RECENT ADVANCES IN MEASUREMENT OF GROUT PENETRABILITY, IMPROVEMENT OF GROUT SPREAD, AND EVALUATION OF RTGC THEORY

Nya framsteg i mätning av inträngningsförmåga av injekteringsmedel, förbättring av spridning av bruket och utvärdering av RTGC-teorin

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Abstract

This paper presents a short summary of a PhD project conducted on grout penetrability properties in rock fractures. After review of the methodologies developed to measure grout penetrability, three of which that were more recognized in Swedish grouting industry were selected for a comparison. The aim was to determine which one is more reliable and how. The study showed positive aspects of Short-slot. Afterwards, the so-called varying aperture long slot (VALS) was developed to study the gout penetrability at more realistic conditions. Then, a low-frequency rectangular pressure-impulse was employed to improve the grout spread by successive erosion of eventual filter cakes in consecutive cycles. The results showed considerable improvement in experiments using Short-slot. The dissipation of the pressure-impulses was then investigated using VALS, where the remaining amplitudes along the slot were noticeable. Finally, VALS was once again used to examine the performance of the RTGC theory in a more realistic geometry condition. The study showed a relatively satisfactory agreement between the experimental and the analytical results of grout propagation using the hydraulic aperture.

Sammanfattning

amplituderna längs spalten var märkbara. Slutligen användes VALS för att undersöka utförandet av RTGC-teorin i ett mer realistiskt geometrisk tillstånd. Studien visade en förhållandevis tillfredsställande överensstämmelse mellan försöksresultaten och förutsägelserna av spridningen hos injekteringsmedel när man använde hydrauliska öppningen som medelstorlek på spalten.

Introduction

One of the main concerns in subsurface infrastructures is to provide and maintain the sealing required during both construction and operation. Ingress of water into underground projects during the construction increases the time and costs. It can be accompanied by environmental issues such as lowering the groundwater tables, settlement of the structures, and destruction of vegetation. During the operation, it might also be hazardous to human life, e.g., falling icicles in tunnels in cold climate. It reduces the life cycle of the projects and increases the maintenance costs.

To provide the sealing required, one of the governing parameters is to obtain sufficient spread of grout in fractures surrounded the facility (Gustafson and Stille 2005; Fransson 2008; Stille 2015). This has been achieved using cement-based and/or chemical grouts (Houlsby 1990; Karol 2003). Despite showing satisfactory spread and sealing efficiency, the use of chemical grout is prohibited in many countries due to several environmental issues (Weideborg et al. 2001). Cement-based grout, which is cheaper with less environmental problems, is more common in the grouting industry. However, in use of cement-based grout, filtration, which occurs due to the arching of the cement particles at a fracture constriction, is an obstacle that restrict the grout spread (Eriksson et al. 2000; Eklund and Stille 2008; Draganovic and Stille 2011). On this basis, this study was dedicated to studying the grout penetrability properties in fractured hard rock.

Background

Several test methodologies have been developed over the years to study penetrability properties of cement-based grout. The disagreement over the results obtained, however, is an indication that those methods might not replicate the filtration process at a real fracture in rock satisfactorily (Draganovic and Stille 2014). That is probably due to the deficiency in their design being based on diverse and occasionally unrealistic assumptions, limitations, and test conditions (Ghafar et al. 2017a). Therefore, our first concern in this study was to investigate among the existing methodologies developed to measure grout penetrability, which one was more reliable and how? Furthermore, a standard method for evaluation of grout penetrability in fractured hard rock has not yet been established. The results obtained from the existing methodologies were difficult to relate to grouting in rock fractures. Therefore, a new methodology to replicate the filtration at a fracture constriction more realistically was required.

One of the factors governing the filtration and the grout spread is the applied pressure. A sufficient increase in pressure decreases the filtration and improves the grout spread by increasing the potential for erosion of the unstable filter cakes (Eriksson et al. 1999; Nobuto et al. 2008). High-frequency oscillating pressure superimposed on an underlying constant pressure has been shown to improve the grout spread by virtue of reducing the
grout viscosity due to the high-frequency oscillation (Pusch et al. 1985; Borgesson and Jansson 1990; Mohammed et al. 2015). Besides the promising results, use of dynamic grouting has not yet been industrialized due to the limited efficiency and quick dissipation of the oscillation. This suggested that to improve the grout spread in fractures effectively, a proper solution might be use of different shape and frequency of the applied pressure.

One of the major issues in rock grouting is insufficient spread of grout, which deteriorates the obtained sealing and the resulting durability. Moreover, the unnecessary spread of grout beyond the required limits is uneconomic and is sometimes accompanied by environmental issues. Optimization of the grout spread is therefore of huge significance in rock grouting. Hence, several stop criteria have been developed to control the grout spread, from which the real time grouting control (RTGC) theory has got a lot of attention in the Swedish grouting industry. It predicts the spread of grout over time in fractures using the grout’s rheological properties and the applied pressure (Gustafson and Stille 1996, 2005; Gustafson et al. 2013; Stille 2015). It has been developed based on assumptions, the most significant of which is the uniform fracture aperture. Accordingly, all the laboratory works, aimed to verify the theory, were conducted in either pipes or parallel plates with constant apertures (Håkansson 1993; Gustafson et al. 2013). This means that the theory has not yet been investigated in the lab at presence of constrictions similar to the geometry of a real fracture in rock.

Accordingly, this study was carried out in four different parts with the objectives summarized as follows:

a) Which of the existing test methodologies developed to measure grout penetrability are more reliable and how?
b) How can grout penetrability be measured more realistically?
c) How can the grout spread be improved effectively using dynamic pressure impulses?
d) Is it feasible to employ the RTGC theory to predict the grout spread in an artificial fracture with variable aperture?

Part (A): Measurement of grout penetrability (Existing methodologies)

In this part, a review was first conducted on the existing methodologies developed to measure grout penetrability with details presented in Ghafar (2017). The study showed that the disagreements/contradictions over the results obtained using various methodologies were in conjunction with either or a combination of differences between their applied pressures, constriction geometries, and grout volumes, as well as some deficiencies in their evaluation methods.

Filter-pump and Penetrability-meter, two recognized methods in Swedish grouting industry, were then selected for a comparison against Short-slot with more realistic test conditions and more accurate evaluation method. To make a fair analogy, the test apparatus and procedure in both Filter-pump and Penetrability-meter were adjusted to operate under as similar test conditions as possible to those in Short-slot. The aim was to better understand the grout penetrability and fairly evaluate the reliability and functionality of the methods. Fig.1 shows five different test setups (T1-T5) used in the experiments with details that can be found in Ghafar et al. (2017a).
Fig. 1 Schematic view of regular Filter-pump (T1), modified Filter-pump manually and mechanically operated (T2, T3), modified Penetrability-meter (T4), and Short-slot (T5)

T1 shows regular Filter-pump, manually operated, using total volume of passed grout as the evaluation method. T2 and T3 are modified Filter-pump, manually and mechanically operated, respectively, both using the weight-time measurement as the evaluation method. Finally, T4 and T5 represent modified Penetrability-meter and Short-slot both using the same evaluation method as in modified Filter-pump.

The criteria that were used to evaluate grout penetrability in this study were $b_{\text{min}}$ (the min fracture aperture that a specific grout can penetrate at all) and $b_{\text{crit}}$ (the min fracture aperture that a specific grout can penetrate without filtration) as defined by Eriksson and Stille (2003). These parameters were determined in each test using the graph of weight-time measurement, where constant gradient/mass flow rate was representative for no filtration condition and variation in gradient/mass flow rate was an indication of filtration. The materials used, mixing process, and test plan can be found in detail in Ghafar et al. (2017a).

Some results are presented in Fig. 2. To the left, various flow rates (red lines) and different total weights of passed grout (black lines) are shown in the results obtained from test setup T2 using the same materials, mesh size, operator, and test procedure. By mechanizing the test setup in T3 (Fig. 2 right), with the aim to apply similar pressure in each test constantly, the results showed a better agreement in the experiments conducted at similar test conditions. This shows the extent of influence of the applied pressure on grout penetrability measurement.

Conclusions

Diversity in the applied pressure, grout volume, evaluation method, and constriction geometry were found as the main origins of uncertainty/contradiction in the results of the grout penetrability measurement. Use of Filter-pump and Penetrability-meter is no longer recommended to evaluate grout penetrability, but Filter-pump can still be used for quality control of cement and mixing process. Accordingly among the three methods, use of Short-slot is considered to be more reliable due to more realistic geometry, test condition, and evaluation method.
Some results of test setup T4 are presented in Fig. 3 (left) to show the uncertainties induced by the grout mass/volume. As can be seen, when the grout weight was < 1.0 kg, there was no change of mass flow rate (red line), meaning no filtration in the process. When the grout weight was between 1.0-1.5 kg, there was still no trace of filtration (pink line). However, by exceeding the grout weight from 1.5 kg, change of the flow rate can be seen in the results (brown dashed-lines), which is representative for filtration. Finally, the uncertainties induced by the evaluation methods are presented in the results of test setup T3 in Fig. 3 (right). Using the total weight of the passed grout, there is no trace of filtration in the experiments conducted using 61 μm mesh filter, since in all experiments the full capacity of the Filter-pump was filled with grout. But, using the weight-time measurement, change of the flow rate (blue line) is an indication of filtration.

**Conclusions**

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Part (B): Measurement of grout penetrability (New method)

Based on the achievements from the first part of the study, a new test method, so-called varying aperture long slot (VALS), was then developed in the form of a four-meter long artificial fracture to measure grout penetrability properties more realistically. The test apparatus primarily consists of two steel plates (top and bottom plates), bolted together with 11 constrictions of 230-10 μm and chambers of 500 μm in between (Fig. 4). Twenty three holes have been constructed on top plate before and after each constriction to locate pressure sensors for tracking the grout front and filtration and erosion processes. Twelve valves have also been designed under the bottom plate that can be used as the inlet and outlet. The rest of the test setup and the evaluation method used are similar to those in Short-slot. The method was applicable to test grout of any kind at static and dynamic pressure conditions up to 15 bar. More details of the materials, method, mixing process, and test plan can be found in Ghafar et al. (2017b). The main advantages of the new method compared to Short-slot are more realistic geometry and the possibility to evaluate $b_{\text{min}}$ and $b_{\text{crit}}$ in one test using only one batch of grout mix.

Some results are presented in Fig. 5. As can be seen (to the left), the traces of filtration (change of the flow rate) was observable all the way by opening valves V5-V10, except for valve V11, which was therefore representative for the measure of $b_{\text{crit}}$. To the right, the same test results are shown but with better resolution. Only in V11, there was no change of flow rate. In this experiment, $b_{\text{min}}$ and $b_{\text{crit}}$ were evaluated as 50 and 230 μm, respectively.

![Fig. 4 Schematic depiction of varying aperture long slot (VALS)](image-url)
Conclusions
The study showed the potential of the method to investigate the fundamental behavior of rock grouting at varying parameters with satisfactory repeatability at both static and dynamic pressure conditions.

Part (C): Improvement of grout spread using dynamic pressure impulses

Investigation in parts A & B revealed that among the factors influencing the grout spread, the applied pressure is the key element. Pusch et al. (1985) initiated a series of laboratory and field investigation to examine the influence of high-frequency oscillating pressure on improving the grout spread. Even though the results obtained were promising, the corresponding improvement was not so significant. The mechanism of action was reported as reduction in the grout viscosity due to the high frequency oscillation. The main issues were, however, found as insufficient spread and quick dissipation of the oscillation along a fracture. Nowadays, stepwise pressure increment is the method normally used in the grouting operations in field with much better results. The mechanism of action is erosion of the produced filter cakes due to increase in pressure. However, the main issues are yet filtration of the cement particles and poor spread in fractures < 70 μm. What we did at KTH was to combine these two methods and apply a low-frequency rectangular pressure impulse to improve the grout spread more effectively. The mechanism is, however, interpreted as erosion of the produced filter cakes due to change of flow pattern at consecutive cycles, where improved spread in fractures < 70 μm and longer dissipation length were anticipated.

Hence, a test setup similar to that presented in Short-slot was employed by slightly adjustment to change the applied constant pressure to programmable dynamic pressure. The experiments were then conducted at 4s/8s and 2s/2s peak/rest periods. The total weight of passed grout and the min-pressure envelope (i.e. a polyline connecting the minimum pressures obtained in each cycle) were the main evaluation methods used to assess the efficiency of the applied pressure. Using the min-pressure envelope, any upward trend represents the filtration and any downward trend is an indication of erosion (Fig.6). More details of the test setup, evaluation methods, materials, mixing process, and the test plan can be found in Ghafar et al. (2016).
Among the results obtained, the total weight of passed grout showed roughly 3 times improvement in the experiments conducted at 4s/8s and 11 times improvement at 2s/2s peak/rest periods using 30 μm slot compared to the results obtained from the static pressure tests. The min-pressure envelope presented in Fig. 7 with random upward and downward trends shows the counterbalancing filtration and erosion as the main reason to keep the slot open for a longer period to obtain more penetration.

Conclusions:

The low-frequency rectangular pressure impulse showed a substantial control on filtration and improved the grout spread within parallel plates with constrictions ≤ 70 μm, where the results of 2s/2s peak/rest period showed a better efficiency than 4s/8s. However, the potential comment on the method was yet quick dissipation of the pressure-impulses along a fracture.

On this basis, in the next step of the study, the dissipation of the pressure-impulses was examined in a considerably longer artificial fracture. Hence, VALS was once again introduced with pressure sensors located at 2.7, 2.0 m, and at the beginning of the slot. The details of the test setup, evaluation methods, materials, mixing process and test plan can be found in Ghafar et al. (2017c).

Some results are presented in Fig.8. The blue line is the pressure variation at the beginning of the slot, the red line at 2.0 m and the green line at 2.7 m. As can be seen, even though the shape of the applied pressure is different, but we got 46% and 25% of the initial amplitude of the applied pressure after 2.0 and 2.7 m with aperture range of 230-60 and 230-40 μm, respectively.
Conclusion:
The study showed the potential of the method on improvement of grout spread in fractured hard rock specially in apertures <70 μm.

Part (D): Evaluation of the RTGC theory in more realistic condition

The RTGC theory is a stop criteria for estimating the grout spread to provide a reliable and economic tight zone around any underground facility. Due to one of the primary assumptions, i.e. uniform fracture aperture, the theory has been mainly tested using laboratory setups with constant aperture. In addition, the aperture size that previously used in the early stages of the development of the theory was hydraulic aperture, $b_h$. However, it is not $b_h$ that governs the grout take in grouting operations; it is the fracture’s mean physical aperture, $b_{phy}$. This, which is used nowadays in application of the RTGC theory, is roughly twice the size of $b_h$. The questions in the last part of the study were therefore whether it is feasible to employ the RTGC theory to predict the grout spread in an artificial fracture with variable aperture and how good the quality of the predictions would be using $b_h$ or $b_{phy}$.

To examine the theory in this part, VALS was once again used but with pressure sensors located at 0.99, 1.71, and 2.43 m from the slot’s beginning to track the grout front. Fig.9 presents the flow chart that summarizes the formulations for prediction of the grout propagation over time using RTGC theory for 1D flow condition. In this flow chart, $b_h$ can be obtained through some water tests using the cubic law, whereas $b_{phy}$ can be simply calculated using the average of the aperture sizes of the slot between the inlet and the outlet (Ghafar 2017). Finally, the viscosity and yield stress, which are needed as in-data in the calculations, can be obtained using some routine rheological measurements. More details of the materials, methods, and test plan can be found Ghafar (2017).
Fig. 9 Prediction of the grout propagation using the RTGC theory for 1D flow condition

A comparison between the experimental results (the green lines), the predictions using \( b_h \) (red line), and the predictions using \( b_{phy} \) (blue line) are presented in Fig. 10. As can be seen, the predictions using \( b_h \) are in much better agreement with the experimental results.

**Conclusion:**

The predictions of grout propagation obtained from the RTGC theory using \( b_h \), the way that the theory was used previously in the early stages of the development, showed relatively good agreement with the experimental results for all the tested materials. However, the predictions using \( b_{phy} \), the way that the theory is nowadays used in the field applications, showed considerably faster spread. This suggests that use of \( b_{phy} \) does not always give a better approximation of the fracture apertures than \( b_h \) to employ in predictions using the RTGC theory.

Fig. 10 Experimental and predicted grout propagation over time for grout R1 (G2-T1 and G2-T2)
References


