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Radial penetration of cementitious grout – Laboratory verification of grout spread in a fracture model

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ABSTRACT

During the past two decades of research and development in the field of grouting in hard jointed rock, the design process has taken a number of significant leaps forward. A grouting design in hard rock can now be based on the penetration length of grout in individual rock fractures. For cementitious grouts, the most common rheological model used is the one for a Bingham fluid. The model is a conceptualisation of grout spread where two rheological properties of the grout – viscosity and yield stress – govern the penetration length along with the fracture aperture and applied grouting overpressure.

This paper focuses on verification of radial Bingham flow of cementitious grout using a fracture model constructed from acrylic glass. Each test conducted using the fracture model was filmed, allowing the grout spread to be analysed as penetration length over time. The measured penetration lengths were then compared with analytical solutions derived for Bingham grout in a plane parallel fracture.

The results indicate that the penetration of cementitious grout in fracture apertures of 125 μm and 200 μm is verified for up to 40% of the maximum possible penetration length. This can be compared to normal grouting, where the penetration lengths achieved are around 20% of the maximum penetration length.

1. Introduction

During the past two decades of research and development in the field of grouting in hard jointed rock, the design process has taken a number of significant leaps forward. A grouting design in hard rock can now be based on the penetration length of grout in individual rock fractures. Gustafson and Stille (2005) show how a grouting design can be created. The design includes taking into account the apertures of the fractures in the rock mass, the type of grout used, the rheological properties and the grouting procedure, i.e. pressure and grouting times.

In the case of cementitious grouts, the most common rheological model used is the one for a Bingham fluid. The model is a conceptualisation of grout spread where two rheological properties of the grout – viscosity and yield stress – govern the penetration length along with the fracture aperture and applied grouting overpressure. The shear stress (from the motion) must be greater than the yield stress of the grout for the fluid to move. The Bingham model is easy to apply when calculating the penetration length, which is probably why it is so widely used. The maximum possible penetration length for a cementitious grout depends on the applied pressure (Δp [Pa]), the fracture aperture (b [m]) and the yield stress of the grout (τ_0 [Pa]) (Lombardi, 1985; Hässler, 1991).

One critical parameter that has been a source of debate is the hydraulic aperture. When conducting hydraulic tests in boreholes, a robust value for the hydraulic aperture can be derived by using the well-known "cubic law". The question of whether the hydraulic aperture represents the geometrical aperture field of a fracture entirely will not be discussed in this paper. However, it appears to be sufficient for the purposes of grout flow estimations, and it is used in this paper.

Not all fractures are equal in size, Gustafson and Fransson (2006) suggest the use of the Pareto distribution to describe in statistical terms the hydraulic apertures of fractures encountered in core drilling. This is coupled with hydraulic tests performed in the borehole. Thörn et al. (2015) facilitated the analysis with a calculation tool designed to determine the fracture distribution and aperture distribution of the fractures that intersect a cored borehole.

In Gustafson et al. (2013), a full derivation of a radial Bingham flow in a fracture is described. The grout used is a cement suspension with a yield stress and a viscosity. In the same paper, the formulation for one-dimensional flow is verified using results from Håkansson (1993).

This paper deals with verification of radial Bingham flow of cementitious grout using a fracture model constructed from acrylic glass.

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Each test conducted using the fracture model was filmed, allowing the grout spread to be analysed as penetration length over time. The properties of the cementitious grout were checked using field tests (see e.g. Fransson et al., 2016) to measure density, yield stress, flowability and penetrability.

2. Method

The Bingham model is used in this context to characterise a cement suspension. Its characteristics are yield stress (τ_0) and plastic viscosity (μ_g). Dai and Bird (1981) formulated the differential equation for the pressure distribution for Bingham flow and Hässler (1991) solved the equation numerically. According to Hässler (1991), the velocity ($v_g(r)$) of the Bingham fluid in a circular disc under a pressure gradient (dp/dr) can be described as

$$v_g(r) = -\frac{dp}{dr}\cdot\frac{b^2}{12\mu_g}\cdot\left[1-3\cdot\frac{Z(r)}{b}+4\cdot\left(\frac{Z(r)}{b}\right)^3\right],\quad r_b \leqslant r \leqslant r_b + I. \tag{1}$$

where b is the aperture between the plates and $Z(r)$ is the half Bingham plug thickness. Z is then a vertical coordinate starting from the centre of the motion (the centre of the open space between the plates). The plug thickness ($Z(r)$) depends on the yield stress (τ_g) of the grout according to:

$$Z(r) = \frac{\tau_g}{\left|\frac{dp}{dr}\right|} = \frac{\tau_g}{-\frac{dp}{dr}},\quad Z < \frac{b}{2}. \tag{2}$$

It can be seen that the plug thickness can only vary over the aperture and that it varies according to the pressure gradient. When the pressure gradient is high, i.e. when grouting commences, the plug thickness is small. As long as the penetration length continues to increase, the pressure gradient will decrease and the plug thickness will increase. The negative value of the pressure gradient is the result of the pressure decreasing from the borehole to the grout front.

2.1. Laboratory set-up

The laboratory set-up was created to demonstrate the flow between two parallel plates. The fracture model is made up of two 40 mm thick acrylic glass sheets, fastened together using 35 bolts. The aperture can be changed by placing washers (shims) of a known thickness (0.100, 0.050 and 0.025 mm) between the plates, close to the bolts. The aim of the bolt pattern is to minimise the expansion of the aperture when grouting. The plates are 1.8 m × 1.0 m (L × W) in size. The grouting hole (diameter = 50 mm) is placed equidistant to three sides, see Fig. 1. There is a rubber seal along the side of the acrylic glass.

Water pressure can be applied to the shorter edges, referred to as the upstream and downstream sides. This enables grouting to take place in an artificial groundwater gradient and it makes it easier to clean the model. The upstream pressure is connected to a water container and the downstream pressure to a container used to collect wastewater and grout. When these two pressures are set at the same level, the water pressure in the model remains stationary. The grouting pressure is then set at the total pressure, i.e. the sum of the stationary pressure and the overpressure. Pressure regulators ensure that the upstream and downstream pressures remain constant. The water flow in the model is regulated by altering the pressure of the upstream and downstream pressures.

Verification of the penetration length takes place by changing the aperture of the model and measuring the penetration length of the grout at different times. Each grouting test is recorded using an HD video camera. The recording is then used to determine the penetration length at different accumulated times and the grout front is drawn for each of the time steps. An example of a test is shown in Fig. 1.

The penetration length is then plotted against time for four different axes (upstream, downstream and the two sides). Fig. 1 illustrates the difficulty in estimating the penetration length in closed boundary conditions (oval shaped final penetration lengths). The boundaries will affect the penetration length when it reaches closer to the walls. However, for shorter period, the spread of grout is almost circular and up to 30 cm of spread, estimation of the penetration length can be done. The grouting trials in this paper are optimised to reach a certain length over a certain time not to reach the boundaries in such a way that comparison between theory and experimental data can be compared.

2.1.1. Grouting and framework design

The physical aperture between the plates is set using washers of precise thickness. When the plate set-up is complete, a hydraulic test is carried out to compute the hydraulic aperture using the well-known "cubic law". The flow through the fracture model is calculated by measuring the water collected in the waste container. The pressure through the packer is kept constant and the volume over time is derived.

The fracture model is designed for use with maximum 0.2 MPa pressure. FEM calculations was used for scoping the material dimensions at acceptable levels of deformation under maximum pressure

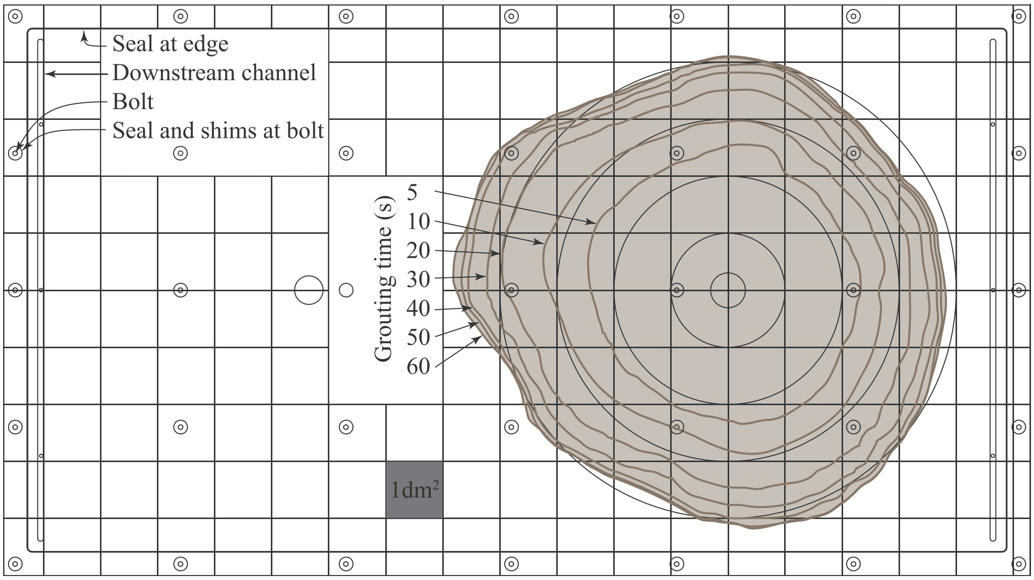

Fig. 1. Grout spread at 5, 10, 20, 30, 40, 50 and 60 s after grouting commenced.