Study on influencing factors of microbial induced carbonate precipitation in a cross fracture network

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Abstract. Microbial mineralized precipitation has been widely used in anti-seepage of fractured rock mass due to its environmentally friendly characteristics. The mineralization and sedimentation of the fractured network with vertical and horizontal crosscutting directly affect the anti-seepage of its engineering. Based on the Navier-Stokes equations, solute transport equations, biochemical reaction equations, solution transport, and carbonate precipitation law of the cross fracture networks in rock mass were analyzed. The influence of the Reynolds number (Re) at the inlet, Angle (α) between principal fractures and branch fractures, and fracture aperture degree on the calcium carbonate precipitation were investigated. The results showed that under the condition of two branch fractures, when 1≤Re≤5, there is a weak nonlinear relationship between flow rate (Ra) and Re, where Ra is unaffected by the change of α. When 5<Re≤100, the nonlinear relationship between Re and Ra increased sharply. For 45°≤α≤180°, Ra and α showed a positive correlation due to the gradual increase of the inertial force. After Re>100, Ra gradually became steady. The influence of Re and Ra on the calcium carbonate precipitation in the cross fracture is mainly realized by controlling the change of Ra. For the α=45° model, when Re=1, the amount of calcium carbonate precipitation in the two branch fractures is approximately the same. When Re=100, the maximum concentration of calcium carbonate in the left branch fracture was 60.2 mol/m³, significantly higher than that in the right branch fracture. The research results provide a useful reference in MICP seepage prevention technology applications in a fractured rock mass.

1. Introduction
Surrounding rock seepage and water leakage seriously threaten mountain tunnels and urban subway functions and service lives [1-2]. To ensure long-term safety and stability, seepage and leakage prevention of engineering rock mass has become the focus of scholars in recent years[3].

With gradual advancement in research on biomineralization, microbe-induced carbonate precipitation (MICP) has been increasingly applied in seepage prevention and leakage control engineering[4-5]. Compared with cementitious materials such as cement, the viscosity of microbial solution (bacterial and cementitious solutions) is lower, and it is easier to migrate and diffuse internal rocks and soil media[6].

However, the complex fracture network of rock mass has resulted in a variety of solution migration, mineralization, and precipitation characteristics in the rock mass. Therefore, many domestic and foreign scholars have carried out several experimental analyses and simulation research.

Jasinski[7] used the Brinkman equation to describe the fracture seepage with columnar obstacles, and established the fracture flow condition model, and obtained the permeability estimation formula. For fractures with irregular barriers (such as full filling of microbial mineralization products) and rough surfaces (such as a small amount of microbial mineralization products covering), Singh[8] established a numerical method for permeability prediction based on the Navier-Stokes equation to
predict the decrease in fracture permeability based on the production of calcium carbonate. El Mountassir [9] conducted experiments on MICP treatment of fracture groups wherein the effects of fluid dynamics (flow rate and aperture) on MICP were systematically investigated. The experimental results show that there is a feedback mechanism between flow rate and precipitation for uniform initial fracture aperture with a stable flow rate, resulting in the concentrated flow of mineral precipitation distribution into a few self-organizing channels that remain stable.

Wu [10] conducted seepage simulation analysis of MICP-treated single fractures based on the Navier-Stokes equations and identified two different flow types of rock fractures: rough surface flow and channel flow. For the rough surface flow, the fracture surface covered with MICP precipitates showed a different roughness because calcium carbonate precipitates in the lower part of the fracture model. For channel flow, the fracture is partially blocked by precipitation, revealing the channel contour. Tobler [11] used the MICP technique to treat granite fracture and performed backscattered electron (BSE) imaging on the treated fracture section, which directly demonstrated the growth and evolution of the precipitate from the fracture wall to the center.

Based on the Navier-Stokes equation, solute migration, and chemical reaction equations, this study explored the cross fracture network and the influence of Reynolds number, angle, and aperture on calcium carbonate precipitation during microbial grouting.

2. Methodology

2.1. The Governing Equation of Fracture Flow

For fractures with irregular obstacles (such as full filling of microbial mineralization products) and rough surfaces (such as a small amount of microbial mineralization products covering), the flow state can be simulated based on the Navier-Stokes equations, as shown below [10]:

$$\rho \nabla \cdot (\nabla u) = \mu \nabla^2 u - \nabla P$$

where \(\rho\) is the density of the solution, \(u\) is the flow rate of solution, \(\mu\) is solution dynamic shear viscosity, and \(P\) is the local fluid pressure.

2.2. Chemical Species Transport: General Form

Calcium ion, urea, and cell migration in solution were described by convection dispersion equation, whose general formula is [12-13]:

$$\frac{\partial (c_i)}{\partial t} = \nabla \cdot (D_i \cdot \nabla c_i) - \mu \nabla u \cdot c_i + R_i$$

where \(c_i\) (mol/m\(^3\)) is the concentration of the chemical composition, \(D_i\) (m\(^2\)/s) is the dispersion tensor, \(R_i\) is the chemical source/sink, representing the chemical reaction caused by the mass change of a specific solute component.

3. Solution Flow and Calcium Carbonate Precipitation in Cross Fracture

3.1. Geometric Model

The simulated object was cut into a cross fracture as shown in Figure 1 on a granite plate (500 mmx300 mm), where the MICP solution inlet was located at the top of the fracture. The solution flowed through the primary fracture and into the left and right branch fractures. Then flowed out from the two outlets at the lower end. Thus, the angle between the primary fracture and the right branch fractures was \(\alpha\), and the angle between the two fractures was \(\beta\).
3.2. Parameter Setting
There is a correlation between fracture aperture and length, as shown in equation (3) [14]:

\[
I = \left\{ \frac{l_{\text{min}}^D}{l_{\text{max}}^D} + \left[ \frac{g(h_{b}) - g(h_{a})}{g(h_{b}) - g(h_{a})} \right] \times \left\{ l_{\text{min}}^D - l_{\text{max}}^D \right\} \right\}^{-1/D}
\]

(3)

where \( g(h) \) is the error function of the first and second moments of the log-normal distribution of openness, \( h_{a} \) and \( h_{b} \) are the minimum and maximum values of the aperture degree, respectively. \( l_{\text{min}} \) and \( l_{\text{max}} \) are the lower and upper limits of the fracture length, \( D \) is the fractal dimension of the fracture network. For the geometric model dimensions, the fracture aperture was set as 1 mm.

Bacteria liquid (OD\(_{600}\)=1) and the cementing fluid were mixed and one-time injected into the fracture. The molar concentration of urea and calcium chloride in the cementing solution was 1 mol/L. The pressure difference (\( \Delta P \)) between inlet and outlet was set, and the solution injection process simulated where calcium carbonate precipitation occurred via biochemical reactions. The basic hypothesis of this simulation is shown in table 1.

3.3. Interpretation of Results

3.3.1. Effect of Included Angle on Flow Velocity of Cross Fracture Solution

The law of solution migration in the cross fractures is the critical factor determining the precipitation of calcium carbonate, with the solution migration also affected by many factors. To investigate the effect of the angle, \( \alpha \) between the primary and branch fractures on the flow rate of the solution, the \( \alpha \) was successively adjusted to 45°, 60°, 90°, 120°, 150°, and 180° for simulation.

The Reynolds number (Re) at the inlet is defined as follows [15]:

\[
Re = \frac{\rho Q}{\mu w}
\]

(4)

where \( Q \) is the flow rate of the fluid, \( w \) is the depth of the fluid perpendicular to the flow surface.

Velocity distribution is shown in Figure 2 when the inlet Re was 1 and 100, respectively. With the increase of \( \alpha \), the fracture velocity of the right branch increased significantly, and that of the left branch decreased gradually. When \( \alpha = 150° \), the average flow velocity of the right branch fracture exceeded that of the left branch fracture and reached the highest value when \( \alpha = 180° \).

Compared with Figure 2a and Figure 2b, Reynolds number significantly influences the flow velocity distribution of cross fracture solution. The following will further explore the influence mechanism of Reynolds number on the flow velocity distribution on the cross fracture solution.
3.3.2. Flow Distribution Rate of Branch Fracture

The flow distribution rate (Ra) was defined as the ratio of the flow rate of the single branch fracture to the flow rate of the primary fracture to represent the flow characteristics of the solution. Thus, the sum of the Ra of each branch fracture was 1. Combined with the Navier-Stokes equation, the flow characteristics of the solution in the cross fracture were studied to explore the nonlinear change of Ra with a change in Re at the inlet and on the migration law of the solution in the cross fracture.

According to the simulation results under different conditions, the flow distribution rate of the left and right branch fractures was calculated. The flow was the line integral (cm$^2$/s) of the flow velocity at the inlet and the exit of the left and right branch fractures. The results were plotted as Re-Ra and $\alpha$-Ra curves, as shown in Figure 3 and Figure 4.

According to the Re-Ra curve, when $1 \leq \text{Re} \leq 5$, there is a weak nonlinear relationship between Ra and Re, and the change of the Ra caused by Re change is less than 1.5%. Also, when $5 < \text{Re} \leq 100$, the nonlinear relationship between Re and Ra is enhanced. For cross fractures at $\alpha = 45^\circ$, the maximum variation range of distribution is more than 30%, and the Re-Ra curve is approximately a quadratic function. When Re $> 100$, the nonlinear relationship between Re and Ra gradually weakens, and Ra tends to be stable.

When $\alpha$ is small, the Ra of the right branch fracture decreases with the increase of Re. For $\alpha = 45^\circ$, the right branch fracture always maintains the lowest distribution rate. When $\alpha$ is larger than the angle between the primary fracture and the left branch fracture, the distribution rate of the right branch fracture exceeds 50% and continues to increase with the increase of $\alpha$.

As shown in Figure 4, when Re is low (Re = 1), Ra is not affected by $\alpha$ and is always stable at 50%. With Re increases, the variation amplitude of $\alpha$-Ra curve increases gradually. When Re = 90, the maximum variation amplitude of $\alpha$-Ra curve is obtained. When the primary fracture and the two branch fractures have the same angle $\alpha_s = 135^\circ$, Ra is stable around 50% for any Re value. When Ra is

**Figure 2.** (a) The distribution of flow velocity in the $\alpha$ cross fracture is roughly the same when Re = 1, the primary fracture of the maximum velocity of fracture twice, around the fracture velocity distribution is similar, (b) For Re = 100, each different $\alpha$ with different velocity distribution results. When $\alpha$ was 45° or 60°, the left fracture’s average velocity was greater than the right.
not affected by Re, the angle $\alpha_s$ has the following relationship with the angle $\beta$ of the two branch fractures:

$$\alpha_s = \frac{2\pi - \beta}{2}$$

(5)

Figure 3. The relationship of Ra with Re.

Figure 4. The relationship of Ra with $\alpha$.

3.3.3. Growth Law of Calcium Carbonate in Cross Fractures

Combined with the above solution migration rules, the $\alpha = 45^\circ$ model, which is the most sensitive to Reynolds number Re, obtained the growth rules of calcium carbonate in cross fractures under the two conditions where Re at the inlet is 1 and 100, respectively, as shown in Figure 5a and Figure 5b.

When Re = 1, the calcium carbonate precipitates in the two branch fractures are the same. When Re = 100, the maximum calcium carbonate concentration in the left branch fracture is 60.2 mol/m$^3$, significantly higher than in the right branch fracture. Under the influence of flow distribution rate, bacteria, urea, and other substances migrate along with a large amount of solution in the left branch fracture, resulting in higher calcium carbonate precipitation.

Secondly, as the microbial cells are more likely to adsorb and deposit near the fracture wall, the wall becomes the base bed for the chemical reaction and calcium carbonate crystal formation such that a large amount of calcium carbonate is precipitated on the fracture wall at the initial stage. As time increases, the calcium carbonate crystals gradually develop toward the center of the fracture.

Figure 5. Growth rule of calcium carbonate.
3.3.4. Effect of Aperture on Calcium Carbonate Precipitation

According to the Re-Ra and α-Ra curves (Figure 3 and Figure 4), when Re is small, α has a weak influence on the flow distribution rate. Therefore, to minimize the effect of α, Re=1 was employed at the inlet, the number of branch fractures was increased, the aperture of each branched fracture was changed, and the seepage field and calcium carbonate precipitation rules of complex cross fractures were explored.

The seepage field was simulated (Figure 6) using different apertures (0.5 mm, 0.7 mm, and 1 mm) and variable aperture cross fracture, and the results of 500 min of calcium carbonate precipitation are shown in Figure 7. For the same fracture aperture, the solution’s mean velocity and velocity distribution are similar, under the condition of low Re, with a very weak angular influence. However, for the variable aperture cross fractures, export 3 (1 mm) is the advantageous flow channel of the solution with a velocity greater than that of export 1 (0.5 mm) (Figure 6d). At low Re, the solution flow rate of the variable aperture cross fracture positively correlated with its aperture.

Analysis of calcium carbonate precipitation results in Figure 7a showed a higher calcium carbonate concentration (86.8 mol/m³) in the branch fractures than the primary fractures. Comparison between Figure 7a, Figure 7b, and Figure 7c showed that the amount of calcium carbonate concentration reduced to from 86.8 mol/m³ to 29.2 mol/m³ in the fracture with different apertures, mainly due to the low aperture fracture. In addition, the bacterial cells of the lateral migration space are relatively small. The fracture surface can also absorb more cells, such that, Ca²⁺ and CO₃²⁻ has a higher probability of migration to the fracture surface and precipitation to form crystallization to produce a higher concentration of calcium carbonate precipitate. However, in the cross fractures of the varied aperture, although the apertures at outlet 1 and 2 are smaller, there is a higher concentration of calcium carbonate precipitate at outlet 3. It is speculated that the branching fractures with larger apertures can form the dominant solution channel, resulting in a higher flow distribution rate, producing more calcium carbonate precipitates.

4. Discussion
In Figure 4, the curves of the different Res converged at point (135°, 0.5), at αs= 135° for both the primary fracture and the two branch fractures. In addition, Ra was not affected by changes in Re. It can be inferred that the αs value is closely related to β, by the equation (5): αs=(2π-β)/2. In this study, β was fixed at 90°. The value of αs and its change rule may be related to the junction fracture shapes. This may change the β and the shape of the fracture junctions. Hence, investigation of multiple
directions of $\alpha_s$ can be considered in future studies.

In addition, this study employed a simplified fracture geometry with several assumptions compared to the actual project conducted in a highly complex geological environment with a complicated fracture network of microbial induced calcium carbonate precipitation. Will try to consider fracture network under the condition of different roughness (JRC) solution of migration and precipitation of calcium carbonate, constantly improve cross fracture model of the calcium carbonate precipitation.

5. Conclusion

Based on the Navier-Stokes equation for solute migration and chemical reaction, the laws of solution migration and carbonate precipitation in the cross fracture network in rock mass were analyzed. The main conclusions are summarized as follows:

1. Under the condition of two branch fractures, when $1 \leq \text{Re} \leq 5$, $Ra$ and $Re$ have a weak nonlinear relationship, and $Ra$ is not affected by $\alpha$. When $5 < \text{Re} \leq 100$, the nonlinear relationship between $Re$ and $Ra$ is enhanced. For the angle between $45^\circ \leq \alpha \leq 180^\circ$, $Ra$ and $\alpha$ show a positive correlation due to inertial force. When $Re > 100$, $Ra$ tends to be stable gradually and no longer changes significantly with the increase of $Re$.

2. The influence of the $Re$ at the inlet and angle between the primary and branch fractures on the calcium carbonate precipitation in the cross fracture is mainly achieved by changing $Ra$’s dominant flow distribution rate.

3. For different branched fracture aperture models, the low aperture fractures are more likely to produce higher concentrations of calcium carbonate precipitates at the same solution flow.

6. References

[1] Huiying L and Hongwei S 2007 Chongqing Jiaotong Daxue Xuebao, Ziran Kexueban 26 54-56,64
[2] Yongliang L 2017 Analysis and research on the cause of water leakage in deformation joint of urban operation tunnel (Tianjing: Hebei University of Technology)
[3] Qingwen L 2005 The study of waterproofing techniques in metro (Chengdu: Southwest Jiaotong University)
[4] Kirkland C M, Thane A and Hiebert R 2020 J. Pet. Sci. Eng. 190 0920-4105
[5] Liyang Y, Chaosheng T, Yuehan X, Chao L, Ningjun J and Bin S 2019 Yantu Lixue 40 2525-46
[6] Phillips A J et al 2016 Environ. Sci. Technol. 50 4111-17
[7] Jasinski L and Dabrowski M 2018 J. Geophys. Res.: Solid Earth 123 242-263
[8] Singh K K, Singh D N and Ranjith P G 2015 Rock Mechan and Rock Engineering 48 987-1000
[9] El Mountassir G, Lunn R J, Moir H and MacLachlan E 2014 Water Resour. Res. 50 1-16
[10] Chuangzhou W, Jian C, Shifan W and Hong Y 2019 Eng. Geol. 249 23-30
[11] Tobler D J, Minto J M, El Mountassir G, Lunn R J and Phoenix V R 2018 Water Resour. Res. 54 8295-308
[12] Xuerui W and Udo N 2020 Adv. Water Resour. 140 0309-1708
[13] Minto J M, Lunn R J and El Mountassir G 2019 Water Resour. Res. 55 7229-45
[14] Richeng L, Yujing J, Bo L, Xiao shan W and Bangshu X 2014 Yantu Lixue 35 2394-400
[15] Richeng L, Yujing J, Shuchen L, Bo L and Xiao shan W 2015 Yantu Lixue 36 1581-90

Acknowledgments

The financial supports from the National Natural Science Foundation of China (No. 41602290) and the Open Foundation of the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection (Chengdu University of Technology) (No. SKLGP2017K012) are greatly acknowledged.