Research on the Grout Diffusion Law in Karst Fissure Media for Protecting Ordovician Limestone Groundwater Environment

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Abstract. Researching the internal features of the grouted media, fully understanding the property of the grouting material, comprehensively considering the concrete engineering geological situation have important significance for selection of grouting technology, arrangement of grouting equipment and design of grouting operation. In this paper, the factors influencing the flow law of the grout, including property of the grout, karst fissure features, and grouting technology, were provided. And the grout diffusion law in karst fissure media was analyzed to achieve the optimal grouting effect to protect Ordovician limestone groundwater environment.

Introduction

In grouted karst fissure media, factors such as the property of grout, the characteristics of dissolved fissures, the grouting technology act together on the flowing law of grout. The analysis on the influence of different factors on the grout diffusion effect is the precondition to study the flow process of the grout and to control the interaction of different factors so as to achieve the optimal grouting effect. Recognizing the internal features of the grouted media, fully understanding the property of the grout, comprehensively considering the concrete engineering geological situation have important significance for selection of grouting technology, arrangement of grouting equipment and design of grouting operation.

According to the analysis of the flow process of the grout, the factors influencing the flow law of the grout may be divided into property of the grout, karst fissure features, grouting technology and other factors. During grouting design, each factor must be taken into account, neglecting any factor will result in the consequence that the grouting effect cannot reach the expected one, even influence the safety of grouting operation.

Properties of the Grout

The properties of the grout include mainly grouting materials, particle diameter, water-cement ratio, viscosity, setting time, uniform stability, bleeding ratio and so on. Of them, the viscosity and its time-dependent nature are the core indexes influencing the diffusion of grout, while grouting materials, water-cement ratio and setting time are the major factors influencing the viscosity of grout they are discussed as follow.

Viscosity

The influence of the viscosity on grouting is reflected in the diffusion velocity and radius of grout in fractured rock mass. The viscosity determines the viscous resistance that the grout bears during diffusion, indirectly bringing forward requirement for control of grouting pressure and flow. The grout with high viscosity has poor fluidity, poor grout ability, but good stability, grouting operation is
easy to control; the grout with low viscosity has good fluidity, good grout ability, but poor stability, is easy to induce uneven grouting range.

For the same design of grouting, when the grout with poor maintaining ability of fluidity is selected, the grouting time is long, the required grouting pressure is high; when the grout with good maintaining ability of fluidity is selected, the grouting time is short, the grouting process is easy to control. When grout diffuses to the preset position, maintenance of fluidity will make the grout diffuse to the useless place, at this moment, it is hoed that the grout can lose rapidly the fluidity and remain inside the designed grouting boundary. This shows that the ideal manifestation of the grouting grout is: at the beginning of grouting, the viscosity is lower; during grouting, the viscosity does not change a lot, the maintaining ability of fluidity is high; when the grout reaches the preset position, the viscosity increases rapidly, the fluidity loses.

**Grouting Materials**

According to the properties and the use conditions, grouting materials are divided into two types: cement base grout and chemical grout.

Cement base grout includes ordinary Portland cement, superfine cement, cement-clay, cement-water glass, etc. Each kind of grout has different nature. Ordinary Portland cement forms stone body of higher strength, good endurance, has rich resources, low price, grouting equipment and technology are simple, but the particle size of the grout is not stable, it is easy to bleed and settle, the stability of the grout is poor, it is suitable for rock mass with higher fracture development degree, for rock mass with undeveloped fractures, because the particle size of the grout is relatively big, it is difficult to enter into thin fractures, grouting effect is poor. While the superfine cement has particle size much smaller the ordinary Portland cement, can enter into the fractures with smaller aperture, the cohesive force produced after coagulation of the grout is relatively big, the formed stone body has higher strength, grouting effect is good, but the superfine cement has high cost, is not suitable for grouting construction with large usage amount. The nature of cement-clay and cement-water glass grout is seriously influenced by the proportion of the two kinds of materials.

Grout composed of chemical materials has good stability, strong injectability, high seepage velocity, can adapt to different rock mass, and the gelation time of the grout can be adjusted artificially. But the defects of the chemical grout are also evident, for example, the stone body formed by it has strength lower than that formed by cement grout, poor endurance and high price, and generally the chemical grout has strong corrosivity and toxicity, higher requirements for grouting system and threat to workers’ safety. Due to its different grout materials, the chemical grout has evident properties, good adaptability to specific construction conditions. [3]

**Water Cement Ratio**

Water cement ratio is the weight ratio of water to cement used when mixing cement grout. When the water-cement ratio increases, the viscosity decreases with it, the flow resistance will also decrease with it, the diffusion distance increase, but the particles of the grout are easier to settle, the stability of the grout becomes poor. The cement volume injected into fractured rock mass is equal to the product of the water cement ratio and the injected grout volume. Under conditions of higher water cement ratio, although the the diffusion radius of the grout is bigger, the filling ratio of fractures will decrease, more bleeding water will also weaken the strength of stone body.

**Setting Time**

The setting time is the time from the mixture of grout materials with water to coagulation and no longer flowing of the grout.

The influence of the setting time on the grouting design is mainly reflected in: when larger diffusion radius is required in a grouting design, in consideration of the seepage velocity of the grout, the setting time of the grout must be long enough and is related to the grouting pressure; when moving groundwater is needed to consider in a grouting design, in order to prevent the prepared grout from
being diluted or washed away, the grout is required to congeal rapidly; when a grouting design is required to form rapidly the strength, the coagulation velocity also must be shortened correspondingly. The major factors influencing the coagulation of the grout include the nature of grout materials, burdening of grout and additives, etc.

**Fracture Features**

Fracture features include mainly aperture, roughness, occurrence, trace length, connectivity and filling status and so on. Of them, the key factors are aperture, roughness and connectivity of fractures. They are discussed separately as follow.

**Aperture**

The aperture of fractures refers to the perpendicular distance between two structural planes of a fracture, may be also called gap width. The aperture size of a fracture is related to lithology, texture of rock, roughness of fracture and filling degree. The aperture of fracture is an important indicator to measure the permeability of fractures, the larger the aperture, the larger the flowing space of grout, the smaller the flow resistance, the larger the diffusion radius of grout is under the same grouting pressure. The formula for the diffusion radius of newtonian fluid in smooth single fracture is as follows:

\[ P = \frac{6\mu Q}{\pi b^3} \left( \ln r - \ln r_0 \right) + P_0 \]  

Where, \( P \) is grouting pressure, MPa; \( P_0 \) is hydrostatic pressure, MPa; \( \mu \) is viscosity of grout, MPa·s; \( Q \) is grout flow, L/s; \( b \) is aperture of fracture, m; \( r \) is diffusion radius of grout, m; \( r_0 \) is radius of grouting borehole, m.

Thus it can be seen that when the grouting pressure keeps constant and the injected grout amount is also constant, the diffusion radius increases rapidly with the aperture of fracture and the amplitude of variation is relatively big.

The influence of the fracture aperture on a grouting design is reflected mainly in the selection of grout particle diameter, water cement ratio and grouting pressure. The critical fracture aperture allowing grout with different water cement ratio to inject, worked out by predecessors, is shown in table 1.

| Water cement ratio W/C | 0.6 | 0.8 | 1.0 | 1.5 | 2.0 | 3.0 | 4.0 | 6.0 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Critical fracture aperture /mm | 0.53 | 0.47 | 0.46 | 0.44 | 0.43 | 0.37 | 0.30 | 0.32 |

The classification of fracture aperture is shown in table 2. The major factors influencing the size of fracture aperture include mainly fracture scale and mechanics cause. Generally large fractures are enlarged gradually from the tip of small fractures, therefore, the larger the fracture scale is, the larger the aperture is. Analyzed from the mechanics formation process, the stress of two structural planes of tensile fractures same but in opposite direction, resulting in larger aperture; while compression or compression-shear fractures are effected by compression, the aperture is restricted and smaller. The measurement methods of fracture aperture include filler gauge(for large fractures) and photography image(for thin fractures).
Table 2. Classification of fracture aperture.

| State description | Fracture aperture /mm | Class        |
|-------------------|------------------------|--------------|
| Very close        | <0.1                   | Closed fracture |
| Close             | 0.1~0.25               |              |
| Partially open    | 0.25~0.5               |              |
| Open              | 0.5~2.5                | Cracking fracture |
| Medium wide       | 2.5~10                 |              |
| Relatively wide   | 10~100                 |              |
| Very wide         | 100~1000               | Open fracture |
| Cave-like         | >1000                  |              |

As shown in figure 1, grout flow increases with fracture aperture, the increase amplitude of flow is much bigger than that of fracture aperture. Within the same time, more grout enters into the fractures with large aperture, and the diffusion distance is also big. When the fracture aperture increases to certain value (0.3mm in the figure), grout flow tends to increase first and then decrease, the reason is that after grout diffusion reaches certain distance, the grout pressure at the most significant end decreases gradually, the flow velocity slows down, the energy required for overcoming fracture resistance increases, all this delays the step of entrance of subsequent grout into fractures. Thus it can be concluded that for the same fracture, the initial grout flow is big, the grout flow at the middle and later periods decreases gradually.

![Figure 1. Influence of the aperture of fracture on grout flow.](image)

**Roughness**

Roughness refers to the roughness level of the structural plane of fractures. The influence of roughness on grout diffusion is mainly to reduce the cross section of flow paths, to produce flow resistance, and to retard grout flow. The methods describing the roughness of structural plane of fractures include mainly characterization of height of projection, joint roughness coefficient (JRC) and characterization of fractal dimension. \(^{[4]}\)

During seepage of the same grout in the same rock mass, in unit time, the flow passing through a wide but rough fracture is equal to the flow passing through a narrow but smooth fracture. In this case, the seepage effect of the two kinds of fractures is accordant, the gap width of the smooth fracture may be considered as the equivalent hydraulic gap width.
Connectivity

The connectivity of fracture includes two aspects: one is the connectivity of a single fracture, for single fracture, two structural planes are not always completely separated, have point or surface contact, the contact area is equal to the total area of the points and the surface, the distribution of the contact surface in single fracture is influenced by the complex factors such as the distance of the structural planes and the lithology, at present no direct measurement method is available, the contact surface can be only indirectly estimated through grout diffusion test; another is the connectivity among fractures, the intersection of fractures forms fracture network, the passage of grout from a fracture to another fracture is influenced by the aperture, the strike and the dip of fractures, the diffusion law would also change.

For the connection of fracture network, generally interconnected fractures are unparallel, and have certain included angle, this determines the uncertainty and the complexity of the diffusion channels of the fracture network. According to the classification of connectivity, fracture network is divided into completely connected fracture network, partially connected network and non-connected network.

Connected fracture network: any fracture in rock mass is connected with one or several fractures, each fracture has at least two openings, within the borehole rock mass, there is no fracture with dead end. Thus it can be seen that the connected fracture network has very rigorous conditions, so to speak, it is an idealized status. In actual engineering rock mass, completely connected network does not exist, while in order to study related problem, people builds such kind of model. Partially connected fracture network: the two ends of fractures in rock mass are connected with another fracture, form one way channel, in the fracture, there are multiple entrance and exits of grout, composing complex diffusion channel network; some fractures have only one end connected with another fracture, forms fracture with dead end. This kind of fracture network reflects the reality of general engineering rock mass, is relatively practical, but complicated to analyze. During grouting, under action of grouting pump pressure, grout flows firstly in the connected fracture network, the pressure drives the grout to continuously search for a connected network at the rear, in the fractures with dead end, when the grouting pressure increases to certain value, the grout will split off constantly the tip until the grout pressure is balanced with the splitting stress, the split fractures connect possibly another fractures to form new diffusion channels, also possibly exist in form of fractures with dead end.

Non-connected fracture network: two or several fractures are interconnected, form local fracture set, some fractures are not connected with other fractures, there is no connection between fracture sets, it is called independent system. After entering into a fracture set, grout diffuses inside the fracture set rather than infiltrate to another fracture set, there is basically no permeability in the wboolesterol rock mass. This kind of rock mass has minimum probability of existence, mainly occurs in undisturbed elastic intact rock mass.

Grouting Factors

Grouting technology includes grouting technology, grouting pressure and amount, is discussed separately[5].

Grouting Technology

Commonly used grouting technology includes filling grouting, permeation grouting, fracturing grouting, etc.

Permeation grouting refers to that under grouting pressure, slurry permeates slowly into fractures or voids in rock mass to play role of reinforcement and water shutoff. The permeability of slurry and the grouting effect are seriously influenced by the development and the occurrence of fractures and voids. For larger fractures or voids, equipment can be used in advance to clean the fillings existing in voids, then cement slurry, clay slurry and water glass are injected, similar to filling grouting, the required pressure is not too high, formed stone body has high strength. In order to improve the grouting effect,
the grouting pressure can be increased to augment the diffusion extent of slurry, but under higher grouting pressure, the safe stability of the grouted rock mass is seriously threatened, therefore careful consideration is needed. For medium and tiny fractures, the grouting effect is codetermined by the permeability of fractures and voids as well as the own properties of the slurry. The setting time of grout influences the selection of the grouting pressure, but when the diffusion extent reaches certain degree, the diffusion velocity of the grout slows down, the slurry coagulates, stays in fractures, block diffusion channels, resulting in increase of subsequent grouting pressure. Therefore, the reasonable selection and combination of grouting slurry and pressure decides the effect of permeation grouting.

Fracturing grouting is to increase grouting pressure, makes the grout open continuously fractures under high pressure to increase diffusion cross section or open fractures with dead end so as to form new diffusion channels. Fracturing grouting is favorable for the further extension of fracture network and increase of the permeability in rock mass, higher grouting pressure will results in heaving rock mass surface even collapse, casing safety accident. It is suitable for rock mass with higher strength and lower permeability.

Grouting Pressure
Grouting pressure is an important factor influencing the grouting effect of rock mass, is reflected in following aspects:

a) Grouting pressure provides grout with the initial velocity power to flow in fractures as well as energy for overcoming different resistance. With the ultimate breaking strength of rock mass, the higher the grouting pressure, the bigger the diffusion radius of grout, the better the grouting effect.

b) The amplitude of grouting pressure reflects the magnitude of the force of grout on the structural plane of fractures, decides the speed, the degree and magnitude of grout pressure on the opening and fracturing process of fractures.

c) The magnitude and pattern of manifestation of grouting pressure decide the coupling mode and degree of grout- surrounding rock stress. In field operation, there is no identical standard for selection of grouting pressure, it relies often on experiences, and codetermined by influencing factors such as properties of grout, stress and permeability of surrounding rocks as well as groundwater.

Grout Amount
An important index for measuring the grouting effect is grout amount, in the same volume of rock mass, the more the injected grout amount, the smaller the porosity in rock mass, the higher the strength of formed stone body is. At the same time, more injected grout will make the grout have larger diffusion radius.

Summary
In grouted karst fissure media, factors such as the property of grout, the characteristics of dissolved fissures, the grouting technology act together on the flowing law of grout. The analysis on the influence of different factors on the grout diffusion effect is the precondition to study the flow process of the grout and to control the interaction of different factors so as to achieve the optimal grouting effect.

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