All of the aperture scatter points are assigned to discrete mesh points according to the corresponding random numbers on the mesh points. The surface shape of a 10 mm × 10 mm rough fracture is shown in Figure 2.

The effects of injection pressure and confining pressure on the deformation of the fracture are also considered. During the grouting process, the injection pressure is applied only to the entrance of the fracture while the exit of the fracture is open to the atmosphere, so one side of the boundary is set to specific injection pressure and the other side is set to 0 since the reference pressure for the entire model $P_{ref}$ is 1 atmospheric pressure. In fluid-heat transfer field, the entrance is set to 20°C, which represents the initial temperature of the grout. Meanwhile, the environmental temperatures are set to 20°C, 40°C, 60°C, and 80°C, respectively, and the surface of the fracture is set to allow thermal exchange with the environment to analyse the effect of the temperature field.

The required input parameters of sandstone for the model are taken from Wu’s experiment [25], and the other

| Number | Fracture length (m) | Fracture width (m) | Injection pressure (MPa) | Confining pressure (MPa) |
|--------|---------------------|--------------------|--------------------------|--------------------------|
| 1#     | 0.05                | 0.025              | 0.5                      | 5                        |
| 2#     | 0.05                | 0.025              | 1.0                      | 5                        |
| 3#     | 0.05                | 0.025              | 1.3                      | 5                        |
| 4#     | 0.05                | 0.025              | 1.0                      | 1                        |
| 5#     | 0.05                | 0.025              | 1.0                      | 10                       |
| 6#     | 0.05                | 0.025              | 1.0                      | 20                       |
| 7#     | 25                  | 5                   | 2                        | 5                        |
| 8#     | 50                  | 5                   | 2                        | 5                        |
| 9#     | 75                  | 5                   | 2                        | 5                        |
| 10#    | 100                 | 5                   | 2                        | 5                        |
| 11#    | 50                  | 5                   | 0.5                      | 5                        |
| 12#    | 50                  | 5                   | 1                        | 5                        |
input parameters are set according to the guidance of COMSOL. Input parameters are listed in Table 1. The dynamic viscosity of the grout is a fitting function of time and temperature; the 3D image of which is shown in Figure 3. The equations of $k(T)$ and $C_p(T)$ are expressed in

$$C_p(T) = 12010.147 - 80.407\cdot T + 0.310\cdot T^2 - 5.382\cdot10^{-4}\cdot T^3 + 3.625\cdot10^{-7}\cdot T^4,$$

(10)

$$k(T) = -0.869 + 0.008955\cdot T - 1.584\cdot10^{-5}\cdot T^2 + 7.975\cdot10^{-9}\cdot T^3,$$

(11)

where $C_p(T)$ is the constant pressure heat capacity (J/kg·K) under temperature $T$; $k(T)$ is the thermal conductivity (W/m·K) under temperature $T$.

3.4. Validation of the Model Using Experimental Results. The seepage process in the 50 mm fracture is calculated firstly, and the results are compared with the data from the experiment [25]. The effects of injection pressure and confining pressure on the seepage process in the fracture are analysed in the room temperature of 20°C, and number 1°, 2°, and 3° schemes in Table 2 are used in the experiment. The experimental results and the corresponding data from the COMSOL model for the fracture permeability are shown in Figure 4. The relative errors between the experimental results and the corresponding numerical results are listed in Table 3. Since there is no relative error larger than 10%, the validation of the model can be confirmed. The error of the numerical model is mainly derived from two aspects. The permeability of sandstone itself is ignored considering that it is much smaller than that of the fracture, so the total permeability of the model is relatively small. Meanwhile, only elastic deformation of the sandstone is considered, so the actual deformation of the fracture is slightly different from that in the numerical model. The error of the numerical model could be further reduced if these two factors are included in the model, but this error could be accepted in order to simplify the calculation of the model.

All of the other models are built based on the model whose accuracy has been confirmed. These models are used to analyse some conditions which are difficult to be done under laboratory conditions, such as long fracture and high injection pressure. All of the numerical simulation schemes are listed in Table 2. The results obtained for the chemical grout flow behaviour are discussed in the following sections.

4. Results and Discussion

4.1. Effects of Fracture Length on Grouting Time. To investigate the effect of fracture length on the seepage process of grouting, the confining pressure and the injection pressure are fixed at 5 MPa and 2 MPa, respectively. Four different lengths, 25 m, 50 m, 75 m, and 100 m, are designed to study the time it takes for the grout to pass through different distances, and the results are shown in Figure 5. It is assumed that the ratio of the distance from the entrance to the corresponding time is the average speed of the grout. What the
four diagrams have in common is that as the flow distance of the grout increases, the average speed decreases exponentially. There are two factors leading to this result. The first one is that the dynamic viscosity of the grout increases with the increasing hydration time in all of the models, as shown in Figure 6, and this phenomenon is particularly noticeable in the 75 m and 100 m fractures. However, the dynamic viscosity of the grout does not increase significantly with the process of grouting in the 25 m and 50 m fractures. The decrease of the average speed is also caused by the change of the aperture along the length of the fracture since the spatial distribution of the aperture is not only related to its natural distribution but also to the injection pressure. When the injection pressure is set to 2 MPa, the deformations of apertures along the central axis of the fracture under injection pressure in four length conditions are shown in Figure 7. As the grout penetrates into the fractures, the aperture of the fracture is getting smaller, leading to the rapid decline of its average speed.

A comparative analysis of the four diagrams in Figure 5 is performed, and the time required to complete grouting in different length conditions at the same temperature is studied. The time required to complete grouting of 25 m, 50 m, 75 m, and 100 m fracture at 80°C is 20 min, 135 min, 555 min, and 1237 min, respectively. This result is similar to the decreasing average speed of the grout as it flows through a single fracture, which is mainly due to the increasing viscosity as it flows through longer fractures. The effect of different temperatures on grouting time under the constant length conditions is also analysed. For 25 m and 50 m fractures, four different temperatures have little effects on grouting time. The grouting time is only 9 minutes apart between 80°C and 20°C in 50 m fracture model, which can be explained by the little difference in the dynamic viscosity of the grout in the shorter time. However, the time required increases when the grout passes through a longer fracture. The effect of hydration on the dynamic viscosity of the grout begins to appear, so the effect of different temperatures on the grouting time in 75 m and 100 m fracture is greater. The grouting time is about 5 hours apart between 80°C and 20°C in the 100 m fracture. The time required to complete the grouting in a peculiar fracture is different from the time it takes to flow for the same distance in a longer fracture. It can be found in
Figure 5 that the grouting time of the 50 m fracture is 135 min at 80°C. However, it only takes 72 min for the grout to pass through the distance of 50 m in the 100 m fracture. From the perspective of injection pressure, the pressure difference at the entrance and exit is 2 MPa in the 50 m fracture, but it is only 1 MPa between the entrance and the 50 m point in the 100 m fracture. The larger injection pressure difference should be more conducive to the flow of grout if other factors are ignored, but the results of numerical simulation are not consistent with this analysis. The main reason for this result is the impact of aperture change under injection pressure. As can be seen in Figure 7, the aperture shrinks much faster in the 50 m fracture than the 100 m fracture, so the time required for the grout to pass through the 50 m fracture is larger than the time it takes for it to flow for 50 m in the 100 m fracture.

4.2. Effects of Temperature Field on Grouting Time. The differences between the model which considers the temperature field and another model which ignores it are compared to analyse the effect of temperature field on grouting time. The initial temperature of the grout is set to be equal to the environmental temperature in the model that ignores temperature field, which can also be seen that the heat exchange occurs in an instant. This section uses 50 m and 75 m fractures as the research object and the injection pressure is still set at 2 MPa. When heat exchange during the flow of the grout is not considered, the time it takes for the grout to pass through different distances in the 50 m and 75 m fractures is shown in Figure 8. Compared the results in Figure 8(a) and Figure 5(b), it can be found that the time required for grouting in the model considering temperature field is only 135 min at 80°C, which is less than the time without considering it. For the model with an environmental temperature of 40°C and 60°C, the effect of the temperature field on grouting time is even less. However, the impact of external temperature on the fluidity of the grout becomes greater as the fracture length is longer, especially at 80°C. After considering heat exchange, the grouting time will be reduced by 156 min at 80°C in the 75 m fracture while the lower environmental temperatures have a relatively limited effect on the results.

The difference of the grouting time caused by heat exchange is mainly controlled by the dynamic viscosity.
Figure 9 shows the dynamic viscosity of the grout when it reaches different distances without considering heat exchange. As for the 50 m fracture, comparing the data in Figure 9(a) with that in Figure 6(b), it can be found that whether temperature field is considered has less effect on the dynamic viscosity at 20°C to 60°C since the maximum gap in viscosity coefficient is less than 1 mPa·s. The gap in the dynamic viscosity begins to widen at 80°C, so the difference in grouting time between the two models occurs. The effect of temperature field on the dynamic viscosity is greater in the 75 m fracture, in which case the dynamic viscosity of the grout is always less than 6 mPa·s until it flows for about 65 m at 80°C. Without considering the temperature field, the dynamic viscosity has been reached 6 mPa·s with the grout flowing for only 35 m at 80°C, which makes a huge difference between the results.

The temperature distribution and dynamic viscosity distribution of the grout in the fracture are analysed when grouting is completed. It can be seen in Figure 10 that the temperature of the grout increases gradually along the length of the fracture when the environmental temperature in the 75 m fracture is above 20°C. The temperature difference between the entrance and exit is the largest at 80°C. Dynamic viscosity is a function of temperature and time, so the...
temperature determines the dynamic viscosity of the grout at each position of the fracture at the fixed time. The dynamic viscosity of the grout also increases along the length of the fracture, as shown in Figure 11. For the model with an environmental temperature of 80°C, the gap between the dynamic viscosity of the grout at the entrance and the exit is the greatest. This gap narrows gradually with the decrease of environmental temperature.
4.3. Effects of Injection Pressure on Grouting Time. The grout is usually supercharged by increasing injection pressure in grouting engineering. The grouting time under three different injection pressures is compared, and the fracture length is set to 50 m. As seen in Figure 12, different environmental temperatures have an obvious impact on the grouting time when the injection pressure is only 1 MPa, and it takes 515 min to complete the grouting at 80°C. When the injection pressure is further reduced to 0.5 MPa, about 1900 min is required in an 80°C environment. However, once the injection pressure reaches 2 MPa, Figure 5(b) shows that the grouting time in the corresponding temperature environment is less than half of the time when the injection pressure is 1 MPa, and the effect of different environmental temperatures on the grouting time is reduced, which

Figure 12: Time it takes for the grout to pass through different distances under different injection pressures: (a) 1 MPa and (b) 0.5 MPa.

Figure 13: Deformation of aperture along the centre axis of the fracture under different injection pressures.

Figure 14: Displacements of aperture under 2 MPa injection pressure.
indicates that the increase of injection pressure can greatly improve the efficiency of the grouting.

The reasons for the shortening of grouting time due to increased injection pressure are analysed. The increasing of injection pressure directly increases the flow speed of grout, which should be linear if other conditions are unchanged. However, the increase of injection pressure leads the grouting time to decrease exponentially, indicating that the increase of injection pressure changes other factors in the grouting process. As mentioned in Section 4.1, the presence of injection pressure causes the aperture of the fracture to change. Figure 13 shows the deformations of the aperture along the central axis of the fracture under different injection pressures, which suggests that when the injection pressure is higher, the aperture of the fracture will be larger correspondingly. For example, at the entrance of the fracture, the aperture is 0.465 mm at 1 MPa injection pressure, compared with 0.73 mm at 2 MPa injection pressure. According to cubic law, the greater aperture of the fracture leads to the greater permeability, so the increase of aperture accelerates the flow of grout indirectly.

Figure 13 only shows the deformations of the aperture along the central axis of the fracture under different injection pressures, but there are considerable differences in the deformations along the width of the fracture. Figure 14 shows the deformations of the upper and lower surfaces of the fracture under 2 MPa injection pressure. The closer to both sides of the fracture, the smaller the deformations of the fracture because the two sides of the fracture along the length direction are in contact with the sandstone. Meanwhile, the deformations at the central axis positions are the maximum compared with other positions along the width of the fracture. This deformation characteristic of the fracture causes the difference in the speed of the grout along the width of the fracture during the flow process. When the grouting is completed under 2 MPa injection pressure, the velocity distribution of the grout in the 75 m fracture is shown in Figure 15. The speed along the central axis of the fracture is the maximum compared with other points along the width of the fracture.

5. Summary and Conclusions

In this study, a sandstone model with a fracture is established in COMSOL and characteristics of the fracture such as the surface roughness and aperture nonuniformity are included to simulate the geometric structure of a real fracture. The heat exchange between the sodium silicate-ester grout and the environment is considered in the fluid-heat transfer module where hydrothermal coupling is realized. The COMSOL model is validated using laboratory experiments to verify the accuracy of the results.

1. Grouting time is highly affected by the length of flow distance in a single fracture. As the flow distance of the grout increases, grouting time rises exponentially because of the increasing viscosity and the decreasing aperture under injection pressure. A higher environmental temperature and longer fracture lead to a larger grouting time because the gap in the viscosity of the grout at different temperatures enlarges with the increasing hydration time.

2. The effect of the temperature field on the grouting time becomes more critical when the environmental temperature is higher and the hydration time is longer because the viscosity of the grout rises more slowly considering the temperature field.

3. In terms of the distribution of temperature and viscosity in the model, both variables of the grout increase gradually along the length of the fracture. The maximum difference of both variables between the entrance and the exit exists in the model with 80°C environmental temperature.

4. The increase of injection pressure can greatly improve the efficiency of the grouting since the grouting time needed reduces exponentially, which is the result of a combination of increasing pressure difference, larger aperture, and smaller hydration time (viscosity). The deformation of the aperture is not uniform along the width direction of the fracture under injection pressure and the maximum value is located at the midpoint along the width direction, which determines the same distribution of grout’s velocity.

The results of the numerical model can provide some guidance for practical engineering. The increase of grout’s viscosity should be controlled in grouting engineering by
changing the ratio of each material or reduce its initial temperature, and the injection pressure should be appropriately increased to ensure the complete grouting, especially when the environmental temperature is high and the fracture length is long.

In the study, a sandstone model with a fracture is established because this simple model is beneficial for clearly exploring the seepage process of the grout. But due to the spatial distribution and the geometric complexity of rock fractures, a fracture network that is the same as the actual fracture geometry network is worth studying in the future. Besides, the permeability of the sandstone itself is ignored in the numerical model, so an improved numerical model should be developed in the future, and then, the permeability law of other rocks with large permeability can also be carried out according to this improved model. A single fluid type (Newtonian fluid) is used in this study to describe the seepage law of the grout in the fracture, which can be improved by a model considering the transformation of the fluid type under the increasing hydration time.

**Abbreviations**

- $d_f$: Fracture aperture
- $T$: Temperature of the grout
- $d_{fm}$: Mean of the fracture aperture
- $q$: Heat flux
- $\sigma$: Average variance of the aperture
- $k$: Thermal conductivity
- $p$: Pressure of fluid in the fracture
- $h$: Heat transfer coefficient
- $\kappa_f$: Permeability of fracture
- $T_{ext}$: Environmental temperature
- $\rho_f$: Density of fluid
- $\rho_s$: Density of sandstone
- $\mu$: Dynamic viscosity of fluid
- $E$: Elastic modulus of sandstone
- $u$: Darcy velocity of the fluid
- $\nu$: Poisson’s ratio of sandstone
- $f_f$: JRC of the fracture
- $b$: Aperture data in grid form
- $C_p$: Constant pressure heat capacity.

**Data Availability**

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

**Conflicts of Interest**

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

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**References**

[1] O. Saedidi, H. Stille, and S. R. Torabi, "Numerical and analytical analyses of the effects of different joint and grout properties on the rock mass groutability," Tunnelling and Underground Space Technology, vol. 38, pp. 11–25, 2013.

[2] A. Mortazavi and A. Maadikhah, "An investigation of the effects of important grouting and rock parameters on the grouting process," Geomechanics and Geotechnics-An International Journal, vol. 11, no. 3, pp. 219–235, 2016.

[3] L. Zou, U. Hakansson, and V. Cvetkovic, "Two-phase cement grout propagation in homogeneous water-saturated rock fractures," International Journal of Rock Mechanics and Mining Sciences, vol. 106, pp. 243–249, 2018.

[4] Y. Zhou, Z. Wu, and Q. Liu, "Seepage characteristics of chemical grout flow in porous sandstone with a fracture under different temperature conditions: an NMR based experimental investigation," International Journal of Rock Mechanics and Mining Sciences, vol. 142, p. 104764, 2021.

[5] S. An, C. Ai, D. Ren, A. Rahman, and Y. Qiu, "Laboratory and field evaluation of a novel cement grout asphalt composite," Journal of Materials in Civil Engineering, vol. 30, p. 040181798, 2018.

[6] S. Wang, C. He, L. Nie, and G. Zhang, "Study on the long-term performance of cement-sodium silicate grout and its impact on segment lining structure in synchronous backfill grouting of shield tunnels," Tunnelling and Underground Space Technology, vol. 92, p. 103015, 2019.

[7] X. Ma, L. Zhang, and J. Zhou, "Experimental study on the relationship between grouting pressure and compressive strength of hardened cement paste," Iranian Journal of Science and Technology-Transactions of Civil Engineering, vol. 44, SUPPL 1, pp. 483–489, 2020.

[8] L. Li, S. Li, and J. Cui, "Experimental research on chemical grout for treating water inrush in rock mass," Rock and Soil Mechanics, vol. 30, no. 12, pp. 3642–3648, 2009.

[9] M. Zhu, Q. Zhang, X. Zhang, and B. Hui, "Comparative study of soil grouting with cement slurry and cement-sodium silicate slurry," Advances in Materials Science and Engineering, vol. 2018, Article ID 1893195, 2018.

[10] A. Bras, F. M. A. Henriques, and M. T. Cidade, "Effect of environmental temperature and fly ash addition in hydraulic lime grout behaviour," Construction and Building Materials, vol. 24, no. 8, pp. 1511–1517, 2010.

[11] E. Demircan, S. Harendra, and C. Vipulanandan, "Artificial neural network and nonlinear models for gelling time and maximum curing temperature rise in polymer grouts," Journal of Materials in Civil Engineering, vol. 23, no. 4, pp. 372–377, 2011.

[12] W. Han, S. Li, Q. Zhang, R. T. Liu, and L. Z. Zhang, "Experimental study on viscosity behavior and its temperature influence of cement silicate grouts," Applied Mechanics and Materials, vol. 256-259, pp. 153–156, 2012.

[13] L. Weng, Z. Wu, and Q. Liu, "Influence of heating/cooling cycles on the micro/macrocracking characteristics of Rucheng granite under unconfined compression," Bulletin of
[14] Z. Wu, M. Li, and L. Weng, “Thermal-stress-aperture coupled model for analyzing the thermal failure of fractured rock mass,” *International Journal of Geomechanics*, vol. 20, p. 0402017610, 2020.

[15] Z. Xu, Y. Miao, H. Wu, X. Yuan, and C. Liu, “Estimation of viscosity and yield stress of cement grouts at true ground temperatures based on the flow spread test,” *Materials*, vol. 13, p. 293913, 2020.

[16] Y. Xue, J. Liu, X. Liang, S. Wang, and Z. Ma, “Active iron-rich belite sulfoaluminate cements: clinkering and hydration,” *Environmental Science & Technology*, vol. 44, no. 17, pp. 6855–6862, 2010.

[17] M. Tang, H. Li, and C. Tang, “Study on preliminarily estimating performance of elementary deep underground engineering structures in future large-scale heat mining projects,” *Geofluids*, vol. 2019, Article ID 3456307, 2019.

[18] Y. Bai, P. Cui, C. Wu, and Y. Li, “Ecological risk assessment of soil and water loss by thermal enhanced methane recovery: numerical study using two-phase flow simulation,” *Journal of Cleaner Production*, vol. 334, p. 130183, 2022.

[19] J. Liu, Y. Xue, Q. Zhang, H. Wang, and S. Wang, “Coupled thermo-hydro-mechanical modelling for geothermal doublet system with 3D fractal fracture,” *Applied Thermal Engineering*, vol. 200, p. 117716, 2022.

[20] M. Hao, X. Li, X. Wang et al., “Experimental study on viscosity characteristics of expanding polymer grout,” *Journal of Wuhan University of Technology-Materials Science Edition*, vol. 36, no. 2, pp. 297–302, 2021.

[21] S. Li, W. W. Han, Q. Zhang, R. Liu, and X. Weng, “Research on time-dependent behavior of viscosity of fast curing grouts in underground construction grouting,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 1, pp. 1–7, 2013.

[22] Y. Yu, J. Zhang, L. Fan, Z. Shi, and L. Sun, “Experimental study on grouting of elliptical fractured rock mass at various temperatures,” *Arabian Journal of Geosciences*, vol. 14, p. 182718, 2021.

[23] H. Guo, L. Yuan, Y. Cheng, K. Wang, and C. Xu, “Experimental study on seepage diffusion movement in fractured rock fractures,” *Rock and Soil Mechanics*, vol. 41, no. 11, pp. 3553–3562, 2020.

[24] J. Liu, Z. Li, Y. N. Yang et al., “Feasibility and experimental study of visualized seepage device of rock fracture,” *Rock and Soil Mechanics*, vol. 2020, no. 12, pp. 1–12, 2020.

[25] Z. J. Wu, K. Lu, L. Weng, Q. S. Liu, and J. Q. Shen, “Investigations on the seepage characteristics of fractured sandstone based on NMR real-time imaging,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 40, no. 2, pp. 263–275, 2021.

[26] S. Chen, G. Wang, S. Zuo, and C. Yang, “Experimental investigation on microstructure and permeability of thermally treated Beishan granite,” *Journal of Testing and Evaluation*, vol. 49, no. 2, pp. 20180879–20180895, 2021.

[27] J. Funehag and J. Thorn, “Radial penetration of cementitious grout - laboratory verification of grout spread in a fracture model,” *Tunnelling and Underground Space Technology*, vol. 72, pp. 228–232, 2018.

[28] R. Abdelazim, “An integrated approach for relative permeability estimation of fractured porous media: laboratory and numerical simulation studies,” *Journal of Petroleum Exploration and Production Technology*, vol. 10, no. 6, pp. 2499–2516, 2020.

[29] K. Wang, L. Wang, B. Ren, and H. Fan, “Study on seepage simulation of high pressure grouting in microfractured rock mass,” *Geofluids*, vol. 2021, Article ID 6969882, 2021.

[30] Y. Yan, E. Wang, and S. Wang, “Numerical simulation of rheological properties of rocks in seepage field,” *Rock and Soil Mechanics*, vol. 31, no. 6, pp. 1943–1949, 2010.

[31] P. A. Lapcevic, K. S. Novakovski, and E. A. Sudicky, “The interpretation of a tracer experiment conducted in a single fracture under conditions of natural groundwater flow,” *Water Resources Research*, vol. 35, no. 8, pp. 2301–2312, 1999.

[32] A. J. Cuberos, A. G. De la Torre, G. Alvarez-Pinazo et al., “Active iron-rich belite sulfoaluminate cements: clinkering and hydration,” *Environmental Science & Technology*, vol. 44, no. 17, pp. 6855–6862, 2010.

[33] F. Cassagnabère, M. Mouret, G. Escadeillas, P. Broilliard, and A. Bertrand, “Meta-kaolin, a solution for the precast industry to limit the clinker content in concrete: mechanical aspects,” *Construction and Building Materials*, vol. 24, no. 7, pp. 1109–1118, 2010.

[34] Y. Cui and Z. Tan, “Experimental study of high performance synchronous grouting materials prepared with clay,” *Materials*, vol. 14, p. 13626, 2021.

[35] X. Wei, J. Hong, and G. Wei, “Research on dot shield tunnel back-filled synchronous grouting diffusion and segments circumferential pressure distribution,” *Journal of Wuhan University of Technology*, vol. 34, no. 10, pp. 106–110, 2012.

[36] X. Li, L. Wang, M. Hao, Y. Zhong, and B. Zhang, “An analytical solution for the radial flow of variable density grout in rock fractures,” *Construction and Building Materials*, vol. 206, pp. 630–640, 2019.

[37] H. Kim, J. Lee, M. Yazdani, E. Tohidi, H. R. Nejati, and E. S. Park, “Coupled viscous fluid flow and joint deformation analysis for grout injection in a rock joint,” *Rock Mechanics and Rock Engineering*, vol. 51, no. 2, pp. 627–638, 2018.

[38] Z. Yang, K. Hou, and T. Guo, “Study on the effects of different water-cement ratios on the flow pattern properties of cement grouts,” *Applied Mechanics and Materials*, vol. 71-78, pp. 1264–1267, 2011.

[39] Z. Huang, K. Zhao, X. Li, W. Zhong, and Y. Wu, “Numerical analysis of fracture-induced water inrushes in karst underground engineering,” *Journal of Basic Science and Engineering*, vol. 29, no. 2, pp. 412–425, 2021.

[40] T. J. Yang, S. H. Wang, Y. N. Zhang, and K. H. Tong, “Seepage-deformation coupling analysis of unsaturated slope three-phase flow model under the rainfall,” *Journal of Basic Science and Engineering*, vol. 29, no. 2, pp. 355–367, 2021.

[41] H. Yu, S. Zhu, and X. Wang, “Research on groundwater seepage through fault zones in coal mines,” *Hydrogeology Journal*, vol. 29, no. 4, pp. 1647–1656, 2021.

[42] L. F. Fan, J. W. Gao, Z. J. Wu, S. Q. Yang, and G. W. Ma, “An investigation of thermal effects on micro-properties of granite by X-ray CT technique,” *Applied Thermal Engineering*, vol. 140, pp. 505–519, 2018.

[43] S. Yang, P. G. Ranjith, H. Jing, W. L. Tian, and Y. Ju, “An experimental investigation on thermal damage and failure mechanical behavior of granite after exposure to different high temperature treatments,” *Geothermics*, vol. 65, pp. 180–197, 2017.
[44] J. Zhang, L. Zhang, L. Zhao, D. Liu, Q. L. Guo, and Q. Q. Pei, “Property changes of anchor grout calcined ginger nuts admixed with fly ash and quartz sand after accelerated ageing tests,” *Journal of Central South University*, vol. 26, no. 11, pp. 3114–3125, 2019.

[45] Z. Yu, L. Yang, S. Zhou, Q. Gong, and H. Zhu, “Durability of cement-sodium silicate grouts with a high water to binder ratio in marine environments,” *Construction and Building Materials*, vol. 189, pp. 550–559, 2018.