Anisotropic Propagation of Chemical Grouting in Fracture Network with Flowing Water

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ABSTRACT: This paper presents an experimental investigation on the propagation of chemical grouting in a two-dimensional permeated fracture network with various aperture widths. As grouting engineering is often concealed in most experiments, the propagation of grout in fractures is not fully understood. The anisotropic permeability of geological masses with different aperture widths was found and has been investigated since 1960. The deflection flow effect was first found by Tian for groundwater flow in two groups of fractures with different aperture widths. Field grouting indicated that the grout propagates along a group of fractures with larger apertures that are longer while propagating a shorter distance along fractures with small apertures. This phenomenon implies a deflection for grout propagation in fractures with different aperture widths. The results of our study confirm this and indicate that there would be an anisotropy of grout propagation when the two groups of aperture widths are different. The water flow conditions also cause the difference in grout propagation length. When the aperture widths of the two groups of fractures are the same, the propagation shows symmetrical ellipse propagation. The results show the anisotropy of the grout increases as the aperture width ratio increases. This study helps in understanding the mechanism of chemical grouting in fractures with different apertures and flowing water and outlines some implications for grouting design in a fractured rock mass.

1. INTRODUCTION

Grout is widely used in underground engineering and mining to deal with water inrush or seepage issues. Geological faults and fissures usually create a pathway for groundwater, which often causes groundwater inrush accidents, contributing to more than 90% of the total groundwater inrush accidents and seepage problems in underground tunnels and mines, according to statistics; therefore, grouting in fractures with flowing water is commonly employed to manage the groundwater inrush or seepage problems found in underground rock engineering and mining.¹,²

Grout propagation in a single fracture was considered as a basis for understanding grout propagation in a fracture network. The factors influencing the penetration length, sealing efficiency, design, and practice were discussed in refs 2−5. Different equations for the penetration length or radius of the Newtonian and the Binghamian fluids into an ideal parallel fracture were proposed.⁶−¹⁵ The fracture aperture width, grouting pressure, grouting time, and grouting material properties, such as viscosity, were considered in the calculation of the penetration length.¹⁶−¹⁸ Fracture dilation and fracture−fracture interaction during grouting were also investigated by Gothäll and Stille,¹⁹,²⁰ who developed a model to predict fracture dilation during grouting and concluded that the dilation of fractures may facilitate grout penetration in fractures that already are sealable.

Most natural fractures exist in the form of fissure networks, so the investigation of the propagation of grout in the fissure network is more in line with the actual situation and geological conditions. Analytical, experimental, and numerical methods were developed to simulate grout propagation in fracture or fracture networks.⁴,²¹−²⁷ For example, Zhan et al. developed a model to calculate the penetration length in a fracture with flowing water.²² The influence of flowing water on the propagation of grouting and joint strength was investigated.²⁸,²⁹ The results of the investigation showed that the grout propagation front changes from a circular shape in standing water into an elliptic or a U-shape in a fracture with flowing water.²³,²⁴ A two-phase flow model for a Bingham fluid in a single fracture was presented by Zou et al. and then generalized and improved to yield-power-law fluids in a

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network of fractures. Transparent soil experimental techniques were used to investigate the spread of chemical grouts in a three-dimensional fissure network and the results of penetration length were validated.

The anisotropic permeability of rock mass with different aperture widths was found and has been investigated since 1960. Snow found that anisotropic permeability is proportional to the average of the cubes of apertures, and the coarse ones dominate the permeability. Tian found that the water flow is biased to the side with a wider fissure in the cross-fracture model with unequal fissure widths, which is called the “deflection effect.” Wilson and Witherspoon conducted a series of experiments to investigate the interference effects at fracture intersections using circular conduits. Their results indicated that the interference effects are negligibly small when the flow is in the laminar regime. Tsang and Neretnieks found that the flow channeling or preferred flow path is a common phenomenon for water flow in heterogeneous fractured rocks. “Flow channeling” was defined as “the phenomenon that liquids flow through a geologic system with its heterogeneous structure focused along a few preferred pathways” by Tsang and Neretnieks. Neretnieks and Larsson et al. presented studies that showed that the transversal spread of solute particles, the channeling width, and the related quantity depend on the heterogeneity structure of a fracture aperture. Johnson et al. found that the flow of the cracks with variable aperture would lead to the channeling phenomenon and the flow channeling of the intersected fracture with rough walls significantly enhanced the mixing of the two solutes. Wennberg et al. pointed out that most fluid flows mainly occur in a few dominant channels, and channeling is obvious in shear fractures. Zou et al. numerically simulated the fluid flow and solute transport through three-dimensional cross rock fissures, intuitively showing the channeling phenomenon and pointing out that the change of the local pore size is an important variable for the channeling phenomenon.

The anisotropic permeability has been also found in porous geological mass. Margolin et al. studied the influence of the geometry of fracture and the diameter change of void on fluid using a three-dimensional fracture model and found that the channel effect increases with the increases in pore diameter change rate and lattice sparseness. Ishibashi et al. evaluated the heterogeneous aperture distributions, resulting in channeling flows for granite fractures of various sizes under confining stress. Zhang et al. studied the distribution of high permeability zones and the pore radius of the preferred seepage channel and proposed a quantitative analysis method as well as a blocking scheme for the preferential flow paths. Yang et al. conducted a comparative study of Darcy and non-Darcy seepage flows with high flow rates using cross fractures with different split width ratios and different roughness and found that the phenomenon of deflection flow was obvious under non-Darcy conditions and also increased with the increases in split width ratio and roughness.

The phenomenon of the anisotropic propagation of grout in fracture has drawn the attention of researchers because it will influence the design of the layout of the grouting boreholes, grout take rate, etc. Rafi and Stille studied the mechanism of elastic jacking and the influence of the change in fracture aperture on the grout spread, transmittance, and permeability of slurry. Lin used a two-dimensional distinct element method program (UDEC) to simulate the seepage of a fractured rock mass in a high-pressure tunnel and obtained the preferential flow passage and seepage control effect rule of fractured rock. Xu et al. developed full-scale modeling equipment with an aperture ranging from 0.2 to 8 mm that could run under a high grouting pressure and high water pressure. They concluded that for grouting in deep underground rocks via pregrouting from the surface, a final grouting pressure set to two times the groundwater is acceptable. Wang found that when the grouting pressure and the injected grout amount remain constant, the diffusion radius increases rapidly with the fracture aperture and the amplitude of variation is relatively large.

The above-mentioned progress of the research on grout propagation has deepened our understanding of the grouting mechanism in the fracture network; however, due to the limitation of the test conditions, many experiments need to split the model to observe the diffusion of slurry, and the propagation of the slurry was inferred but was not monitored in real-time. Numerical simulations are often limited by the constitutional relationship and algorithm, and model verification is difficult. Considering the complexity of geological conditions and the concealment of grouting engineering projects, we suggest that most of the grouting projects still rely on the experience for design and construction; therefore, there are still many issues that need further study for grouting in the fracture network. The anisotropic propagation of the grout due to the deflection flow effect in fractures with different aperture widths is one issue among them that needs addressing. Consequently, the purpose of this study was to investigate the phenomenon of anisotropic propagation of grout in fractures with different aperture widths and with flowing water using scale model tests. The influence of flowing water on the anisotropic propagation of grouts was also investigated. The findings contribute to the potential evaluation of the water-blocking effect and grouting design.

2. RESULTS AND ANALYSIS

Figure 2 shows the grout propagation in the four trials with an initial water flow rate of 2 cm/s. Images from 10 screenshots with an interval of 5 s were chosen for the analysis. In Trial M1, the grout preferentially propagated along the fractures with an aperture width of 2 mm, showing obvious dominant paths, which appeared to have a diffusion pattern within fractures of 2 mm as the backbone and within 1 mm cracks as branches. In Trial M2, the grout spread in a symmetrical shape with the horizontal line where the grouting borehole is located because the aperture widths of the two groups of fractures are both 2 mm. In Trial M3, the grout preferentially spread along the 3 mm fractures. The dominant paths of grout propagation because the difference in the aperture width was obvious, which had a diffusion pattern with 3 mm fractures as the backbone and 2 mm fractures as branches. In Trial M4, the grout preferentially diffused along the 4 mm fractures after entering the fractures. Compared to Trial M3, the dominant path was more obvious. This indicates that the greater the difference in the fracture aperture widths between the two groups, the more obvious the anisotropy of grout propagation caused by the difference in aperture widths.

Figure 2a shows the penetration length in fractures with different aperture widths, and Figure 2b shows the difference and ratio of the major to the minor axis length of the propagation ellipse outline surrounding the penetration lengths in the two groups of fractures. In Trial M1, the difference in...
the penetration length of the grout in the two groups of fractures was the largest and most obvious. The ratio of the major to the minor axis length of the propagation ellipse in the two groups of fractures was from 2.45 to 2.57. In Trial M2, the total penetration length in the two groups of fractures was the same because they both had the same aperture width. In Trial M3, the difference in the total penetration length in the two groups of fractures fluctuated between 0 and 20 cm. The ratio of the major to the minor axis length was 2.14 at the beginning and stabilized at approximately 2.18–2.41. In Trial M4, the difference in the major to the minor axis propagation ellipse in the two groups of fractures was less than that in Trial M3 because of the lower grout in Trial M4. The difference in the total penetration length varied from 0 to 20 cm; the ratio of the major to the minor axis propagation ellipse was 1.95–2.42, quite close to that in Trial M3.

Figure 3 shows the grout propagation of the other four trials with an initial water flow rate of 3 cm/s. In Trial M5, after the grouting started, the grout preferentially propagated along the fractures with an aperture width of 2 mm, and the dominant path was obvious. When the grout flowing within 1 mm fractures reached the intersection of the fractures, it preferentially spread along the 2 mm fractures. In Trial M6, since the aperture widths of the two groups of fractures were both 2 mm, the grout propagation still formed a symmetrical shape like in Trial M2. In Trial M7, the grout preferentially spread along the 3 mm fractures, and the dominant path of propagation was more obvious due to the different aperture widths. In Trial M8, after entering the fracture, the grout preferentially spread along the 4 mm fractures. Its dominant direction was more obvious compared to that in Trial M3 due to the larger water flow rate.

Figure 4a shows the penetration length, and Figure 4b shows the difference and ratio of the major to the minor axis length of the propagation ellipse in the two groups of fractures. In Trial M5, the difference in the total penetration length of the grout in the two groups of fractures was the biggest, and the difference was the most obvious, ranging from 20 to 90 cm. The ratio of the major and the minor axis lengths of the propagation ellipse in the two groups of fractures was decreased from around 2.64 to 2.16. In Trial M6, the total penetration length in the two groups of fractures and the ratio of the major to the minor axis lengths was still approximately the same around 1.40–1.70. In Trial M7, the difference in the total penetration length in the two groups of the fractures varied from 0 to 20 cm, and the ratio of the major to the minor axis lengths of the propagation ellipse was approximately from 1.96 to 2.22. In Trial M8, due to the increasing grout take rate, the grout reached the edge of the model at 40 s after the beginning and then flowed out of the model. In the first 40 s, the difference in the total penetration length in the two groups of fractures varied from 0 to 40 cm, which was larger than that for the initial water flow rate of 2 cm/s. The difference and the ratio of the major to the minor axis lengths of the propagation ellipse was larger compared to that in Trial M7 in the first 30 s, showing a more obvious difference.

3. DISCUSSION

3.1. Influence of Aperture Width and Water Flow Rate on the Anisotropy of Grout Propagation. The propagation of the grout showed a symmetrical propagation pattern in the fractures when the aperture widths of the two groups of fractures were the same. The propagation of the grout in the fracture network showed anisotropy due to the
different aperture widths because when the grout was injected into the fracture network, the flow rate and pressure increased, whereas the geometry of the network did not change until the grout gelled. Figure 5 shows that the grouting pressure increases rapidly after the start of grouting and has a trend of increasing despite the locations of sensors 6 and 7. The mixed grout and water that flowed in the fractures with flowing water had the same way of flowing as observed for water. The deflection flow effect for grout propagation occurred in the fractures with different aperture widths, which occurred for groundwater flow in fractures with different aperture widths. When the grout gelled, the propagation shape of grout remained in fractures. The results showed that the existence of flow water increases the effect of the anisotropy of the grout propagation due to the different fracture apertures. When the rate of flow water increases, the propagation anisotropy of the grout caused by the difference of the aperture width becomes more obvious.

The aperture ratio is defined as the ratio of the larger fracture aperture width to the smaller fracture aperture width in the two groups of fractures; therefore, its value is not less than 1. In the above-discussed trials, the aperture ratio was 2 for M1 and M5, where the maximum aperture width was 2 mm and the minimum was 1 mm; 1 for M2 and M6, where the minimum and maximum aperture widths were both 2 mm; 1.5 for M3 and M7, where the maximum aperture width was 3 mm and the minimum was 2 mm; and 2 for M4 and M8, where the maximum aperture width was 4 mm and the minimum was 2 mm. Figures 1–4 show that when the aperture ratio is greater than 1, the propagation of the grout shows anisotropy. The anisotropy of the grout increases as the aperture ratio increases.
Comparing Trials M1 and M4, we observed from Figures 1 and 2 that the propagation anisotropy of the grout in the two groups of fractures in M1 was more obvious than that in M4 under the same water flow rates. However, Figures 3 and 4 show that the propagation anisotropy for M5 and M8 is close. It shows that the aperture ratio cannot be the only index used for the evaluation and analysis of propagation anisotropy, and it should be investigated in future research (Figure 5).

3.2. Limitations and Further Study. Due to the substrain of the laboratory experiment, some remaining issues and limitations should be addressed in future research. For instance, the shape of the fracture network was simple and regular. The properties of the fracture network are challenging to investigate due to their complexity. A more complicated fracture network with different combinations, roughness, dimensions, inclinations, fluid–solid coupling, and gravity in grouting will be further investigated in the future. The water source and pressure is more complicated than in natural conditions, which were simplified in the experiment. In addition, grouting from multiple boreholes was not investigated; only grouting from a single borehole was studied. In the grouting practice, multiple borehole groutings are generally implemented, so the interactions among different boreholes should also be analyzed. The influences of water flow conditions on the anisotropy of grout propagation should be further investigated.

4. CONCLUSIONS

A series of experiments were conducted to investigate the anisotropic propagation of chemical grout in fracture networks with different aperture widths and flowing water. This study was inspired by the deflection flow effect for groundwater flow, which was first identified by Tian. The results showed that the grout propagation was elliptical in the horizontal fractures with an intersection angle of 60° and flowing water. The results also showed that there is anisotropy of grout propagation when the aperture widths of two groups of fractures are different, and the water flow conditions increase, the effect of the difference in the grout propagation caused by different aperture widths. The aperture ratio, which is defined as the ratio of the two groups of fractures by width, influences the anisotropy of grout propagation. The results indicated that the anisotropy of the grout propagation is more obvious as the aperture ratio increases when the aperture ratio is greater than 1. These findings help further our understanding of the mechanism of grouting in fractures with different aperture widths and flowing water. The results have some implications for grouting design in fractured rock masses.

5. MATERIALS AND METHODS

5.1. Chemical Grouts. The grout used in the experiment was a chemical grout with a modified urea-formaldehyde (UF) resin (Liquid A) as the main composition and an oxalic acid solution (Liquid B) as a curing agent. The gel time is the time required for the grout to cure the gel. According to previous research results, the volume ratio of Liquids A to B has an important effect on gel time. Figure 6 shows the viscosity changes of a mixture of Liquids A and B over time measured using a B viscometer. When the volume ratio of Liquids A to B was 1:1, the viscosity rise rate was the fastest, whereas it was the slowest when the volume ratio was 4:1. Before the solidification, the chemical properties of the grout were stable and the viscosity remained relatively the same. After solidifying, the grout stopped flowing and filled the voids and fractures to block water, reinforcing the rock and soil mass.
5.2. Rock Fractures. Polymethyl acrylic methylene, commonly known as acrylic or Plexiglas, with a high degree of light transparency (up to 92%), meets the requirements of this test and has high strength and hardness, with resistance to a variety of chemical corrosions. Figure 7 shows a schematic model of the fracture network, which consists of two plates: the lower one is 30 mm thick and the upper one is 20 mm thick. The entire size of the model is 580 × 1100 mm². There were five inlet holes on the right side of the lower plate and five outlet holes on the left side. There were nine holes drilled in the bottom surface, one for grouting and the others for monitoring the liquid pressures during grouting. A 20 mm wide and 10 mm deep groove was set on each left and right sides. The right one was used to transfer the water injected from the holes into a surface flow, the left one was used for discharge. The fracture network with a depth of 5 mm was cut on the lower plate. The intersection angle of the two sets of fractures was set to 60°. The blue lines in Figure 7 represent the fracture with an aperture width of 1, 2, 3, and 4 mm in the four models, respectively, named A1, A2, A3, and A4 in Table 1; the black lines represent the fracture with an aperture width of 2 mm. The aperture of model fracture was chosen per the International Society for Rock Mechanics, where the fractures with an aperture width of 1 and 2 mm belong to the type of “Open”, and 3 and 4 mm are considered “Moderately wide”.52

5.3. Experimental Setup. The purpose of this experiment was to explore the propagation of grout in the fracture network model under flowing water conditions. The main factors considered in the test included the aperture width of fracture, initial water flow rate, gel time of grout, and grout take rate. Figure 8 shows the experimental setup, which consisted of four parts: water level control, grouting, fracture network replica, and data acquisition.

5.4. Experiment Scheme. An orthogonal array of four factors and four levels is used to arrange the test; 16 trials are scheduled in Table 1, which lists the parameters selected in the experiment. The initial water flow rate was 2 and 3 cm/s (respectively, named B2 and B3 in Table 1). According to the aperture width exposed in many mining areas, one group is 2 mm wide and the other 1, 2, 3, and 4 mm, respectively, of which 1 and 2 mm is a type of open and 3 and 4 mm is a type of moderately wide. Considering the size of the model, the fissure space is small; the grout take is determined to be 30, 60, 90, and 120 mL/min, respectively, named D1, D2, D3, and D4 in Table 1; the gel time 48, 60, 72, and 84 s, respectively, named C1, C2, C3, and C4 in Table 1.

Table 1. Experiment Scheme for Grouting into the Fracture Network with Different Apertures and Flowing Water

| trial no. | symbol | A width of fracture no. 2 (mm) | B initial rate of water flow (cm/s) | C gel time (s) | D grout take rate (mL/min) |
|-----------|--------|-------------------------------|-----------------------------------|----------------|---------------------------|
| M1        | A1B2C2D2 | 1                             | 2                                 | 60             | 60                        |
| M2        | A2B1C1D4 | 2                             | 2                                 | 48             | 120                       |
| M3        | A3B2C4D3 | 3                             | 2                                 | 84             | 90                        |
| M4        | A4B1C3D1 | 4                             | 2                                 | 72             | 30                        |
| M5        | A1B3C3D3 | 1                             | 3                                 | 72             | 90                        |
| M6        | A2B3C1D1 | 2                             | 3                                 | 84             | 30                        |
| M7        | A3B1C2D3 | 3                             | 3                                 | 48             | 60                        |
| M8        | A4B2C4D2 | 4                             | 3                                 | 60             | 120                       |

*Note: the aperture width of fracture no. 1 was 2 mm.

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Notes
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