An Experimental Study to Measure

And

Improve the Grout Penetrability

Ali Nejad Ghafar

Licentiate Thesis

Department of Civil and Architectural Engineering

Division of Soil and Rock Mechanics

KTH Royal Institute of Technology

Stockholm, 2016

TRITA-JOB LIC 2030

ISBN 978-91-7595-896-5

ISSN 1650-951X

PREFACE

The investigation presented in this licentiate thesis was carried out during 2013-2015 at Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, Royal Institute of Technology (KTH).

I would like to express my gratitude to my co-supervisor Dr. Almir Draganovic for initiating the project, constant support, guidance and rewarding comments during the progress of this investigation. Special thanks to my main-supervisor Prof. Stefan Larsson for his patience, encouragement and providing valuable advices in difficult moments of the project. Indeed, I would also like to appreciate scientific suggestions of Prof. Håkan Stille, one of the most well-known scientists in the field, during the production process of my main test equipment. Many thanks to my reference group members for their worthwhile discussions. Further acknowledgements are dedicated to my colleagues at Division of Soil and Rock Mechanics for their friendly and productive challenges especially during our division seminars. Finally, endless assistance of our administration system for smooth running the project has to be acknowledged.

Success in this project would definitely not have been possible without infinite love, patience, and support of my wife Aram and my daughter Delaram.

Stockholm, February 2016

Ali Nejad Ghafar

FUNDING ACKNOWLEDGEMENT

This study was carried out within the frame of Trust 3.3 - GeoInfra (http://trust-geoinfra.se). The project was funded by Rock Engineering Research Foundation (BeFo), Swedish Transport Administration (Trafikverket), and Development Fund of the Swedish Construction Industry (SBUF). The co-founders are warmly acknowledged for their financial and technical supports. Success in this investigation would definitely not have been possible without the much appreciated generosity of BeFo in providing the extra budget required for the project equipment.

SUMMARY

One of the essential requirements in any underground facility is to seal the area against the water ingress and leakage of the reserved materials. This will reduce the duration and cost of the construction process and the corresponding environmental hazards significantly. To achieve the required sealing, obtaining sufficient grout spread is of great importance. Among the grouting materials, the chemical ones despite the improved grout spread showed hazardous environmental impacts, whereas the cement grouts with lower costs and environmental issues have been more reliable. The major issues with the latter are however, the filtration of the cement particles and the grout rheological properties that restrict the grout spread. Several investigations have been therefore aimed to study these properties especially to develop different instruments and methods to measure the grout penetrability properly as a fundamental means to improve the grout spread. Due to the difference in assumptions, limitations, and test conditions, as well as the deficiency in design and evaluation methods the results of different instruments and methods are occasionally in contradiction. The key question here is that how to measure the grout penetrability more realistic? To answer this question, two of the most frequently used measuring instruments, Filter pump and Penetrability meter, were modified to approach to the test conditions as in Short slot. The obtained results were subsequently discussed with respect to different origins of contradictions to comprehend the nature of grout penetrability and better evaluate the reliability and functionality of the instruments.

Among the parameters, influencing the grout spread the applied pressure is apparently a key element. The stepwise pressure increment is the method currently used in practice to improve the grout spread in fractured hard rock. Application of dynamic grouting has been under investigation as a potential solution to improve the grout spread for almost three decades. Despite some promising results, the method has not been yet industrialized due to the limited efficiency and specific issues, which were in common in all those investigations. For instance, the applied pressure was typically a high frequency oscillating pressure that examined through parallel plates without

constrictions with geometries extremely different from a real fracture in rock. In such parallel plates resistance against the grout spread is mainly dependent on the grout rheology, whereas in a real fracture in rock (with numerous constrictions), the filtration is the governing parameter to consider. Meanwhile, the earlier studies were just focused on large apertures (≥100 µm), whereas in facilities with extremely high sealing demands, sufficient grout spread in small apertures (≤70 µm) is crucial. Therefore, finding a new alternative of the applied pressure more effective on improving the grout spread was the other objective of this investigation. A pneumatic pressure control system was consequently employed with Short slot to examine the efficiency of the method in more realistic conditions with constrictions less than 70 µm. The results conclusively revealed the effectiveness of the method and provided a strong basis for further development of the dynamic grouting.

SAMMANFATTNING

Ett viktigt krav när man bygger under mark är att konstruktionen blir tillräckligt tät, så att inläckage av grundvatten minimeras. Detta minskar både projektkostnaden och eventuell miljöpåverkan. För att skapa en tät konstruktion måste injekteringsbruket spridas tillräckligt i bergmassan. Kemiska injekteringsmedel har ofta bättre spridning i bergmassan än cementbaserade bruk, men cementbaserade bruk är både billigare och ger mindre miljöpåverkan. Det finns dock en del problem med cementbaserade bruk, nämligen att cementpartiklarna filtreras och att brukets reologiska egenskaper begränsar brukets utbredning. Ett antal studier har därför utförts för att studera dessa egenskaper hos cementbaserade bruk och utveckla metoder och instrument för att mäta brukets inträngningsförmåga. Detta i syfte att förbättra brukets utbredning. Dagens metoder och instrument ger nämligen ibland motsägelsefulla resultat på grund av de olika antaganden, begränsningar och förutsättningar som används i de olika testerna. Huvudfrågan är alltså hur man kan mäta brukets inträngningsförmåga på ett mer realistiskt sätt. För att undersöka detta modifierades två vanliga mätinstrument – filterpumpen och filterpressen – för att passa förhållandena i testanordningen Short slot. Resultaten diskuterades med avseende på olika typer av skillnader mellan metoderna i syfte att utröna dels vad som påverkar inträngningsförmågan, dels instrumentens tillförlitlighet och funktionalitet.

Bland de parametrar som påverkar brukets spridning i bergmassan har injekteringstrycket en central roll. I dagsläget används stegvis tryckökning för att förbättra brukets spridning i sprickigt, hårt berg. Hur man kan använda dynamisk injektering för att förbättra brukets spridning har dock undersökts under snart tre decennier. Trots lovande resultat av denna metod ännu inte börjat användas i praktiken. Ett problem är svårigheten att ta försök på labb till fältmässiga förhållanden. Ett exempel är att man använde ett tryck som varierade med hög frekvens i en spricka som modellerades med två parallella skivor utan förträngningar, vilket är mycket annorlunda jämförelse med en riktig bergspricka. I modellen blir nämligen brukets spridning starkt beroende av brukets reologiska egenskaper, medan det snarare är filtrering som är

problemet i en naturlig spricka på grund av förträngningarna. Dessutom fokuserade tidigare studier endast på sprickor med en sprickvidd större än 100 μm, trots att god spridning av bruket även i de smala sprickorna med mindre än 70 μm bredd är mycket viktigt när det är höga krav på anläggningens täthet. Ett annat mål med denna licentiatuppsats var därför att hitta nya sätt att förbättra brukets spridning i berget. Därför övervakades trycket med ett pneumatiskt kontrollsystem vid tester i Short slot för att studera hur effektiv denna metod är under mer realistiska förhållanden med förträngningar på mindre än 70 μm. Resultaten visade att metoden är effektiv, vilket utgör en bra bas för att fortsätta utveckla dynamisk injektering.

LIST OF PUBLICATIONS

This licentiate thesis has been prepared based on the work presented in following publications:

i. Nejad Ghafar, A., Ali Akbar, S., Al-Naddaf, M., Draganovic, A., Larsson, S. 2016. Uncertainties in Grout Penetrability Measurements; Evaluation and Comparison of Filter pump, Penetrability meter and Short slot. *Submitted to Journal of Geotechnical and Geological Engineering.*

I developed the methodology and wrote the paper. Ali Akbar together with Al- Naddaf conducted the lab experiments under my supervision. Draganovic and Larsson also supervised and assisted the investigation within the review process of the paper.

ii. Nejad Ghafar, A., Mentesidis, A., Draganovic, A., Larsson, S. 2015. An experimental approach toward the development of dynamic pressure to improve the grout spread. *Submitted to Journal of Rock Mechanics and Rock Engineering.*

I developed the methodology, designed the instrument, and wrote the paper. Mentesidis conducted the lab experiments with my collaboration. Draganovic and Larsson also supervised and assisted the investigation within the review process of the paper.

OTHER PUBLICATIONS

In this project, I have also contributed to the following relevant publications.

i. Place, J., Nejad Ghafar, A., Malehmir, A., Draganovic, A., Larsson, S. 2015. On using the thin fluid layer approach to characterize grout propagation in artificial fractures: insights from ultrasonic measurements. *Submitted to International Journal of Rock Mechanics and Mining Sciences.*

ii. Nejad Ghafar, A., Mentesidis, A., Draganovic, A., Larsson, S. 2016. Ett nytt sätt att förbättra inträngningsegenskaperna hos cementbaserat injekteringsbruk med momentant varierande tryck. *Bygg & teknik nr 1/16.*

iii. Nejad Ghafar, A., Draganovic, A., Larsson, S. 2015. An experimental study of the influence of dynamic pressure on improving grout penetrability. *Rock Engineering Research Foundation, BeFo Report 149, Stockholm.*

Additionally, I have been actively involved in supervising the following M.Sc. projects.

i. Al-Naddaf, M., Ali Akbar, S., 2015. Evaluating and comparing of three penetrability-measuring devices: modified Filter pump, modified Penetrability meter and Short slot.

ii. Mentesidis, A., 2015. Experimental evaluation of the effects of dynamic pressure on improving cement-based grout penetrability: A study performed with the short slot.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

One of the vital issues in any underground infrastructure during both the construction and the operation is to seal the facility against the water ingress and leakage of any sort of reserved gas, liquid and/or waste materials to the surrounding areas.

Water inflow into the tunnels and caverns during the construction process increases the durations and costs of the projects significantly. Moreover, it causes considerable environmental impacts, e.g., lowering the groundwater level, settlement of the surface structures, and destroying the vegetation. In many occasions, it has also been a sever threat for human life. Many construction workers and engineers have lost their lives in different water inrush crises worldwide, e.g., in Lingnan tunnel located in Hangguang railway, in the synclinal area of Liangshan tunnel as well as in Maluqing tunnel of Yiwan railway in China (Zhirong et al. 2004; Junwei et al. 2013).

Several radiation releases, reported from different underground waste repositories, exposed numerous workers and living environment in surrounding areas over the past decades. According to accident report, presented by U.S. Department of Energy Office of Environmental Management, thirteen workers were severely exposed to the hazardous radiation in the crisis occurred in New Mexico's Waste Isolation Pilot Plant (WIPP) in February 2014.

To effectively seal an area in rock various parameters are involved, from which sufficient grout spread, i.e., obtaining adequate penetration length in grouting process is of great importance (Houlsby 1990; Lombardi 2003; Warner 2004; Gustafson and Stille 2005; Fransson 2008; Gustafson et al. 2013; Stille 2015). Different kinds of grouting materials, viz., the cement-based and the chemical grouts have been developed and used in grouting industry worldwide (Houlsby 1990; Karol 2003; Warner 2004). The chemical ones despite the improved grout spread and sealing efficiency showed severely hazardous environmental impacts in a few occasions that made their applicability restricted in some countries (Weideborg et al. 2001). The cement-based grouts with lower costs and environmental impacts, however, have been mostly preferred as a more reliable alternative. The problematic issue with the cement-based grout is the filtration of the cement particles and clusters occurs as a result of arching and plug building at a fracture constriction that restricts the grout spread (Eriksson et al. 2000; Eriksson and Stille 2003; Draganovic and Stille 2011). In addition to the filtration tendency, the other governing parameter controlling the grout spread is the grout rheology (Håkansson 1993; Schwartz 1997; Eriksson et al. 2004; Eklund 2005; Banfill 2006; Eklund and Stille 2008; Rafi 2013; Mohammed et al. 2014). Several research projects have been therefore aimed to study the aforementioned properties as a fundamental means to improve the grout spread.

Accordingly, various instruments and methods have been developed to measure the grout penetrability and filtration tendency, each of which with specific benefits and drawbacks. By virtue of the fact that the instruments have been built based on different assumptions, limitations, and test conditions, their results are occasionally in contradict. Deficiency in design and uncertainty in methods employed to evaluate the grout penetrability are also among the reasons for such disagreements. The leading question here is that which instrument and method provides more realistic measures of grout penetrability and why?

In a literature review concerning the factors influencing the grout spread, applied pressure was considered as a key element. According to Eriksson et al. (1999), Hjertström (2001), Draganovic and Stille (2011, 2014), and Stille et al. (2012), increase in pressure reduces the filtration tendency and improves the grout spread. Nobuto et al. (2008) in their laboratory experiments showed that stepwise pressure increments increase the grout spread. Pusch et al. (1985) was most likely the first who demonstrated the influence of high-frequency oscillating pressure on improving the grout spread. In subsequent investigations on dynamic grouting, the method was recognized as a potential solution to improve the grout spread. Even though the performances were commonly promising, the method has not been yet industrialized due to the limited efficiency. Additionally, the investigations were all limited in specific issues.

The examined pressure was typically high frequency oscillating pressure, while the other alternatives could be more effective on improving the grout spread. Taking lack of constriction within the parallel plates into consideration, the employed artificial fractures in all experiments (made in the form of ideal parallel plates) were extremely different in geometry from a real fracture in rock. Additionally, in such parallel plates resistance against the grout spread is mainly dependent on the grout rheology, whereas in view of a real fracture with numerous constrictions, the filtration is the governing parameter to consider. This makes the presence of constriction within the parallel plates crucial for replicating the filtration process. After all, the earlier studies were just conducted on apertures greater than 100 μm, whereas to seal the facilities with extremely high sealing demands, sufficient grout spread in fractures narrower than 70 μm is essential. Therefore, examining a new alternative of the applied pressure through artificial fractures with constrictions less than 70 μm was the second concern of the study as a means to improve the grout spread in rock effectively.

1.2 Objectives and scope of work

The main objectives of this study are in general answering to two fundamental questions:

A. How to measure the grout penetrability more realistic? and
B. How to improve it?

Accordingly, the study consists of two complementary parts in relation to the aforementioned objectives. Part A represents a brief review on various instruments developed to measure the grout penetrability. To dig deeper into their benefits and drawbacks, Filter pump and Penetrability meter as two of the most commonly used instruments were selected for comparison due to their simplicity in both the lab and the field applications. Short slot even though was just applicable in the lab, due to more realistic geometry and more accurate evaluation method was selected as a basis for this comparison. To make the analogy appropriate, test apparatus and procedure in Filter pump and Penetrability meter were consequently modified to approach to the test conditions as in Short slot. The aim was to comprehend the nature of grout penetrability to better evaluate the reliability and functionality of the instruments, and finally yet importantly figure out how to measure it more realistic.

In Part B, a low frequency instantaneous variable pressure was introduced within a novel experimental approach to better control the filtration as a means to improve the grout spread. Two compositions of peak/rest periods, i.e., 4 s/8 s and 2 s/2 s were examined in manufactured parallel plates having constrictions with apertures of 30 and 43 μm. The aim was to replicate the filtration process within artificial fractures properly in order to evaluate the influence of the method on grout spread more realistic and under fully controlled conditions. It was also to investigate the corresponding efficiency within micro-fractures narrower than 70 μm. Two choices of the peak/rest periods were employed to determine the one with better control on filtration for the selected materials and test conditions and to realize the corresponding reasons. It was finally to follow the filtration evolution within the cycles along the entire experiments to identify and subsequently better control the critical ones in terms of filtration as a means to improve the grout spread.

1.3 Organization of the thesis

This thesis is principally based on the context presented in detail in two aforementioned scientific papers that are under the review process. After presenting an introduction to motivate the current investigation, the objectives, scope of work, and some limitations of the project are discussed in the first chapter. The key questions of “How to measure the grout penetrability more realistic? and How to improve the grout penetrability?” are the bases of the following two chapters. In chapter 2, all previous instruments designed for measuring the grout penetrability are reviewed with discussion on different origins of uncertainty and disagreement in results. The discussion in this chapter is followed by a comparison between three of the most commonly used instruments, i.e., Filter pump, Penetrability meter, and Short slot with focus on their limitations and deficiencies.

Chapter 3 thereafter begins with a short description on parameters influencing the grout penetrability. The discussion in this chapter is continued by focus on the applied pressure as one of the governing parameters improving the grout penetrability. Subsequently, the previous investigations with focus on application of dynamic pressure are briefly described, whereas their limitations and missing parts are discussed in detail. Based on the discussion on chapters 2 and 3, the experimental setups required to address the aforementioned key questions are presented in chapter 4. This chapter therefore explains the test equipment, procedures, evaluation methods, materials, mixing process and the test plans for both of the two parts of the study. In chapter 5, the test results obtained from the aforementioned three measuring instruments are discussed with respect to their main sources of uncertainties to figure out how to measure the grout penetrability more realistic. This chapter is continued by discussing the influence of instantaneous variable pressure (IVP) on improving the grout spread in two slots with different apertures followed by a discussion on possible interpretation of the mechanism of action. Conclusions are drawn in chapter 6 accompanied by the planned future steps and the recommended related projects. Following that, the references are presented in chapter 7. The thesis will be finally finished by papers I and II that presented in detail in appendix.

1.4 Limitations

Limitations of the current investigation comprised of following issues:

1.4.1 Count of the test repetitions

Even though the count of the test repetitions was considered to be sufficient for drawing the conclusions, the more the count of the repetitions, the more reliable would be the results.

1.4.2 Slot’s geometry

Although the geometry of Short slot employed in this study was considered to be more similar to a real fracture in rock than the other instruments, several differences have yet existed that should be taken into consideration in drawing the conclusions and especially in future steps of the project. The most significant ones are, e.g., presence of only one constriction in Short slot in comparison with numerous irregularities in a real fracture, the smooth surface of steel parallel plates compared with the rough surface of fracture walls and eventually the limited width and length of the slot before and after the constriction compared with probable wider and longer areas in a real fracture.

1.4.3 Equipment limitations

Limitation in capacity of the grout tank and rate of the pressure variation system especially rate of the pressure relief were of the equipment limitations which should be improved in further steps of the project.

1.4.4 Technologic limitations

In the second part of the investigation, to verify the proposed mechanism of improvement of grout penetrability under application of instantaneous variable pressure, it was necessary to observe the pattern of the grout flow before the constriction during the grouting process. Due to the limitation in bending capacity of the transparent materials, e.g., Plexiglas and Polycarbonate sheets to withstand against 15 bar pressure, use of these materials in production of Short slot was quite impossible. Consequently, the proper choice for this purpose was stainless steel. To solve this issue, an indirect solution would be use of Computational Fluid Dynamic (CFD) to simulate the flow pattern under the test conditions. This is going to be a part of our future work to verify the mechanism of action in proposed method.

1.4.5 Resources

In the field of dynamic grouting, the language of a few existing articles was in Japanese. This made them approximately impossible to use, whereas the resources in the subject were quite limited. Novelty in the application of low-frequency instantaneous variable pressure was the main issue, which made the previous investigations scarcely beneficial for the design process of the required equipment, evaluation methods and interpretation of the results.

2. How to measure the grout penetrability?

Due to the significance of the grouting operations and the complexity involved, the topic captivated many researchers to investigate it from different perspectives. The corresponding literature review revealed that several measuring instruments and methods have been developed with different assumptions, limitations, and test conditions to better understand and evaluate the grout penetrability, whereas the results were on some occasions in contradiction. This led us to dig deeply into the grout penetrability measuring instruments and methods as presented below.

2.1 Sand column

Sand column is one of the most commonly used instruments for measuring the grout penetrability described in French standard (NF P 18-891). Use of the instrument was reported in several investigations conducted by Bergman (1970), Schwarz (1997), Zebovitz et al. (1989), Paillere et al. (1989), Atkinson et al. (1993), Andreou et al. (2008), Axelsson et al. (2009) and Miltiadou-Fezans and Tassios (2012) among the others. A general depiction of the instrument is illustrated in Fig. 1 (Axelsson et al. 2009).

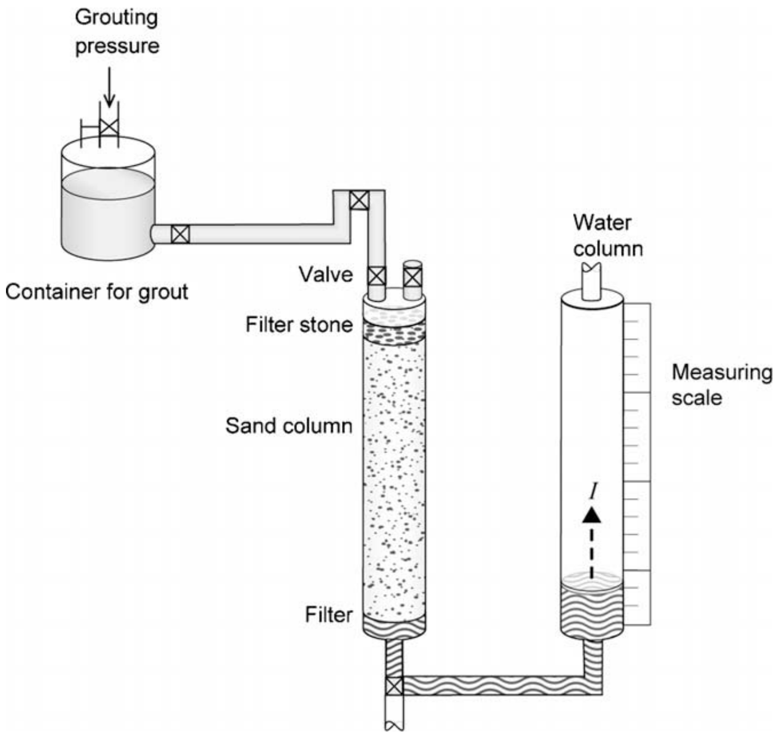


Fig. 1 General depiction of Sand column according to Axelsson et al. (2009)

During the test procedure, the pressurized grout in the grout container is pushed out toward the sand column, a transparent tube filled with sand of predefined particle size distribution. In two conditions with saturated and unsaturated sand, penetrability of the injected grout can be measured using either of the following methods:

- Measuring height of the water in water column in saturated condition
- Measuring total volume of the injected grout in unsaturated condition
- Visual inspecting the penetrated grout through the sand column

Due to the difference in flow pattern in a porous medium and slot geometry, several investigations aimed to study the corresponding mechanisms of filtration. The objective was to correlate the results of the penetrability obtained from a Sand column to a real fracture in rock (Bergman 1970; Gustafson and Stille 1996; Schwarz 1997; Gustafson and Stille 2005; Axelsson and Gustafson 2007; Draganovic 2009; Axelsson et al 2009). Eventually, Axelsson et al. (2009) presented a rather complete interpretation of the mechanism of filtration in a porous medium as follows:

- Clogging, where the grains stick together before entering the aperture
- Filtration, where the grains enter the aperture but gradually separate from the flow and eventually plug the pores
- Resistance, where the grout pressure is balanced by the frictional resistance

However, obtaining a rational relation in grout penetrability between those two media was found quite difficult or rather impossible.

2.2 Pressure chamber or Filter press

Pressure chamber or Filter press is another instrument developed by Gandais and Delmas (1987) for measuring the filtration stability based on the following procedure. The grout is pressurized in grout container by compressed air to penetrate through a filtering medium with known penetrability made of paper, fine sand, soft rock, etc. A general depiction of the instrument is presented in Fig. 2 (Widmann 1996).

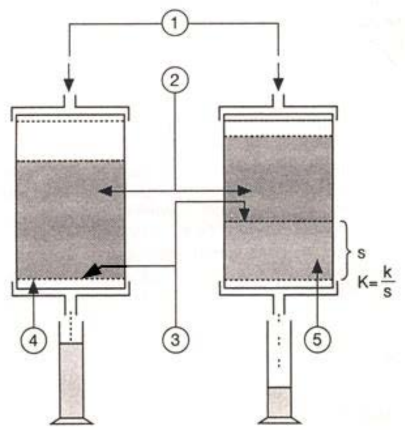


Fig. 2 General depiction of Pressure chamber as seen in Widmann (1996)

According to Gandais and Delmas (1987), density of the filter cake produced at the surface of the filtering medium varies linearly with depth. It is also proportional to the volume of water passed through the filter. The latter considered the mechanism of filtration in Pressure chamber to be representative for what occurs through a real fracture in rock. The grout under pressure is pressed against the fracture walls. Due to the porosity of rock matrix and existing micro-cracks, the grout is filtered through the walls. Eventually, the flow stop occurs due to the plug formation of the cement particles and clusters as presented in Fig. 3. According to Draganovic (2009), this mechanism of filtration is however irrelevant in rock fractures.

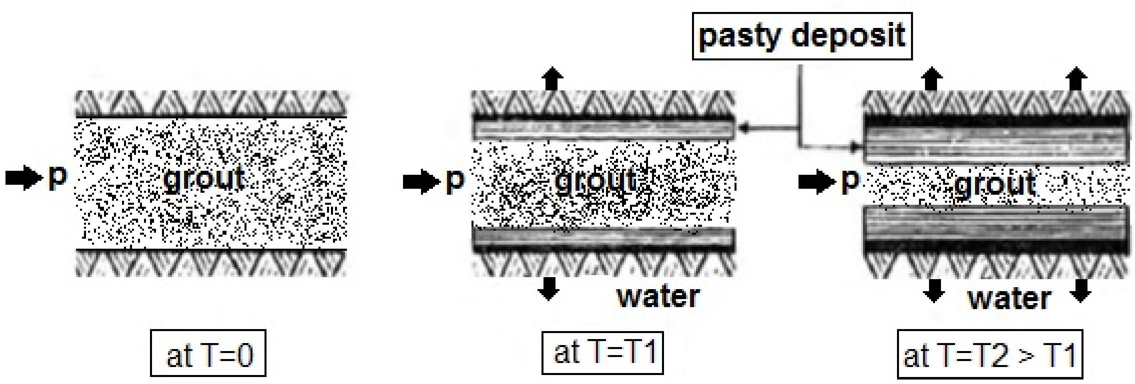


Fig. 3 Plug formation as depicted in Gandais and Delmas (1987)

2.3 Filter pump

Filter pump, developed by Hansson (1995), is another commonly used instrument for evaluating the filtration stability, due to its simplicity to use in both the lab and the field. A general depiction of the instrument is presented in Fig. 4.

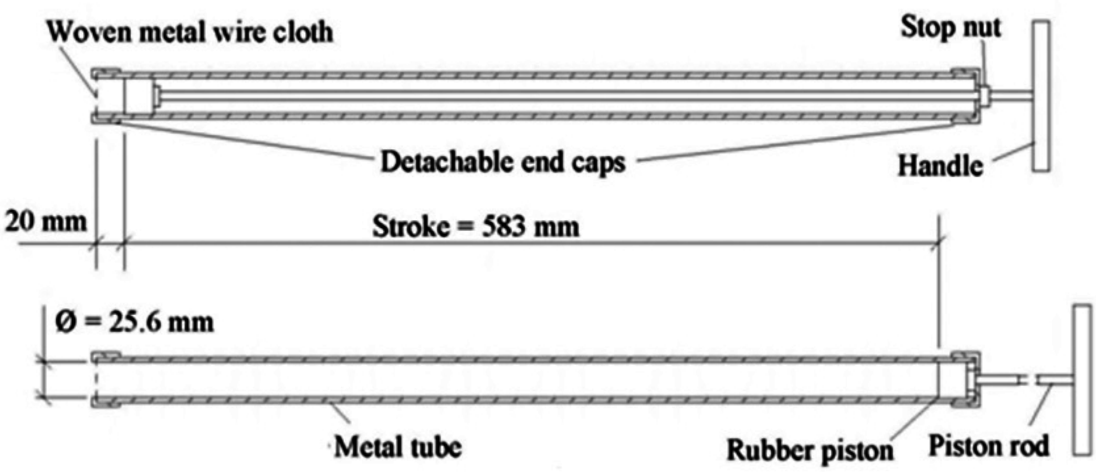


Fig. 4 Filter pump as seen in Hansson (1995)

To start the test, the instrument's handle is pulled out, sucking the grout mix into the instrument's tube through a woven metal mesh filter with different openings of 32, 45, 75, 100 and 125 μm (Hansson, 1995). The total grout volume passed through each filter is then plotted versus the corresponding filter width in successive tests to provide a qualitative evaluation of grout filtration stability (Eriksson et al. 2000). To analyze the graph, the latter suggested two definitions of b_{min} and b_{crit} as presented in Fig. 5. The minimum filter width associated with a volume of passed grout equal to the maximum capacity of the instrument (300 ml) represents the value of b_{crit}, whereas the maximum filter width with negligible passed grout is considered representative as b_{min}. At the aperture sizes between the two limits, the grout is partially filtered, whereas no grout can penetrate through an aperture size below b_{min}. These properties are considered as fundamentals for evaluating the grout penetrability in current investigation.

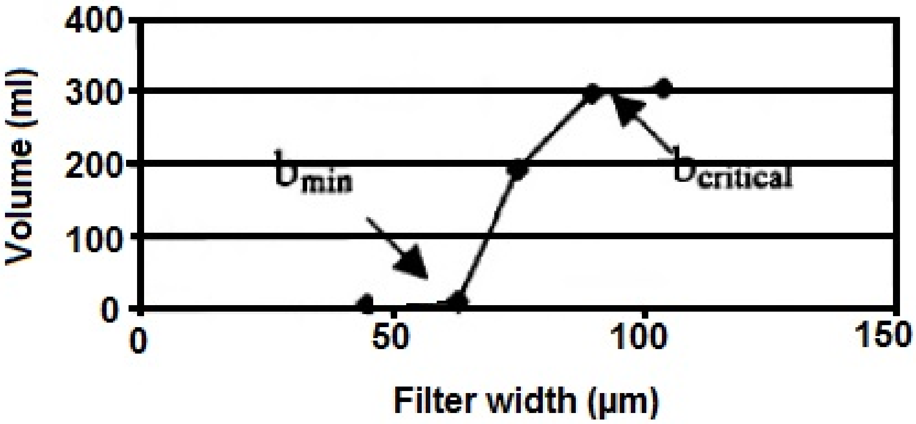


Fig. 5 Evaluation of bmin and bcrit according to Eriksson et al. (2000)

2.4 Penetrability meter

Penetrability meter, developed by Eriksson and Stille (2003), is also one of the most commonly used instruments in grouting industry for measuring filtration tendency and grout penetrability (Fig. 6). The instrument consists of a grout container linked to an air pressure pump on top and an outlet valve at the bottom connected to a tubular filter holder. To start the test, the pressurized grout (under one bar pressure) is pushed out through a woven metal mesh filter with known openings as presented in Filter pump's subsection. In penetrability meter, the filtration tendency is evaluated with the same methodology and parameters, i.e. the values of b_{min} and b_{crit} as defined in Filter pump.

Fig. 6 Penetrability meter developed by Eriksson and Stille (2003)

Penetrability meter was further employed by Eklund and Stille (2008) to study the differences between the mesh and the slot geometries. The latter concluded that the probability of filtration in the mesh geometry (from four sides) is more than the slot geometry (from two sides), whereas the filtration mechanism in the slot geometry is more similar to what occurs in a real fracture in rock (Fig. 7). An alternative for evaluation of filtration tendency was also suggested by the latter as a *k* value equal to the employed aperture size divided by the size of the cement grains (b/d_{95}).

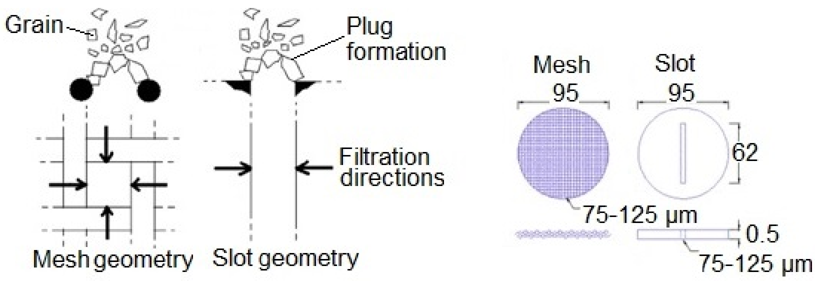


Fig. 7 Mesh and slot geometries in penetrability meter (Eklund and Stille, 2008)

2.5 NES and Nobuto methods

The NES method, developed by Sandberg (1997), consisted of an artificial fracture in the form of two steel parallel plates connected to the bottom of a grout tank (Fig. 8). The grout tank itself was hung from a suspended digital scale for measuring the weight of the passed grout in time. The required pressure was normally provided by a high-pressure gas tank attached to the system on top.

To start the experiment, the pressurized grout (under different pressures) was pushed out through the parallel plates with known geometries. The filtration tendency was normally evaluated based on the same parameters, i.e. the values of b_{min} and b_{crit} as described before. The system supported the high pressures up to 20 bar.

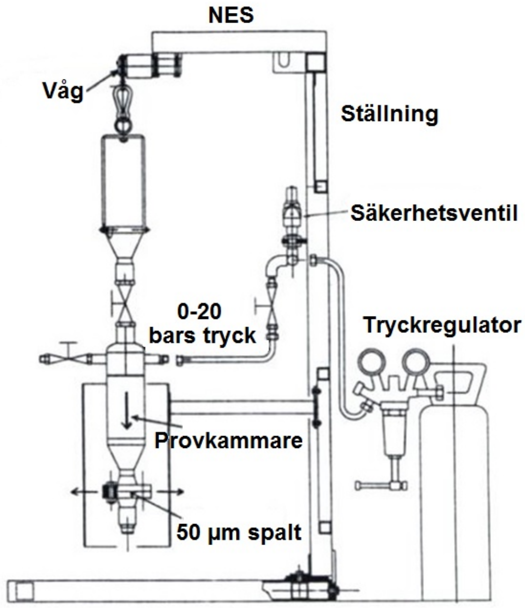


Fig. 8 General depiction of the NES method (Sandberg, 1997)

A modified version of the system with four outflow channels was further employed by Nobuto et al. (2008), using the field mixing, agitation and injection equipment. The system supported the high pressures up to 50 bar. Using stepwise pressure increment, the latter illustrated a significant improvement on grout penetrability with a mechanism of action presented in Fig. 9.

After start of each experiment, following some grout flow through the channels, the flow stop occurred due to the arching/bridging of the cement particles and clusters at the entrance of the fracture. Under the stepwise pressure increments, the unstable arches were collapsed and the channels were reopened for further grout flow resulting in a considerable improvement in grout penetrability.

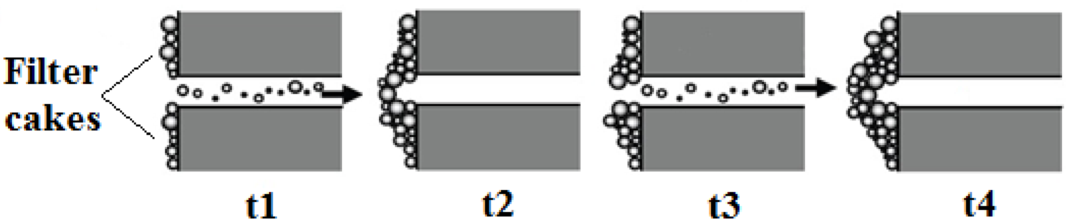


Fig. 9 Suggested sequence of filtration according to Nobuto et al. (2008)

2.6 PenetraCone

PenetraCone, developed by Axelsson and Gustafson (2010), provided another alternative suitable for field penetrability measurement. The instrument comprised of two conical cylinders: the outer, and the inner, with an adjustable aperture by rotating the inner one (Fig. 10). A typical test was usually begun using a proper large aperture providing a steady grout flow. During the test procedure, the initial aperture was gradually decreased by the operator to adjust the constant grout flow to drip. The aperture was then returned back to the initial value with steady grout flow. In the second round, the grout flow was once again reduced gently until the flow stop. The aperture size when the continuous grout flow was turning to drip was defined as a new parameter called b_{filter}, whereas the aperture size at the flow stop was specified as b_{stop} (Axelsson and Gustafson 2010).

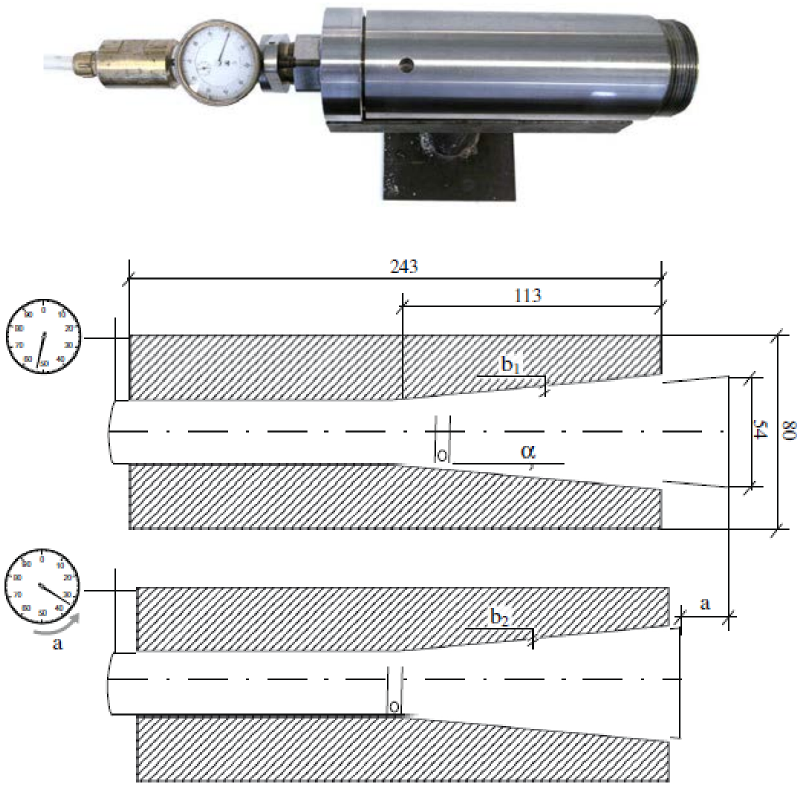


Fig. 10 Illustration of PenetraCone (upper) and cross-section (lower) from Axelsson et al. (2009)

2.7 Short Slot

Sort slot, developed by Draganovic and Stille (2011), was another instrument for evaluating the grout penetrability based on similar setup as in NES method. The instrument consisted of an artificial fracture/slot in the form of two bolted steel parallel plates containing two flow channels, each of which with one constriction. The slot itself was attached to the bottom of a grout tank, suspended from a digital scale for registering the weight of the passed grout in time. The applied pressure (up to 20 bar) was normally provided by a high-pressure gas tank connected to the system on top. The parallel plates were available with several constriction geometries to replicate the filtration process in fractures with various apertures. The main differences between the two instruments were the constrictions and the filtration locations. The filtration phenomenon in Short slot occurred at the constrictions within the slot, whereas in NES method the filtration occurred at connection between the main shaft/borehole and the slot/fracture as presented before. According to Draganovic and Stille (2011), a linear relation in weight – time measurement was an indication of no filtration, while a non-linear relation was considered to represent the filtration. Figure 11 shows cross sections of the constriction and the mechanism of arching/bridging of the cement particles as presented by Draganovic and Stille (2011).

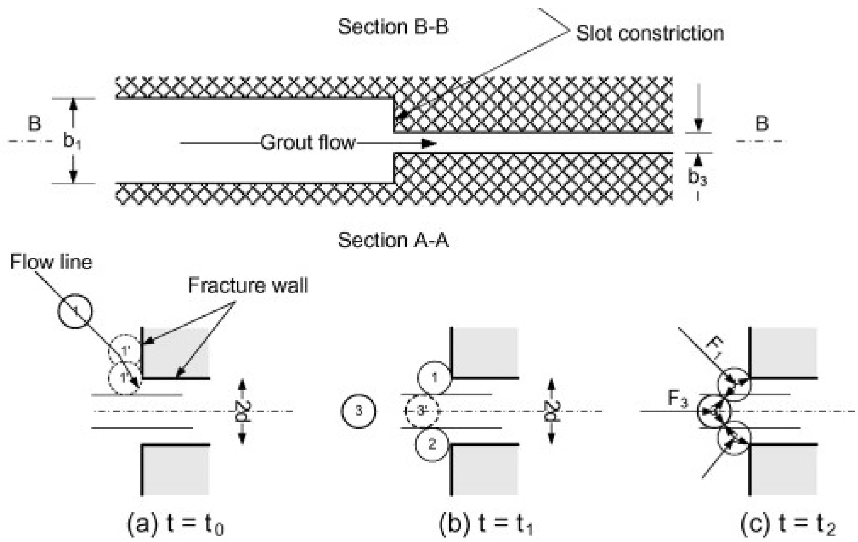


Fig. 11 Slot constriction's section (upper) and arching of the cement particles at the constriction (lower) (Draganovic and Stille 2011)

2.8 Long slot

Long slot is another instrument, developed by Draganovic and Stille (2014), to evaluate the grout penetrability along an artificial fracture with geometries considered more realistic and/or similar to a real fracture in rock in comparison with Short slot (Fig. 12-a). The instrument consisted of a slot in the form of two steel parallel plates with 4 m length containing a 75 µm constriction in the middle. The applied pressure (up to 20 bar) was normally provided by a high-pressure gas tank connected to the grout tank. The experiment started by opening valve V4, injecting the grout mix through the slot. The focus of the latter was to follow the filtration process at the constriction inside the slot using pressure gradient as an indication of filtration. Four different pressure sensors were thus located at the entrance of the slot, before and after the constriction, and right before the outlet along the slot, as presented in cross section in Fig. 12-a.

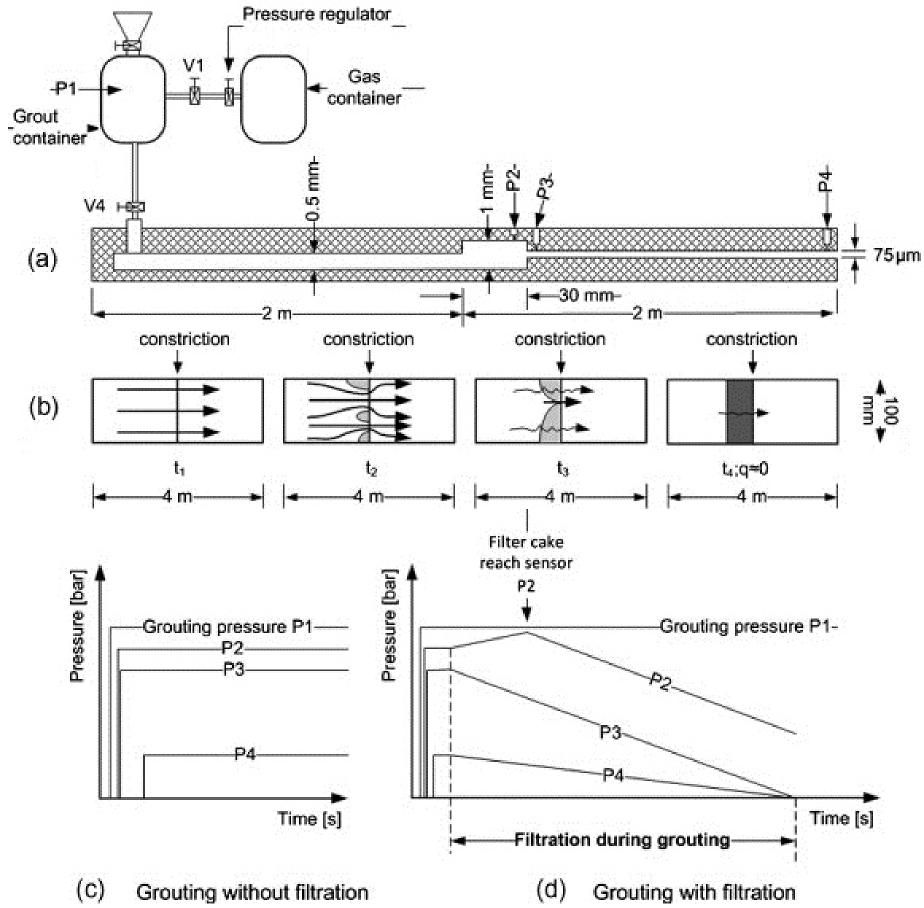


Fig. 12 Long slot section (a), plug building near the constriction (b) and the pressure variation along the slot with and without filtration (c) and (d) respectively from Draganovic and Stille (2014)

The Figure also shows the proposed flow pattern of the grout near the constriction, the evolution of filtration, and the pressure variation in time with and without filtration. In this study, the increase in pressure before the constriction and the decrease in pressure after the constriction were considered as an indication of filtration in time, whereas any sudden reduction in pressure before the constriction considered as an indication of erosion.

2.9 Origins of uncertainties and disagreement in results

Comparisons of the results obtained from different penetrability measuring instruments have usually been in association with some uncertainties, disagreements, and occasionally contradictions. For instance, the experiments conducted using NES method and Penetrability meter illustrated that the grout penetrability is independent of water to cement (*w/c*) ratio (Hjertström 2001; Eriksson and Stille 2003). However, comparison of the results obtained from Filter pump with the ones of Sand column, smooth slot, and Short slot disclosed that increasing the (*w/c*) ratio improves the penetrability (Hansson 1995; Eklund and Stille 2008; Axelsson et al. 2009; Draganovic and Stille 2011). According to Hansson (1995), use of super plasticizer improves the grout penetrability in experiments conducted using the smooth slot and Filter pump. However, Eriksson and Stille (2003) showed that use of super plasticizer has no significant influence on penetrability in experiments with Penetrability meter. These uncertainties and disagreements are primarily based on the difference in assumptions, limitations, and test conditions as well as the deficiency in the test setups, procedures, and evaluation methods. Some of the most significant ones can be discussed as follows.

2.9.1 Difference in filtration mechanisms

Sand column, Pressure chamber and filter press developed by Bergman (1970), Widmann (1996), and Gandais and Delmas (1987), respectively were all found more suitable for evaluating the grout penetrability in a porous medium, e.g., sand and soil than a real fracture in rock. The main reason was described due to the difference in flow pattern and filtration mechanism in different media (Draganovic and Stille 2011). A preliminary assumption in design of Filter press was the filtration mechanism based on the water loss through the fracture walls. The corresponding reason was interpreted due to the porosity of the rock matrix and presence of micro cracks (Gandais and Delmas 1987). This implies that there should be no filtration in fractures with impermeable walls. However, the filtration phenomenon has been clearly observed in results of the experiments conducted by Short slot, Long slot and Penetracone with non-permeable steel walls (Draganovic and Stille 2011, 2014; Axelsson and Gustafson 2010). This observation falsifies the preliminary assumption of Gandais and Delmas (1987) in design of Filter press.

The filtration mechanism in a mesh geometry as in Filter pump and Penetrability meter is best correlated to clogging at the surface of a porous medium in Sand column or filtration at the entrance of a slot geometry as in NES and Nobuto methods compared to what occurs in a real fracture in rock (Hansson 1995; Sandberg 1997; Nobuto et al. 2008; Draganovic and Stille 2011). Draganovic and Stille (2011, 2014) however presented a more realistic filtration mechanism that is filtration due to arching and plug building of the cement particles and clusters at constrictions through a fracture.

2.9.2 Difference in applied pressures and w/c ratios

Sand column and Filter press had been designed to examine grouts with relatively high water to cement ratios (w/c) of about 3 under low pressures less than 2.6 bar. In similar fashion, the pressure capacity in Filter pump and Penetrability meter, developed by Hansson (1995), and Eriksson and Stille (2003) respectively, was less than 2 bar. These conditions were however far from the capacity of the other instruments and the real grouting conditions in field.

2.9.3 Difference in grout rheological properties

According to Hansson (1995), the grout rheological properties in design of Filter pump was assumed closely Newtonian. The design of all other penetrability-measuring instruments was however based on Bingham model. In order to improve the grout stability and control its bleeding property, a common solution is grouting with low to moderate w/c ratio (Lombardi 1985; Draganovic and Stille 2012). According to Yang et al. (2011), this yields the rheological properties close to Bingham model rather than

Newtonian, which is in contradiction with the basic assumption in design of Filter pump.

2.9.4 Difference in constriction geometries

In Filter pump and Penetrability meter, the probability of filtration in the mesh geometry was higher than that compared to the slot geometry. This was suggested by Eklund and Stille (2008), due to the support of the plug formation in the mesh geometry from four sides compared to the two sides supports of the slot geometry. However, based on an engineering judgement the filtration in slot geometry, e.g., in Short slot and or Long slot, is much more realistic and similar to what occurs in a real fracture in rock (Draganovic and Stille 2011; 2014).

2.9.5 Deficiency in evaluation methods

In Penetracone, the value of b_{filter} has been defined to represent the aperture size at the beginning of filtration (Axelsson and Gustafson 2010). To evaluate this, each experiment is normally started with a proper large aperture that is gradually reduced until the steady grout flow changes to drip. The corresponding reduction in grout flow however occurs because of both the decrease in aperture size and the growth in filter cake. In this process, the aperture at the beginning of filtration is larger than that at the start of the dripping. The value of b_{filter} is therefore evaluated smaller than the aperture size at the beginning of filtration. The value of b_{stop} has been defined to represent the smallest aperture that a selected grout can penetrate at all. To evaluate this, the same process is followed until the flow stop occurs due to the decrease in aperture size and the growth in filter cake simultaneously. If one adjusts the aperture size of the instrument to the evaluated value of b_{stop} and repeats the experiment, an immediate flow stop will not occur as expected, due to the lack of filter cake. The value of b_{stop} is therefore evaluated larger than the minimum fracture aperture a grout can penetrate at all. This explains the uncertainties involved and the differences between the results of grout penetrability obtained from Penetracone and the other instruments.

2.10 Comparison of Filter pump, Penetrability meter and Short slot

To obtain a better understanding of the nature of grout penetrability, three instruments were selected to dig deeper in a comparison. Filter-pump and Penetrability-meter were selected, since they are two of the most commonly used penetrability measuring instruments applicable in both the lab and the field due to the simplicity of their performances (Hansson 1995; Eriksson and Stille 2003). Short slot was the third selection, since it has been designed based on the geometry and test conditions much closer to the rock grouting conditions in field; however, it is a bit more complicated in performance and rather applicable in lab (Draganovic and Stille 2011). The results obtained from Penetrability meter and Filter pump, as partly discussed earlier, are associated with some uncertainties and disagreements with the ones obtained from Short slot (Draganovic and Stille 2014). These uncertainties are mainly in connection with either or a combination of four factors: the applied pressure, the grout volume, the constriction geometry, and the evaluation method. These parameters should be considered cautiously in selection of a proper instrument and method for more realistic measurement of grout penetrability.

2.10.1 Problematic issues concerning the applied pressure

One of the most significant issues in Filter pump could be the operator-dependency of the applied pressure, which is clearly not identical in experiments conducted neither by several operators nor by an exhausted operator in successive tests. It should also be considered that the regular applied pressure in Filter pump is somewhat near 0.5 bar (Hansson 1995). This parameter in Penetrability meter and Short slot is however normally set to 1 and 15 bar, respectively (Eriksson and Stille 2003; Draganovic and Stille 2011). Although the applied pressure in Short slot is more realistic, but its considerable difference with the other two instruments is problematic (Draganovic and Stille 2011). It is well known that the grout penetrability is improved by increasing the pressure (Eriksson et al. 1999; Hjertström 2001; Nobuto et al. 2008; Draganovic and Stille 2011; Stille et al. 2012). This implies that the penetrability measurement is undeniably dependent on the grouting pressure and the experiments on identical grout samples under different pressure conditions should definitely reveal diverse or even contradictory results.

2.10.2 Problematic issues concerning the grout volume

Eriksson and Stille (2003) and Eklund and Stille (2008) discussed that the grout filtration tendency will be rationally increased by rising the volume of the grout passed through a mesh filter. The more the grout volume, the higher is the probability of accumulation and clogging of the cement particles and clusters at any constriction. It should be noticed that the grout capacity in Filter pump is approximately 0.3 liter compared with the specified grout volume in Penetrability meter and Short slot that are 1 and 2.6 liter, respectively. This difference will possibly influence the results in examining identical grout samples, disregarding the effects of uneven pressures and geometries.

2.10.3 Problematic issues concerning the constriction geometry

In Penetrability meter and Filter pump, the length of constriction, i.e. the thickness of the woven metal mesh filter is at most 100 µm. In Short slot, the corresponding length is approximately 10 *mm*, i.e. 100 times longer (Draganovic and Stille 2011). This rationally implies that the resisting friction against the grout flow along the mesh filter/constriction in both Penetrability meter and Filter pump will reasonably be negligible, compared with that in Short slot. Furthermore, the total effective area in both Penetrability meter and Filter pump is much higher than that in Short slot. This will possibly lead to further disagreements in examining identical grout samples.

2.10.4 Problematic issues concerning the evaluation method

Grout penetrability measurement in terms of the parameters b_{min} and b_{crit}, developed by Eriksson and Stille (2003), has been one of the most commonly used criteria in grouting industry over the past decade (Draganovic and Stille 2014). As discussed earlier, the volume of grout passed through each filter is the method normally used to evaluate those values in Penetrability meter and Filter pump. The uncertainty of this method becomes discernible at the mesh sizes sufficiently close to the b_{crit}, when using a stepwise bottom-up approach. To visualize this uncertainty, the measure of weight in time as presented in Fig. 13 is employed. By approaching the b_{crit} as shown in tests 5 and 6, despite of slight filtration, i.e. minor deviation from linear relation, the remained opening is still adequate to let the entire specified grout volume pass through. Using the volume of passed grout as the evaluation method, the evaluated value of b_{crit} could therefore be smaller, e.g., equal to the mesh size in test 5, while the weight-time measurement reveals a higher value equal to the mesh size in test 7 with no filtration at all.

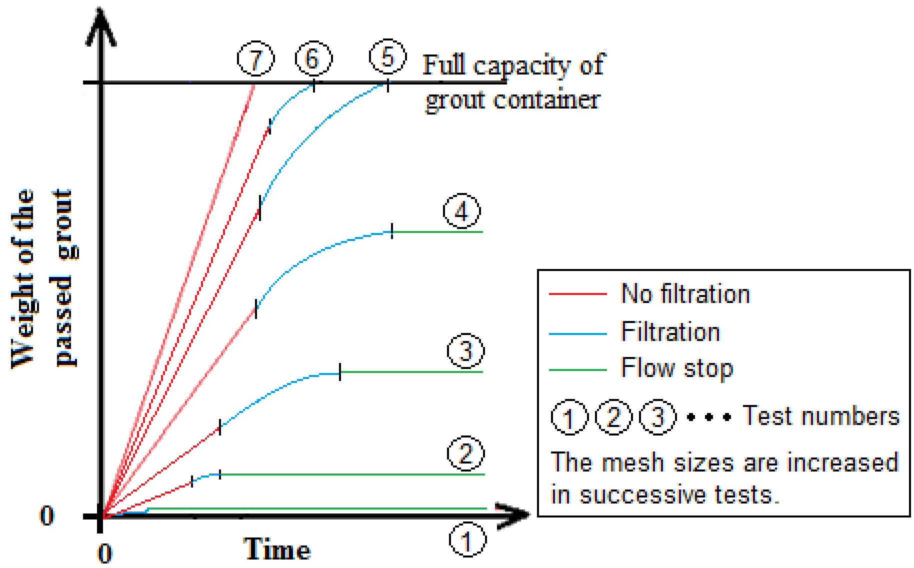


Fig. 13 Application of weight-time measurement to visualize the uncertainty in evaluation of b_{crit} using the total weight of passed grout

3. How to improve the grout spread?

To improve the grout spread through the fractures in rock effectively, one of the significant factors is to have a stable grout with controlled filtration tendency. The effects of various parameters on controlling the filtration and improving the grout penetrability have been therefore investigated by several researchers, whereas the following were found as the governing ones:

- Magnitude and shape of the applied pressure
- Grout rheology (viscosity, shear resistance)
- Water to cement ratio (w/c)
- Cement grain size and distribution curve
- Admixtures (e.g. set retarders, dispersing, and rapid hardening agents)
- Additives (e.g. Fly ash, Silica fume, and Blast furnace slag)
- Aperture size
- Constriction geometry (e.g. slot/mesh geometry)
- Type and speed of chemical reactions (hydration)
- Attraction & repulsion between the cement grains (flocculation, agglomeration)
- Cement storage time
- Waiting time after mixing
- Mixing time
- Mixer type, size and speed of propeller

Investigating all these parameters in detail is a lifetime project so in this investigation we just focus on one of the most significant ones, the magnitude and the shape of the applied pressure.

3.1 The influence of the applied pressure on improving the grout spread

According to Eriksson et al. (1999), Hjertström (2001), Draganovic and Stille (2011, 2014), and Stille et al. (2012), an increase in pressure decreases the filtration tendency and improves the grout spread. Nobuto et al. (2008) further showed that clogging of cement particles could be prevented by applying stepwise pressure increment.

The influence of dynamic/vibrating grouting on improving the grout spread has been first demonstrated by Pusch et al. (1985) in Stripa mine with the mechanism of improvement interpreted as reduction in viscosity due to the high frequency oscillations. Borgesson and Jansson (1990) further illustrated that by superimposing a high frequency oscillating pressure with large amplitude on a high static pressure of 20 bar, even a low water content cement grout can penetrate well through 100 µm artificial fractures. Besides their laboratory experiments, they got satisfactory results in their full-scale field tests as well. The mechanism of action of the method in their investigation was once again explained as reduction in viscosity due to the oscillations. Wakita et al. (2003) thereafter conducted several laboratory and field experiments by adding oscillations to different underlying static pressures, through which the flow rates and the total volumes of grout take were increased. Like the Borgesson and Jansson (1990), the latter interpreted the mechanism of improvement based on the reduction in viscosity of grout suspension due to the oscillations. In similar fashion, Mohammed et al. (2015) showed the influence of dynamic pressure on improving the grout spread within artificial fractures of 100-500 µm. The reason was once again correlated to the reduction in grout viscosity because of disruption in the internal structure of the cement particles and clusters due to the vibration.

3.2 Limitations and missing parts in previous investigations on dynamic grouting

All previous investigations on dynamic grouting were similarly limited on specific regions as discussed below.

3.2.1 Limitation in type and frequency of the applied pressure

The examined pressures were mainly high frequency oscillating pressures, whereas other alternatives of dynamic pressure especially with low frequencies could be more productive in terms of controlling the filtration (Fig. 14).

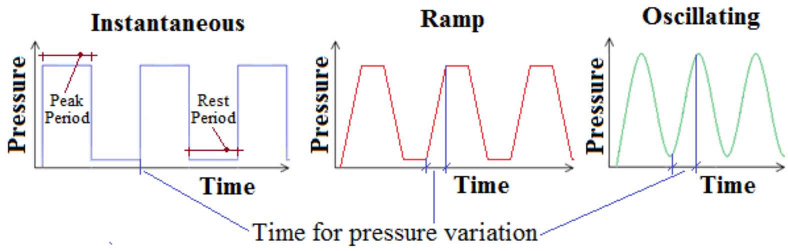


Fig. 14 Different alternatives of the dynamic pressure

3.2.2 Lack of constriction

The laboratory experiments were all conducted on parallel plates without constriction, meaning no filtration appeared along the parallel plates. This is undeniably in contrast with what occurs in a real fracture in rock having numerous constrictions.

3.2.3 Mechanism of action

The mechanism of action of the method was consistently interpreted as reduction in viscosity due to the oscillation. This was due to the fact that the nature of resistance against the grout spread in the ideal parallel plates employed in the previous studies mainly depends on the grout rheology. However, in view of the grout spread through a real fracture in rock, the rheology is not the only governing parameter to consider. The filtration of the cement particles and clusters should also be considered to discover other probable mechanisms of action by replicating the process through parallel plates containing the constriction.

3.2.4 Limitation in aperture size

The earlier observations were all performed through apertures larger than 100 μm. However, successful grouting in micro-fractures narrower than 70 μm is crucial in order to fulfill the required sealing in extremely high sealing demanded areas such as high-level nuclear waste repositories.

3.3 Why instantaneous variable pressure?

Under application of constant pressure in experiments with Short slot, the produced filter cake expands over the constriction in time causing the flow stop, due to the accumulation of the cement particles at the constriction. Based on the literature review, application of stepwise pressure increment is a method used to keep the slot/fracture open for a longer period because of erosion of unstable filter cakes. Another alternative for eroding the filter cakes at a partially plugged constriction is logically variation in flow pattern. Under application of dynamic pressure, any change in grouting pressure varies the flow velocity and consequently the flow pattern. However, the change in flow pattern will hypothetically be productive for eroding the filter cakes, if the acceleration and magnitude of the pressure and velocity variations and consequently the changes in flow pattern are sufficient. In the meantime, the durations at peak and rest pressures have probably certain critical limits (Fig. 15). Above the limits, the plug expands over the constriction to an extent that can no longer be eroded, whereas the durations below the critical limits are insufficient to obtain an effective pressure and velocity variation. Therefore, the key elements for obtaining effective erosion are the acceleration and the magnitude of the pressure variation, which should be maintained at the highest levels, and the durations at peak and rest, which should be kept close to the critical limits.

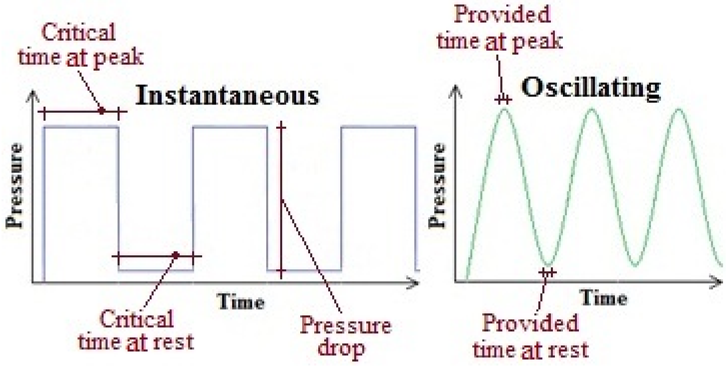


Fig. 15 Critical and provided times at peak and rest during the oscillating and instantaneous variable pressures

In case of oscillating pressure, adjusting the proper durations at peak and rest in each cycle is quite impossible (Fig. 15). The instantaneous and ramp shape variable pressures with adjustable peak and rest, however, simply provide these periods (Fig. 14). In the cases of oscillating and ramp shape variable pressures, depending on the predefined acceleration and magnitude of the pressure variation and the limitations of the system, a short time is needed for the pressure to change effectively (Fig. 14). However, in the case of instantaneous variable pressure, variation in pressure and consequently the flow pattern will apparently occur more quickly. This is due to the predefined instantaneous variation in pressure, even though in practice it does not occur instantly because of the limitations in the system. Therefore, the resulting erosion of any partially built plugs in the latter case will probably be more effective than in other alternatives. Consequently, the instantaneous variable pressure was rationally selected as the focus of this part of investigation. Selection of the proper peak and rest periods corresponding to our selected materials and test conditions are presented in detail in Paper 2.

4. Experimental setup

4.1 Test apparatus, procedure, and evaluation method - Part A

In the first part of the study, the aim was to obtain a deeper understanding of the nature of grout penetrability and to find a proper instrument and method for more realistic measurement of the grout penetrability. In order to have a fair comparison, Filter pump and Penetrability meter were thus adjusted to approach to the test conditions and evaluation methods employed in Short slot. The remained difference between the two instruments was mainly in the specified grout volume, 2.6 liter in modified Penetrability meter (MPM) versus o.3 liter in modified Filter pump (MFP). Due to the higher probability of filtration associated with the larger volume of passed grout, the evaluated b_{crit} from MPM was expected to be larger than the obtained value from MFP. The test setups for the first part of the study are presented below.

4.1.1 Modified Filter pump

The main objectives in adjustment of Filter pump were to raise the applied pressure to 1 bar, to exclude its operator-dependency, and to use the measure of weight in time as the evaluation method. A mass of 20 kg was therefore employed to provide the specified pressure in a partially automated system as presented in Fig. 16. To register the weight of the passed grout in time, a grout pot was also suspended from an S-shaped load cell, as presented in more detail in paper 1.

In each experiment, a mesh filter with 26 µm opening was normally employed for the first trial. By releasing the mass, the grout was sucked into the instrument, while the weight of the passed grout through the mesh filter was registered in time. This process was successively repeated with enlarged mesh filters until no filtration was observable in the results of weight-time measurement. In this method, the maximum mesh size with negligible passed grout was an illustration of b_{min}, while the minimum mesh size with no filtration at all was an indication of b_{crit} (Fig. 17).

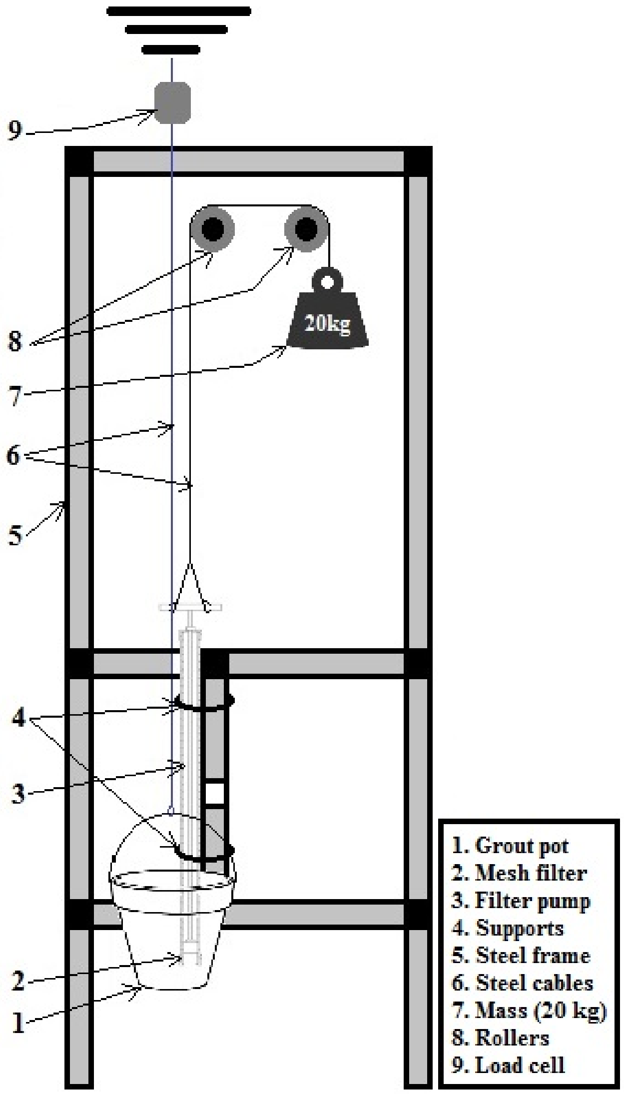


Fig. 16 Schematic depiction of modified filter pump

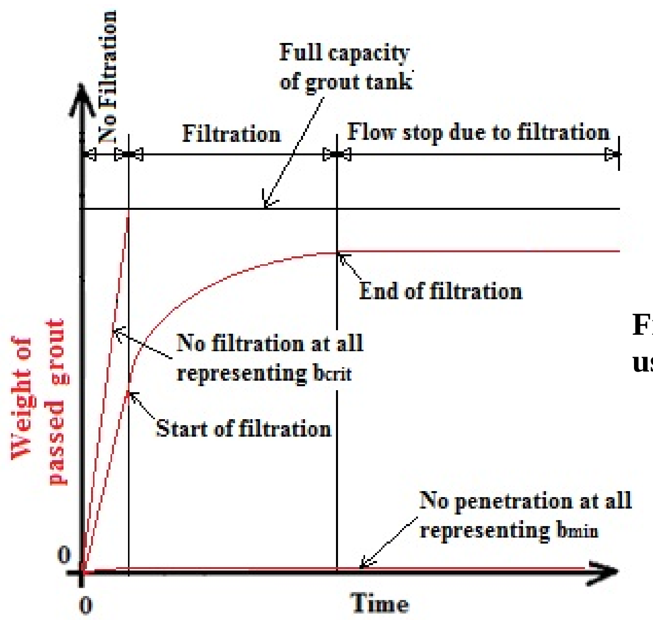


Fig. 17 Evaluation of b_{min} and b_{crit} using the weight-time measurement

4.1.2 Modified Penetrability meter

The main objectives in adjustment of Penetrability meter were to raise the grout volume capacity to 2.6 liter, and to follow the filtration evolution using the measures of weight and pressure in time. A grout tank was therefore suspended from an *S-shaped* load cell, to register the grout weight in time as depicted in Fig. 18. The grout tank was then connected to a high-pressure gas tank providing the required pressure of 1 bar. A pressure transmitter was further added to the tank to record the pressure variation. Finally, a filter holder was attached to the system to replicate the filtration process as in ordinary Penetrability meter. In each experiment, a mesh filter with 26 µm opening was normally employed for the first trial. The grout in tank was primarily pressurized to 1 bar. The test was started by opening the outlet valve, whereas the measures of pressure and weight of the passed grout were recorded in time. This process was successively repeated with enlarged mesh filters until no filtration was observable during the experiment. More details of the test apparatus and procedure can be found in paper 1. The evaluation methods employed in modified Penetrability meter are the weight-time and the pressure-time methods as discussed below.

- **The weight-time method**

The weight-time method employed in modified Penetrability meter (MPM) was exactly as presented in modified Filter pump (MFP).

- **The pressure-time method**

As seen in the plot of pressure in time in Fig. 19, by opening the outlet valve and start of the grout flow a sharp drop in pressure appears until the balance point, in which the gas inflow compensates the grout outflow. After the balance point, the pressure maintains constant, if the grout behaves as a stable fluid without filtration tendency as ideally observed in experiments with water. This has been verified in a couple of water tests with the details presented in paper 1. In contrast, in experiments with unstable grouts, since the mesh opening and consequently the grout flow are progressively decreased due to the filtration, a continuous pressure increase is expected after the balance point. In this approach, a mesh filter maintaining the pressure constant after the balance point is considered representative as b_{crit}, whereas a mesh filter resulting in a negligible pressure drop with an immediate flow stop represents b_{min} (Fig. 19).

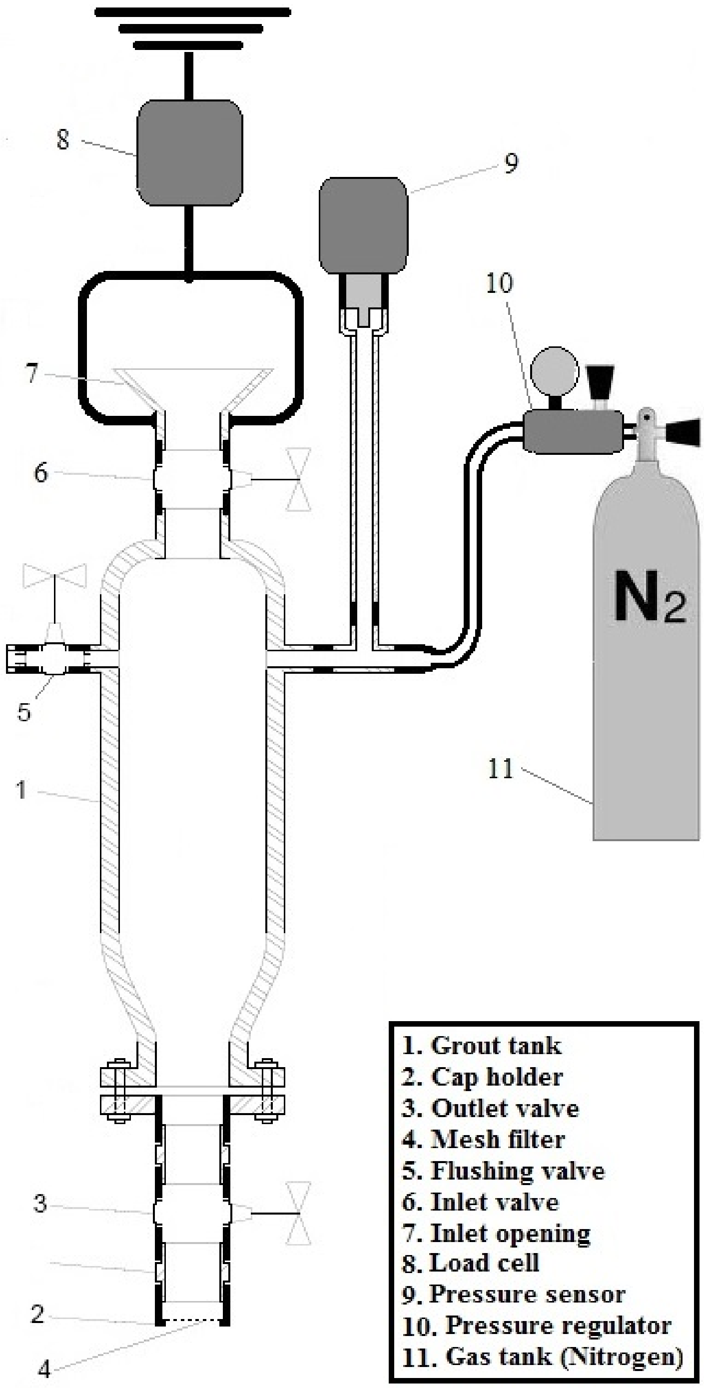


Fig. 18 Schematic depiction of modified penetrability meter

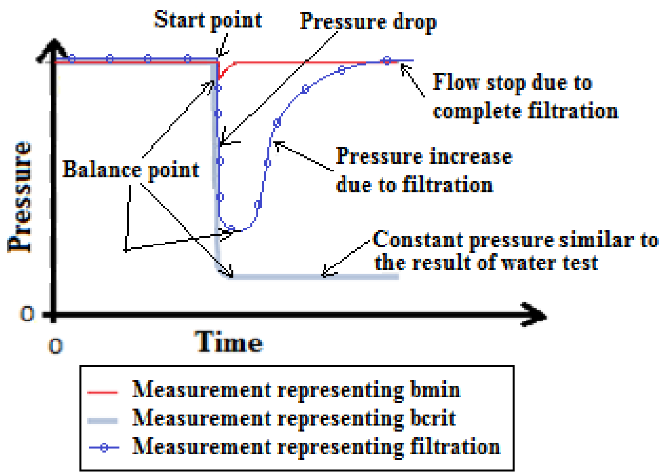


Fig. 19 Monitoring filtration and evaluating the b_{min} and b_{crit} using the pressure-time measurement

4.1.3 Short slot

The test apparatus, procedure, and the evaluation method in experiments with Short slot were exactly as presented earlier in this thesis. More details of the test setup and procedure can be found in Draganovic and Stille (2011).

4.2 Test apparatus, procedure, and evaluation method - Part B

In the second part of the project, the objective was to improve the grout spread using a low frequency instantaneous variable pressure as a means to better control the filtration. Short slot with the aforementioned organization was selected as the main equipment in corresponding experiments due to the advantages presented before. A programmable pneumatic pressure control system was also designed to convert the provided static pressure to a low frequency instantaneous variable pressure with specified durations at peak and rest. The system comprised of an automatic valve, a pressure sensor, and a control unit to measure the grout pressure in time at the entrance of Short slot and compare it with the set pressures to control the valve conditions as depicted in Fig. 20. Each experiment started by setting a control script, defining the magnitudes and the durations at peak and rest. The grout in tank was first pressurized under 15 bar pressure, whereas the automatic valve was fully closed. The valve was then instantaneously opened to start the grout flow under 15 bar pressure. After the peak period, the valve was closed, causing a sharp pressure drop, followed by a gradual pressure reduction over the rest period. This process was reproduced in successive cycles until either occurrence of the flow stop due to the filtration or discharge of the grout tank. More details of the test apparatus and procedure can be found in paper 2.

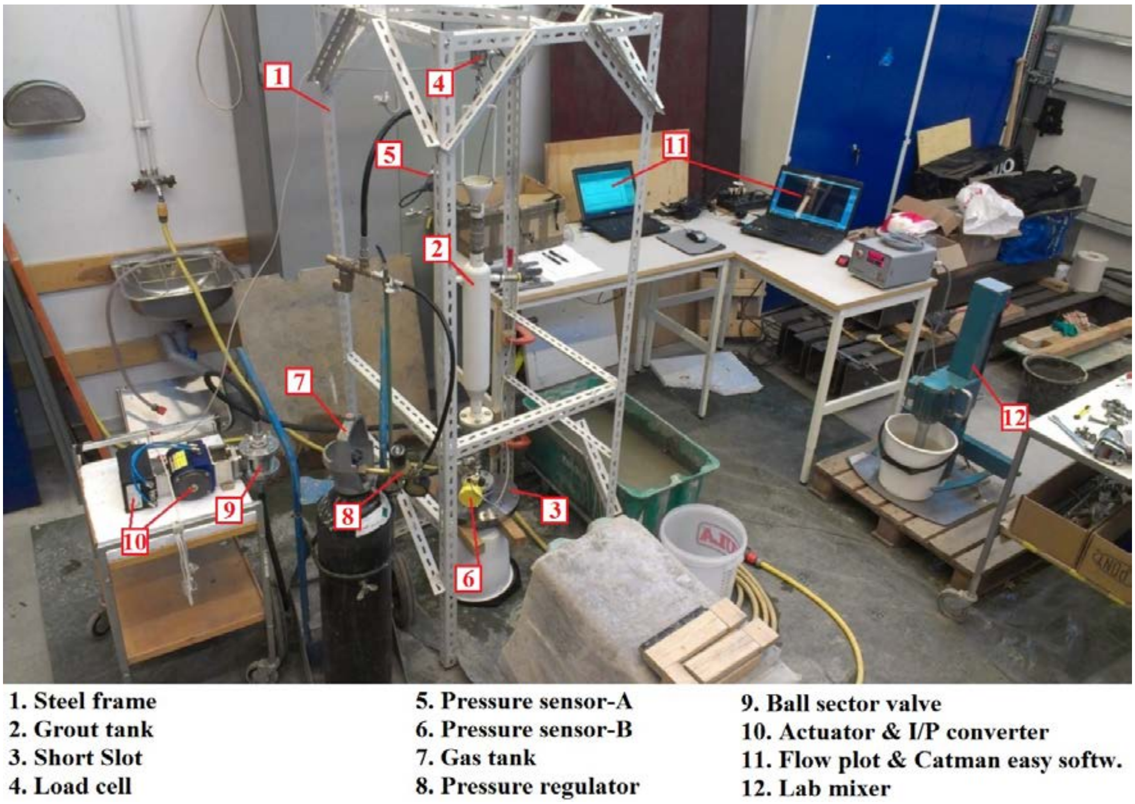


Fig. 20 Depiction of the test setup

The evaluation methods employed to visualize and quantify the effectiveness of the instantaneous variable pressure on improving the grout spread comprised of total weight of passed grout, weight-time measurement, min-pressure envelope and cycle mean flow rate. Three of them are however discussed in brief in following sections due to the significance of their achievements. More details of the methods can be found in paper 2.

- **Total weight of passed grout**

  This method was employed to quantify the differences between the static and dynamic pressure applications. The main drawback of the method however was the disability to monitor the processes of filtration and erosion.

- **Min-pressure envelope**

In this method, the plot of pressure in time accompanied by the min-pressure envelope utilized to visualize both the filtration and the erosion processes along the experiments (Fig. 21). The min-pressure envelope was a polyline connecting the consecutive vertices of the minimum pressure levels of all cycles in the pressure-time diagram. Any positive (upward) trend along the min-pressure envelope was an indication of filtration, while any negative (downward) trend was an illustration of erosion. The main drawback of the method however was the disability to quantify the filtration and erosion processes.

- **Cycle mean flow rate (*CMFR*)**

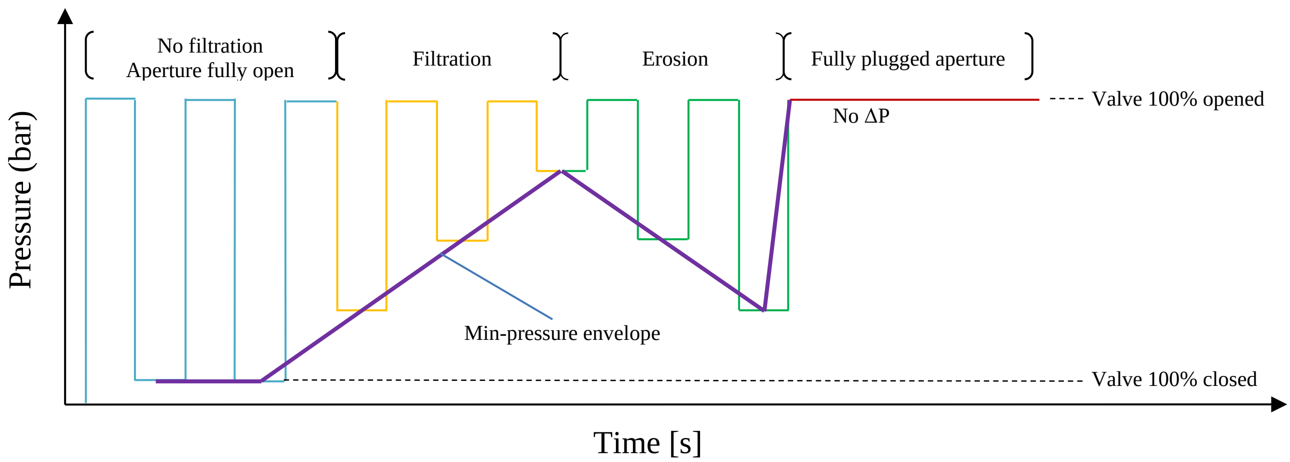


Fig. 21 Use of min-pressure envelope to visualize the filtration and erosion processes

To quantify the filtration and the erosion processes in each cycle and to better distinguish between the influences of different peak and rest periods, a new parameter named cycle mean flow rate (*CMFR*) was introduced. The *CMFR*, defined as the mean value of the volumetric flow rate of the passed grout in each cycle, can be determined as:

$$CMFR = \frac{V}{T} \qquad \text{Eq.1}$$

where V is the volume of the passed grout per cycle, and T is the cycle duration. More details of the method can be found in paper 2.

4.3 Material and mix design – Parts A - B

The mix design employed in both parts of this study was based on one of the most commonly used grout recipes in Swedish infrastructures. It composed of *INJ30* with (d_{95}) of 30 µm as cement, *iFlow-1* with concentration of 0.5% as superplasticizer, with water to cement ratio (*w/c*) of 0.8. A rotor-stator lab mixer was employed to thoroughly disperse the cement particles with 10,000 *rpm* for a period 4 *min*, after 1 *min* of premixing using a handy mixer. The super plasticizer was usually added to the system after 1 *min*. The prepared grout (approximately 2.8 liter in each batch) was subsequently used to run the test immediately. More details of the materials, equipment, and mixing process can be found in Papers 1 and 2.

4.4 Test plan – Parts A - B

A summary of the experimental programs in parts A and B of the study are presented in Table 1 and 2, respectively. Explanation of the test plans and the corresponding purposes can be found in Paper 1 and 2.

Table 1 Test plan Part A

Test group	Pressure (bar)	Test device	Evaluation method	No. of repetitions with every mesh size											No. of repetitions with every slot size					
				26 µm	35 µm	43 µm	54 µm	61 µm	77 µm	90 µm	104 µm	122 µm	144 µm	200 µm	43 µm	50 µm	70 µm	84 µm	169 µm	177 µm
1	1	OFP	WT	1	4	4	4	3	3	2	-	-	-	-	-	-	-	-	-	-
2	1	MFP	WT	-	4	3	3	3	3	2	1	2	1	-	-	-	-	-	-	-
3	1	MPM	WT	-	2	2	2	-	3	1	2	1	3	-	-	-	-	-	-	-
4	1	MPM	PT	-	2	3	3	-	1	-	3	-	3	1	-	-	-	-	-	-
5	1	SS	WT	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	3
6	15	SS	WT	-	-	-	-	-	-	-	-	-	-	-	1	3	1	-	-	-
			Sum=	1	12	12	12	6	10	5	6	3	7	1	1	3	2	-	1	3
			Total No.= 85																	

OFP: Ordinary Filter Pump   MPM: Modified Penetrability Meter   WT: Weight-time
MFP: Modified Filter Pump   SS: Short Slot   PT: Pressure-time

Table 2 Test plan Part B

Test group	Number of tests	Slot size [μm]	Pressure type	Peak/rest period [sec]
C1	3	43	Static	-
C2	3	30	Static	-
V1	3	43	Dynamic	4 s/8 s
V2	3	30	Dynamic	4 s/8 s
V3	3	43	Dynamic	2 s/2 s
V4	2	30	Dynamic	2 s/2 s

5. Discussion on the results

5.1 Discussion on the results of Filter pump, Penetrability meter and Short slot

The values of b_{min} and b_{crit} evaluated in the first part of the study using Filter pump, Penetrability meter, and Short slot with different applied pressures, grout volumes, constriction geometries, and evaluation methods are summarized in Table 3. More details and explanations of the results can be found in paper 1.

Table 3 Summary of the evaluated values of b_{min} and b_{crit}

Test device	Evaluation method	Pressure (bar)	b_{min} (µm)	b_{crit} (µm)
OFP	T	1	35	77
OFP	W	1	35	90
MFP	T	1	43	61
MFP	W	1	43	77
MPM	W	1	43	200
MPM	P	1	35	200
SS	W	1	70	200
SS	W	15	26	50

OFP: Ordinary filter pump
MFP: Modified filter pump
MPM: Modified penetrability meter
SS: Short slot

T: Total volume of passed grout
W: Weight-time
P: Pressure-time

The results are further discussed with respect to the aforementioned differences as the governing origins of uncertainties in grout penetrability measurement to obtain a better understanding of the nature of grout penetrability and fairly assess the reliability and functionality of the instruments.

5.1.1 Uncertainties in measurements induced by the applied pressure

In ordinary Filter pump, the operator dependency of the applied pressure might result in different measures of penetrability for identical grout samples. The corresponding evidence can be seen in uneven and unequal mass flow rates, shown in experiments with 54 - 77 µm mesh filters in Fig. 22, using the weight-time measurement. The results obtained from the modified Filter pump revealed the extent of the uncertainties adjusted by the proposed modification (Fig. 23). Comparing the results of b_{min} and b_{crit} obtained from Short slot under 1 bar pressure (70 and 200 µm) with the ones under 15 bar pressure (26 and 50 µm) discloses the significance of the applied pressure in aforementioned contradictions in grout penetrability measurements.

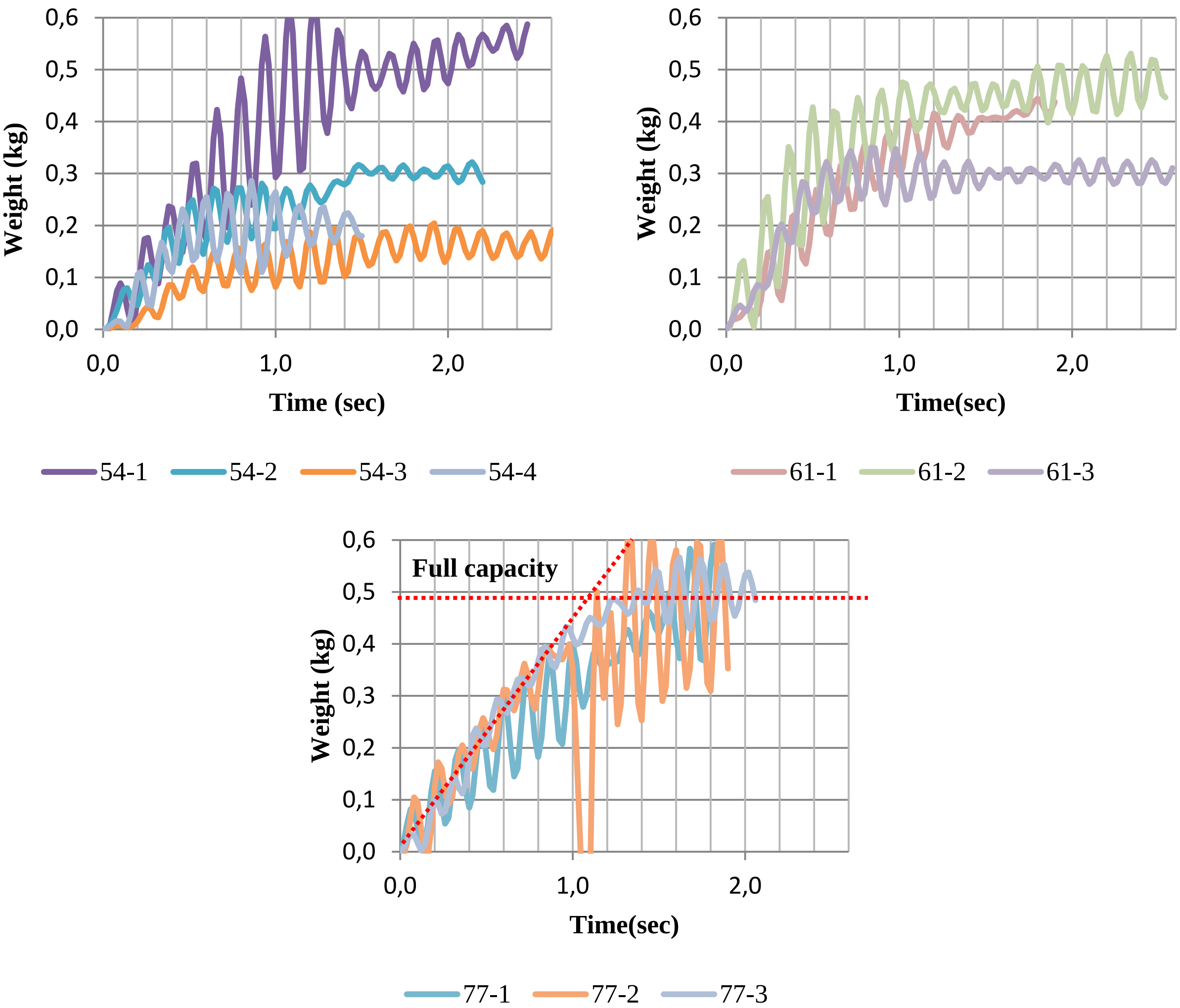


Fig. 22 Results of ordinary Filter pump with 54-77 µm mesh filters using the weight-time measurement

In a grouting operation in a real fracture in rock, the driving pressure that is mobilized at the grout front has the maximum value near the grouting borehole. Due to the grout viscosity and fracture geometries, this pressure decreases along the fracture substantially. This implies that to have a fair evaluation of the grout penetrability in a real fracture in rock, it is essential to measure the grout penetrability in both the high and the low pressures. This suggests that use of Short slot under high pressure of 15 bar as proposed by Draganovic and Stille (2011) does not yield a satisfactory result applicable in the field. The penetrability should be measured with both the high and the low pressures.

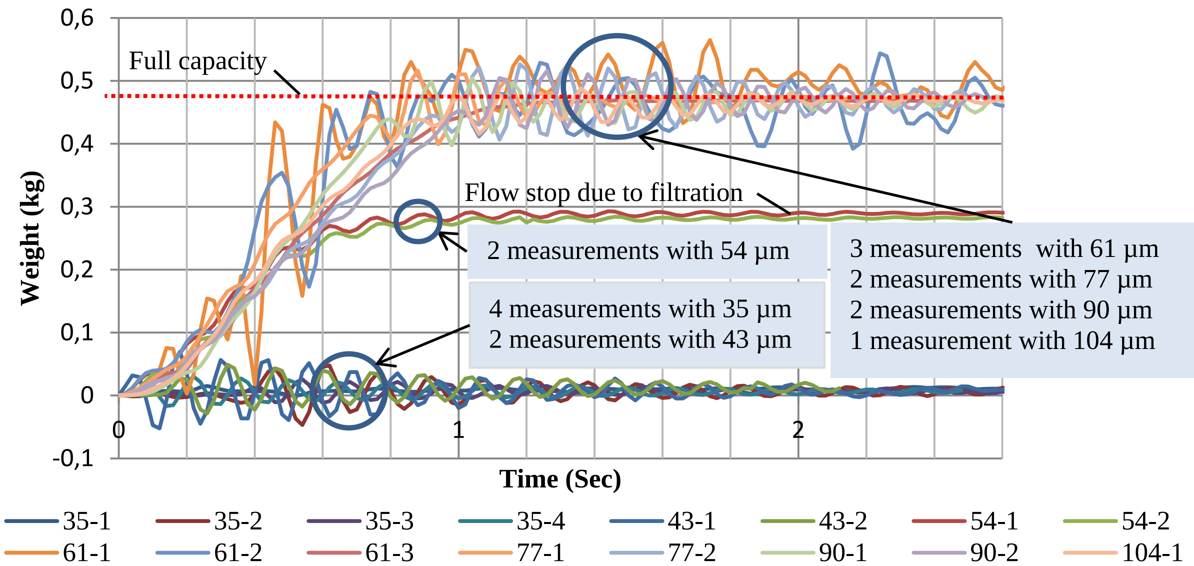


Fig. 23 Results of modified Filter pump with 35-104 µm mesh filters using the weight-time measurement

5.1.2 Uncertainties in measurements induced by the grout volume

In the results of weight-time measurement conducted by the modified Penetrability meter depicted in Fig. 24, the value of b_{crit} could be evaluated 90 µm, if the grout amount was between 1.0 to 1.5 kg. However, the value of b_{crit} could be evaluated 77 µm if the grout weight was less than 1.0 kg similar to the results of modified Filter pump using the weight-time measurement. This implies that the difference in the specified grout weight/volume is the other principal origin of the aforementioned contradictions in grout penetrability measurements that suggests the higher the designated grout volume, the greater the value of b_{crit}.

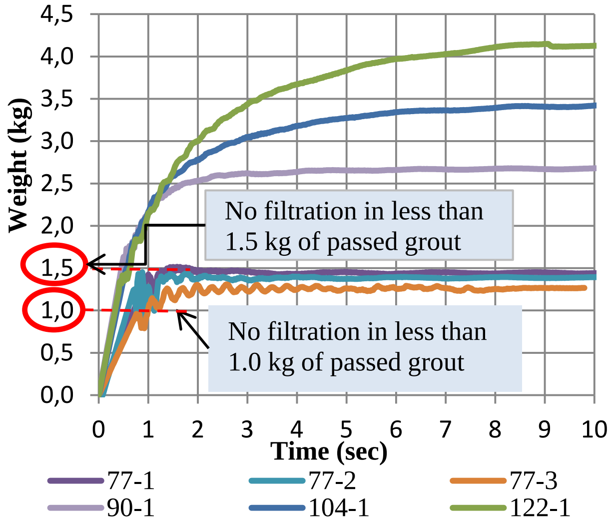


Figure 24 Results of modified penetrability meter with 77-122 µm mesh filters using the weight-time measurement

The required grout volume for a proper evaluation of grout penetrability can be determined based on what is needed in a real fracture in rock. Grøv and Woldmo (2012) suggested that obtaining a penetration length of approximately 5 m around a tunnel is a key to achieve the required sealing. Disk shape fractures with apertures of 50, 100, and 200 µm and a radius of 5 m around a grouting borehole require a grout volume of nearly 10 liter in average. With analogues to one-dimensional grout flow in Short slot, the required grout volume for grouting only one quarter of the aforementioned disk shape fracture yields a fair estimation of approximately 2.5 liter for the required grout volume in experiments with Short slot, if the grout spread in four quarters of the disk are independent. The grout tank capacity in Short slot with the volume of approximately 2.6 liter is therefore considered sufficient for a proper evaluation of grout penetrability, whereas in Filter pump and Penetrability meter, the designated grout volumes of approximately 0.3 and 1 liter are apparently insufficient. This once again contributes to underestimating the values of b_{min} and b_{crit} using Filter pump and Penetrability meter.

5.1.3 Uncertainties in measurements induced by the constriction geometry

The specified grout volume and applied pressure in Short slot with the values of 2.6 liter and 1 bar were approximately identical to those in modified Penetrability meter. The main remaining difference between the two instruments was in constriction geometry.

The constriction length in Short slot (10 mm) was approximately 100 times longer than the mesh thickness in modified Penetrability meter (100 µm). The associated resisting friction against the grout flow and consequently the pressure loss along the constriction in the mesh geometry is therefore negligible compared with the slot geometry of the same size. This suggests a higher expected value of b_{min} for similar grouts using Short slot compared with the modified Penetrability meter. The results presented in Table 3 verified that in closely identical conditions the evaluated value of b_{min} in Short slot (70 µm) was greater than that in modified Penetrability meter (35 and 43 µm). The similar obtained values of b_{crit} (200 µm) from Short slot and the modified Penetrability meter implied that evaluating the b_{crit} was less sensitive to the diversity in geometries (Table 3).

5.1.4 Uncertainties in measurements induced by the evaluation methods

By employing the weight-time measurement in ordinary Filter pump for evaluating the b_{crit}, the variation in mass flow rate visualized the filtration in experiments with 77 µm mesh filter (Fig. 22). Using the total volume of passed grout, the filtration in experiments with the same filter was however not detectable. The reason was that the corresponding mesh size was wide enough for filling the whole capacity of the instrument in spite of some minor filtration. In similar fashion, application of the weight-time method in modified Filter pump once again disclosed the filtration in experiments with 61 µm mesh filter that could not be properly detected previously (Fig. 25). This clearly shows the significance of the accuracy of the evaluation methods that should be cautiously considered in selection of a proper instrument and method for more realistic evaluation of grout penetrability.

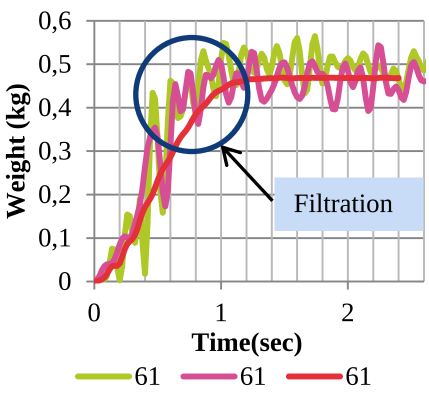


Fig. 25 Results of modified filter pump with 61 µm mesh filter using the weight-time measurement

5.1.5 Uncertainties in measurements induced by a combination of origins

The evaluated b_{min} and b_{crit} obtained from Filter pump are significantly lower than the values obtained from Short slot in 1 bar pressure (Table 3). This is considered to be due to the differences in the grout volumes, constriction geometries, and evaluation methods. Use of Filter pump is therefore not practical for measuring the b_{min} and b_{crit}. However, it can still be applicable for quality control of cement and/or the mixing process as described in SS-EN 14497:2004.

5.2 Discussion on the influence of instantaneous variable pressure (IVP) on improving the grout spread

Results of the experiments conducted in the second part of this study under application of instantaneous variable pressures IVPs with 4 s/8 s and 2 s/2 s peak/rest periods and static pressure using Short slots with 43 and 30 µm sizes were studied by means of different evaluation methods. The aim was not only to investigate the final influence of this type of applied pressure on improving the grout spread, but also to visualize and quantify its effect on filtration and erosion processes along the experiments to interpret the mechanism of action. More details and explanation of the results can be found in paper 2.

5.2.1 The influence of IVP on improving the grout spread in 43 µm slot

The average weights of the passed grout obtained using IVP with both peak/rest periods were more than twice the values obtained from the static pressure tests (Table 4). This was a clear implication for efficiency of IVP on improving the grout spread even through such a small aperture, however, it was impossible to differentiate between the results of the two options of the peak/rest periods.

Table 4 Results of the total weight of passed grout under the dynamic and static pressure conditions, using 43 μm slot

Test group	Test No.	Peak/Rest period [sec]	Weight of passed grout [kg]	Final tank condition	Average weight of passed grout [kg]	Improvement compared with the static pressure condition
	1	-	1.339	Not empty		
C1 (static)	2	-	2.055	Not empty	1.932	-
	3	-	2.402	Not empty		
	1	4 s/8 s	4.189	Empty		
V1 (dynamic)	2	4 s/8 s	4.302	Empty	4.271	2.2
	3	4 s/8 s	4.321	Empty		
	1	2 s/2 s	4.093	Empty		
V3 (dynamic)	2	2 s/2 s	4.177	Empty	4.072	2.1
	3	2 s/2 s	3.947	Empty		

The min-pressure envelopes presented in Fig. 26 were utilized for this purpose by disclosing the filtration and erosion processes in each cycle. In experiments with 4 s/8 s peak/rest period, randomness in filtration and erosion was apparent, however, in experiments with 2 s/2 s, the results illustrated a gradual upward trend, indicating minor accumulation of filtration in consecutive cycles.

Fig. 27 further uncovered an approximately 140% higher average *CMFR* in experiments with 2 s/2 s peak/rest period (1.76 l/min) compared with the ones in 4 s/8 s (0.72 l/min). A higher average *CMFR* in the former case required a wider opening size and/or less accumulated filter cakes. This implies that the filtration process in the tests with 2 s/2 s peak/rest period was better controlled compared with the results of 4 s/8 s. In this evaluation, the entire cycle period was considered as the time for the pressure to act, but with different mean flow rates during the peak and rest periods. Note that discharging the grout tank was also about 140% faster for the former case.

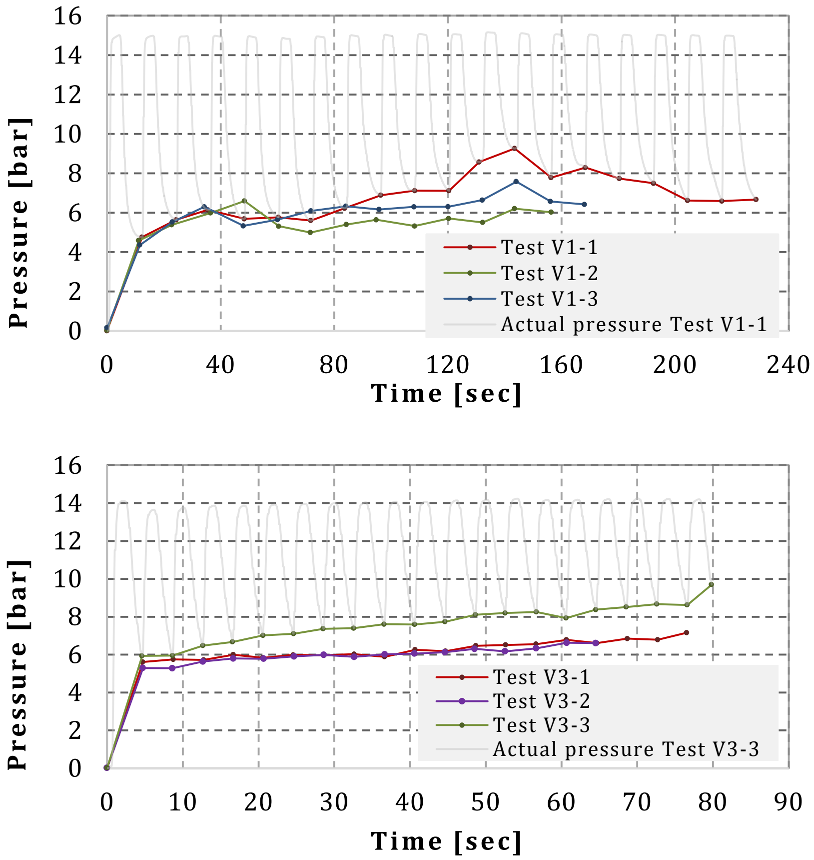


Fig. 26 Min-pressure envelopes for the tests with the peak/rest periods of 4 s/8 s and 2 s/2 s using 43 µm slot

Considering just the duration of the peak period as the time for the pressure to act, the mean values of the sum of peak periods in experiments with 4 s/8 s and 2 s/2 s peak/rest periods can be calculated as 66.7 and 38 sec, respectively (Fig. 27). This indicates 76% longer period and rationally higher expected volume of the passed grout in the case of 4 s/8 s peak/rest period. However, having equal volumes of the passed grout (equal to the grout tank capacity) yields an average flow rate of 76% higher for the tests with 2 s/2 s peak/rest period. In the same figure, the highest value of *CMFR* in the first cycle of each test is an indication of severe filtration with a huge impact on further development of the flow rates along the entire experiments. Meanwhile, the higher *CMFRs* in the first cycles of the experiments with 2 s/2 s peak/rest period compared with the other case is an indication of lower degree of filtration over the first cycles in the former case. This implies that once again application of IVP with 2 s/2 s peak/rest period has a better influence on controlling the filtration and improving the grout spread.

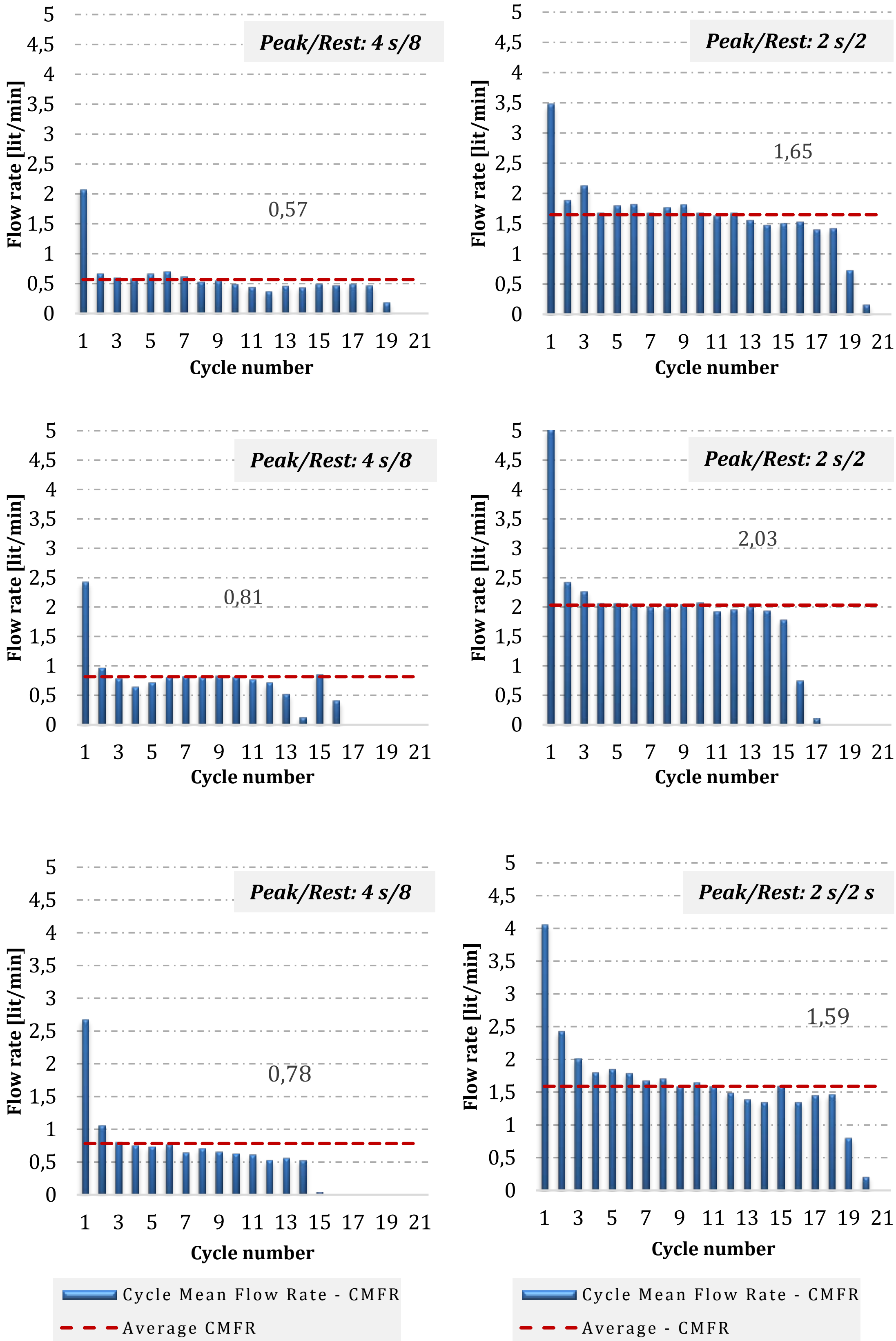


Fig. 27 Cycle mean flow rates (*CMFRs*) and average *CMFRs* for the experiments using 43 μm slot with the peak/rest periods of 4 s/8 s and 2 s/2 s

5.2.2 The influence of IVP on improving the grout spread in 30 μm slot

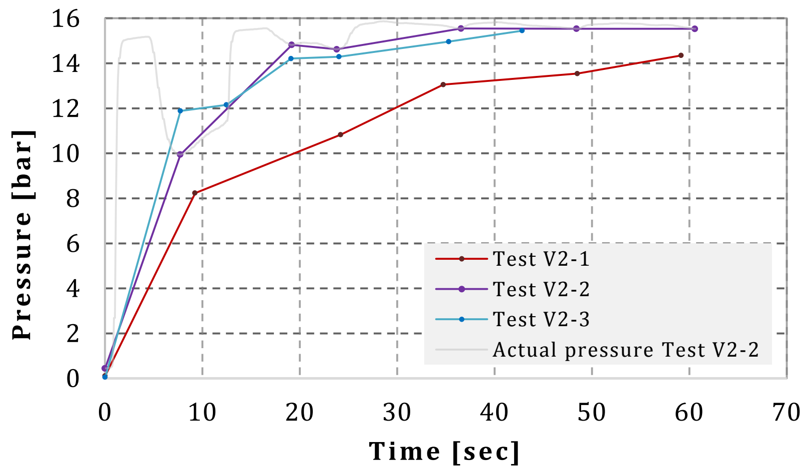
The average weights of the passed grout obtained using IVP with 4 s/8 s and 2 s/2 s peak/rest periods illustrated approximately 2.6 and 11 times improvement compared with the results of the static pressure tests, respectively (Table 5). This was once again a clear implication for efficiency of IVP on improving the grout spread with a better control on filtration using 2 s/2 s peak/rest period through such a small aperture.

Table 5 Results of the total weight of passed grout under the dynamic and static pressure conditions, using 30 μm slot

Test group	Test No.	Peak/Rest period [sec]	Weight of passed grout [kg]	Final tank condition	Average weight of passed grout [kg]	Improvement compared with the static pressure condition
C2(static)	1	-	0.441	Not empty	0.299	-
	2	-	0.181	Not empty		
	3	-	0.275	Not empty		
V2(dynamic)	1	4 s/8 s	0.852	Not empty	0.786	2.6
	2	4 s/8 s	0.824	Not empty		
	3	4 s/8 s	0.684	Not empty		
V4(dynamic)	1	2 s/2 s	2.679	Not empty	3.190	10.7
	2	2 s/2 s	3.702	Not empty		

The min-pressure envelopes presented in Fig. 28 illustrated again that use of 2 s/2 s peak/rest period was highly effective to keep even a 30 μm constriction open for a longer period. Meanwhile, the results disclosed the cycles with dominant erosion as the main cause for re-opening the partially plugged constrictions.

In similar fashion to the results of 43 μm slot, the considerable variation in *CMFR* from the first to the second cycles in each test is again an indication of significant filtration within the first cycles (Fig. 29). Furthermore, the smaller *CMFRs* in the first cycles of the tests with 4 s/8 s peak/rest period compared with the results of 2 s/2 s indicate lower filtrations in the first cycles of the tests with 2 s/2 s peak/rest period. This implies that once again application of IVP with 2 s/2 s peak/rest period has a better influence on controlling the filtration and improving the grout spread.



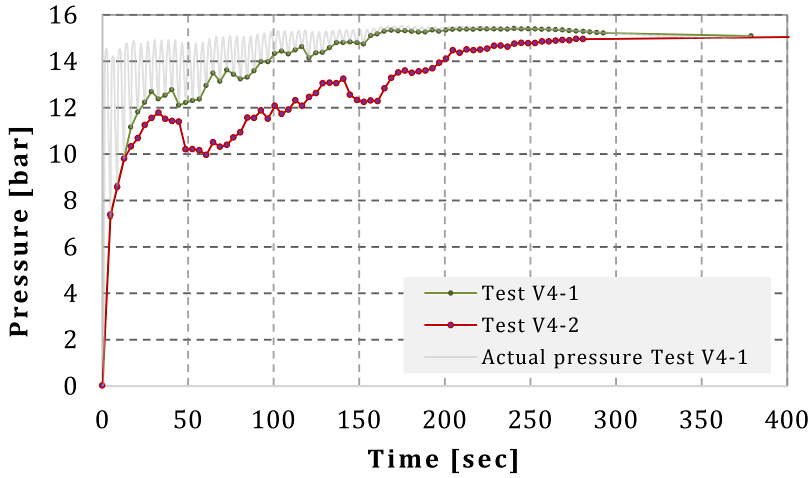


Fig. 28 Min-pressure envelopes for the tests with the peak/rest periods of 4 s/8 s and 2 s/2 s using 30 µm slot

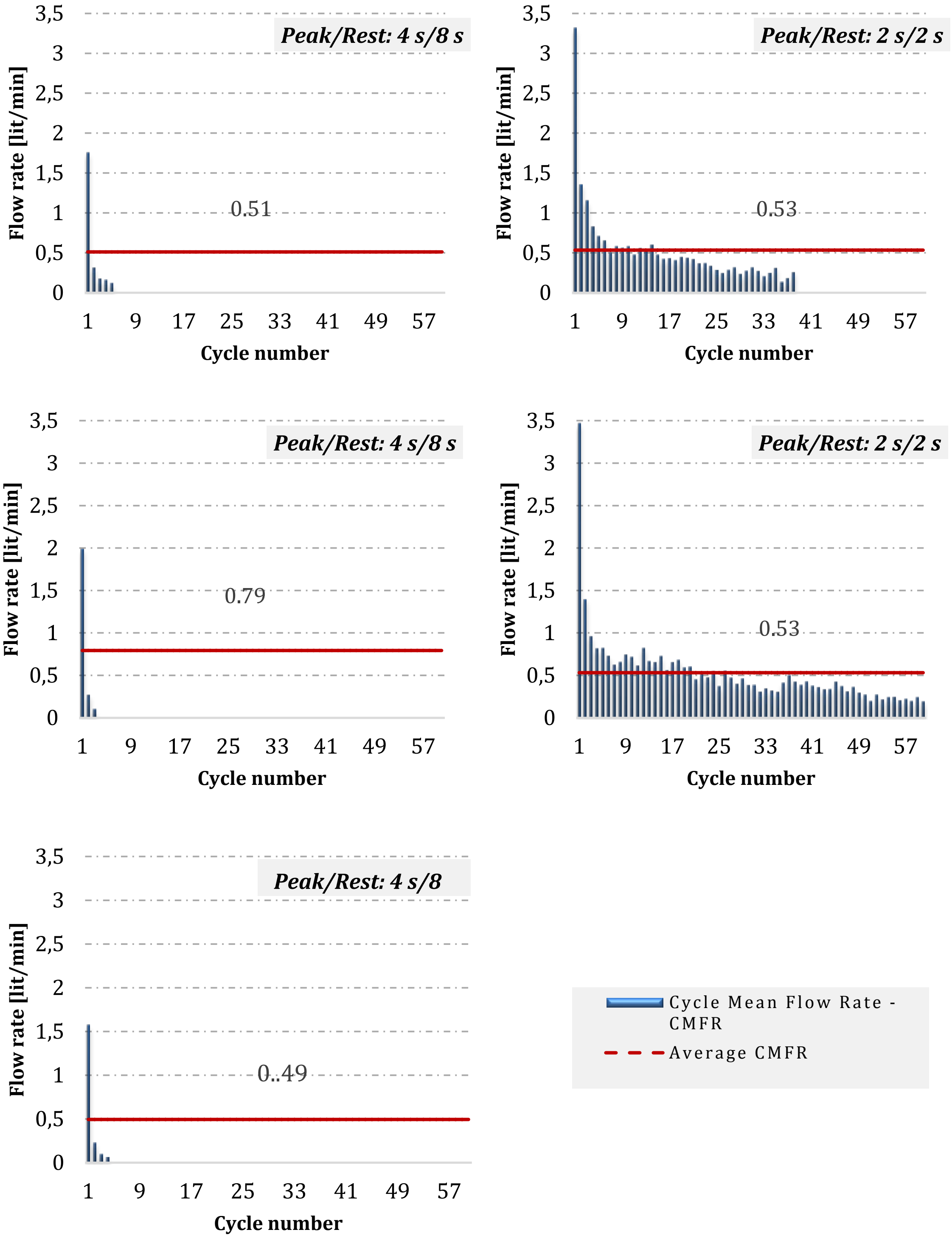


Fig. 29 Cycle mean flow rates (*CMFRs*) and average *CMFRs* for the experiments using 30 µm slot with the peak/rest periods of 4 s/8 s and 2 s/2 s

5.2.3 Possible interpretation of the mechanism of action

To understand the mechanism of action of the proposed method, the first step was to determine the flow types in several pressure levels using the flow equations in laminar and turbulent conditions. The calculation started using the steady-flow energy equation and *Darcy-Weisbach* formula to find the mean flow velocity at the exit point of the slot. It was then continued by determining the mean flow velocity before the constriction within the slot using the incompressible continuity equation. The flow types in different pressures were thereafter evaluated by calculating the corresponding Reynolds-number (White, 1998).

To interpret the corresponding mechanism of action, a conceptual model for the flow patterns within the slot under the static and dynamic pressure conditions is presented in Fig. 30. Under the static pressure application, the high pressure of 15 bar provides a high flow velocity and subsequently a turbulent flow within the slot. The flow velocity is however reduced near the slot/fracture walls due to the resisting friction. This will increase the probability of clogging of the cement particles and clusters before the constriction resulting in a necking phenomenon, i.e. reducing the opening size of the slot in time at the constriction. The result will be the flow stop after sufficient accumulation of the filter cakes.

Under the dynamic pressure application, similar process follows until the pressure and consequently the flow velocity decrease in either of the following cases. In minor pressure variation, limited fluctuation in size and position of the vortices occurs due to minor cyclic changes in the flow velocity. In major pressure variation, however, the flow pattern varies significantly due to the dominant changes in velocity, converting the turbulent flow to laminar and backwards, repeatedly. In both cases, the probability of erosion of the produced filter cakes is increased. However, it would be much more significant in the latter. The result would be a better control on filtration that effectively improves the grout spread (Fig. 30).

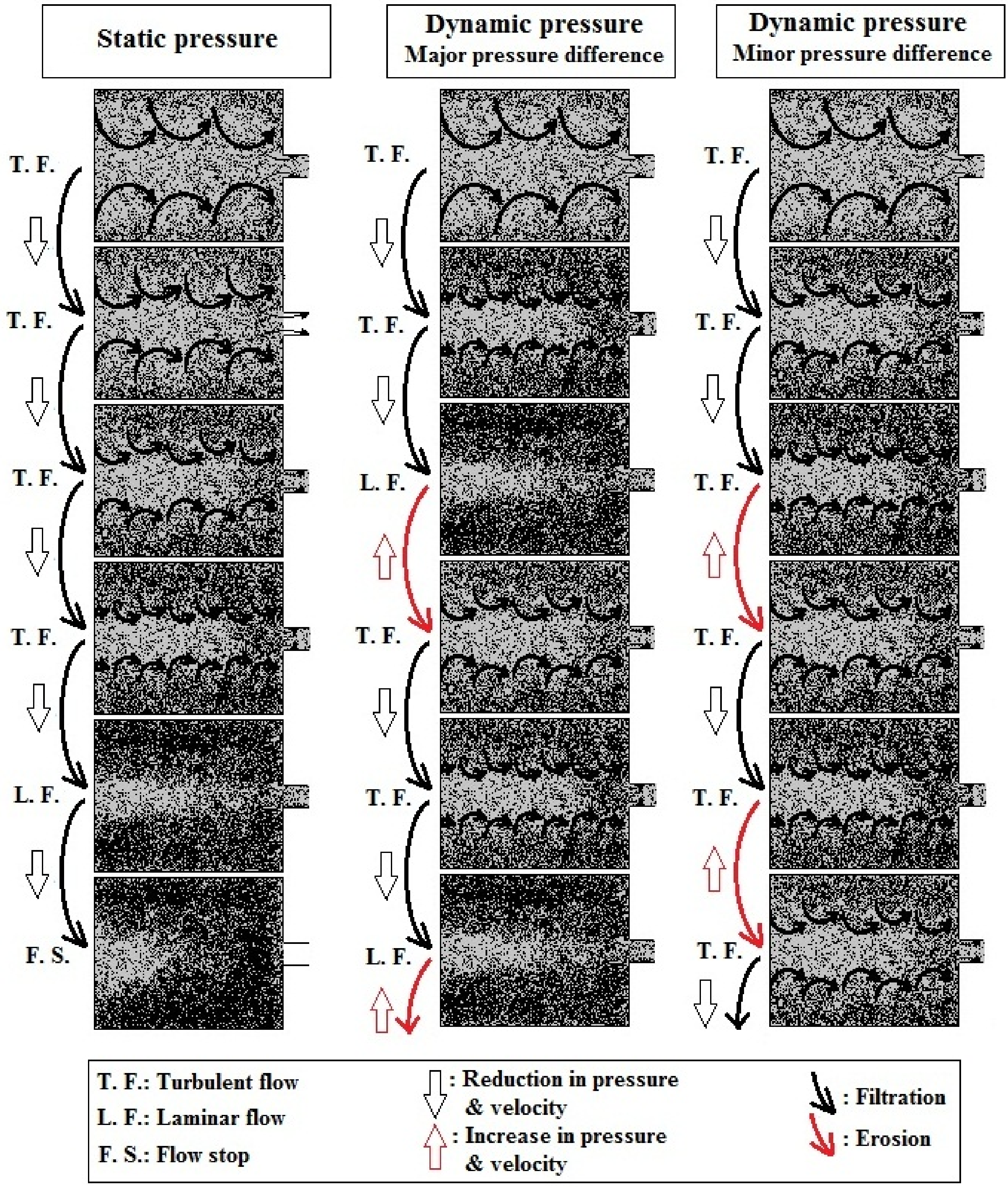


Fig. 30 Conceptual model of the mechanism of action

The obtained results presented in Figs. 26 and 28 to some extent verify the aforementioned mechanism of action. The major pressure variation illustrated in the results of the experiments with 43 μm slot were associated with negligible filtration and remained filter cakes after opening the slot leading to an empty grout tank at the end of the experiments. On the other hand, the minor pressure variation illustrated in the results of the experiments with 30 μm slot were accompanied with severe filtration and remained filter cakes leading to flow stop before emptying the grout tank, even though the slot was kept open for a longer period compared to the static pressure application. This suggests that the major pressure variation corresponding to the significant change in flow pattern is associated with a better control on filtration.

To sum up, under application of IVP, the flow velocity varies in relation to the pressure variation in each cycle. The subsequent change in velocity re-configures the flow pattern and re-organizes the streamlines and the vortices. The variation in flow pattern, if it is significant, erodes the produced filter cakes at the constriction and reopens the fracture. Sufficient pressure variation is therefore required to obtain better control on filtration and to improve the grout spread effectively.

6. Conclusions and future steps

6.1 Conclusions part A

The most significant outcomes of the first part of the project can be summarized as follows:

- Deviation and diversity in applied pressure is one of the governing origins of contradition in the results of penetrability measurements. Determining b_{crit} at both low and high pressures is essential for a fair evaluation of grout penetrability beneficial for the field application.

- Difference in specified grout volume is the second governing origin of contradiction in the results of penetrability measurements. The results of Penetrability meter suggested that the higher the grout volume, the greater the value of b_{crit}. A fair estimation of the required grout volume for a proper evaluation of grout penetrability is approximately considered 2.5 liter. Filter pump and Penetrability meter with the designated grout volume of 0.3 and 1 liter are therefore not recommended any longer for evaluation of grout penetrability.

- Diversity in constriction geometry is the third governing origin of contradition in the results of the penetrability measurements. The value of b_{min} obtained from Short slot was greater than the obtained value from modified Penetrability meter due to the remained differences in the constriction geometries. However, similar evaluation of b_{crit} from both instruments inferred that the value of b_{crit} is less influenced by the diversity in constriction geometry.

- Accuracy in evaluation method is the last governing origin of contradiction in the results of the penetrability measurements. Use of the weight-time measurement in comparison with the total weight of passed grout was found more accurate and practical and suggested to consider in selection of a proper instrument for more realistic evaluation of grout penetrability.

- Use of Short slot for a proper evaluation of grout penetrability was the final recommendation of this study between the three instruments due to the more realistic geometry, more accurate evaluation method, sufficient grout volume capacity, and ability to work under 1 and 15 bar pressures.

6.2 Conclusions part B

The most significant outcomes of the second part of the project can be summarized as follows:

- Application of low frequency IVP showed a considerable control on filtration as a means to improve the grout spread within parallel plates with constrictions even with vary narrow apertures (<70 µm).
- The results of the total weight of passed grout through 43 µm slot illustrated the efficiency of IVP on improving the grout spread, but there was no clear difference between the two options of the peak/rest periods. However, the results of *CMFR* uncovered better control of IVP with 2 s/2 s peak/rest period on filtration evolution, in addition to a shorter time for emptying the grout tank.
- The results of the total weight of passed grout through 30 µm slot illustrated a better control on filtration in the case of 2 s/2 s peak/rest period compared with 4 s/8 s. The min-pressure envelopes further disclosed the cycles with dominant erosion, as the main cause of improving the grout spread.
- The results of *CMFR* in both 43 and 30 µm slots illustrated a leading filtration over the first cycles, dominating the flow rates. The results also disclosed less filtration over the first cycles in the case of 2 s/2 s peak/rest period compared with 4 s/8 s, showing a better control on filtration in the former case. This suggests that a key

factor to improve the grout spread in dynamic grouting is to better control the filtration over the first cycle.

- The results of the pressure records in time further illustrated a major pressure variation in each cycle associated with negligible filtration in 43 µm slot, versus a minor pressure change associated with considerable filtration in 30 µm slot. This once again suggests that under application of IVP, the more the pressure variation, the better the control on filtration.

6.3 Future steps

- To answer the first key question “How to measure the grout penetrability more realistic?”, a varying aperture long slot (VALS) with 4 m length and apertures between 250-20 µm has been designed and built based on our achievements from the first part of the study. Introducing VALS as a new experimental approach to measure the grout penetrability more realistic is therefore the first step in our future work.
- The results of our theoretical study on flow types in different pressure conditions under application of IVP are going to be presented in the next step with the aim to verify the corresponding mechanism of improvement.
- Verification of “Real Time Grouting Control Method (RTGCM)” in lab is going to be the final stage of the study, in which the grout penetration length estimated based on RTGC theory is going to be compared with the obtained results in experiments with VALS.

6.4 Suggestions for future works

To transform the existing grouting technology to a robust grouting technic with more efficiency in rock grouting, a new Ph.D. project is proposed on application of instantaneous variable pressure (IVP) as a supplement to the current investigation. This study can also provide a basis for the new generation of the grouting injections pumps specified for rock grouting. The project can be outlined in three steps:

- To investigate the length of influence (LOI) of instantaneous variable pressure (IVP) in experiments with the most commonly used grout recipes in grouting industry using Varying Aperture Long Slot (VALS).
- To determine the pressure setup appropriate to specific hydraulic conductivities in field for the selected materials using Varying Aperture Long Slot (VALS).
- To verify the obtained results of lab experiments in field using an enhanced programmable pressure control system appended to the grouting rig.

Other related ideas, which can be considered as suggestions for future works with Short slot and/or VALS, are summarized as follows:

- Evaluating the influence of Silica fume/Blast furnace slag/Fly ash on improving grout penetrability of micro-fine cement using Short slot. In collaboration with experts at Skanska, Cementa, and Sika AB.

- Application of computational fluid dynamic (CFD) to investigate the influence of instantaneous variable pressure (IVP) on improving grout penetrability. In collaboration with experts at division of Fluid and Climate Technology - KTH.

- Investigating the influence of water chemistry, i.e. the sulfate content in water, on improving grout penetrability of micro-fine cement. In collaboration with experts at Lund university

- Application of ultrasonic waves for monitoring the grout density and penetration length in time in Varying Aperture Long Slot (VALS). In collaboration with experts at Uppsala university

- Evaluating the influence of Air-entraining agents on improving grout penetrability using Short slot.

7. References

Andreou P, Frikha W, Frank R, Canou J, Papadopoulos V, Dupla JC (2008) Experimental study on sand and gravel columns in clay. In: Proceedings of the Institution of Civil Engineers - Ground Improvement 161(4):189-198. doi: 10.1680/grim.2008.161.4.189

Atkinson RH, Schuller MP (1993) Evaluation of injectable cementitious grouts for repair and retrofit of masonry. ASTM STP 1180, Philadelphia:355-355.

Axelsson M, Gustafson G (2007) Grouting with high water/solid ratios - Literature and laboratory study, Gothenburg: Chalmers University of Technology

Axelsson M, Gustafson G, Fransson Å (2009) Stop mechanism for cementitious grouts at different water-to-cement ratios. Tunn Undergr Sp Tech 24(4):390-397. doi: 10.1016/j.tust.2008.11.001

Axelsson M, Gustafson G (2010) The PenetraCone, a new robust field measurement device for determining the penetrability of cementitious grouts. Tunn Undergr Sp Tech 25(1):1-8. doi:10.1016/j.tust.2009.06.004

Banfill PFG (2006) Rheology of fresh cement and concrete. In: Rheology Reviews 2006. British Society of Rheology, pp 61-130

Bergman S (1970) Tunneltätning. Injekteringsmedelinträngning i sand och smala spalter. Stockholm: Byggforskningen Rapport R45, Rotobeckman AB.

Borgesson L, Jansson L (1990) Grouting of fractures using oscillating pressure. In: Proceedinge of the International Conference on Mechanics of Jointed and Faulted Rock, Vienna, 18-20 April 1990. A. A. Balkeme, Rotterdam: 875-882

Draganovic A (2009) Bleeding and filtration of cement-based grout. Dissertation, Royal Institute of Technology

Draganovic A, Stille H (2011) Filtration and penetrability of cement-based grout: Study performed with a short slot. Tunn Undergr Sp Tech 26(4):548-559. doi: 10.1016/j.tust.2011.02.007

Draganovic A, Stille H (2012) Bleeding and Bleeding Measurement of Cement-Based Grout. In: Proceedings of the Fourth International Conference on Grouting and Deep Mixing, New Orleans, Louisiana, United States, 15-18 February 2012. ASCE:1681-1690. doi: 10.1061/9780784412350.0143

Draganovic A, Stille H (2014) Filtration of cement-based grouts measured using long slot. Tunn Undergr Sp Tech 43:101-112. doi: 10.1016/j.tust.2014.04.010

Eklund D (2005) Penetrability due to filtration tendency of cement based grouts. Dissertation, Royal Institute of Technology

Eklund D, Stille H (2008) Penetrability due to filtration tendency of cement-based grouts. Tunn Undergr Sp Tech 23(4):389-398. doi: 10.1016/j.tust.2007.06.011

Eriksson M, Dalmalm T, Brantberger M, Stille H (1999) Separations-och filtrerings stabilitet hos cementbaserade injekteringsmedel. Raport 3065 (in Swedish), Royal Institute of Technology

Eriksson M, Stille H, Andersson J (2000) Numerical Calculations for Prediction of Grout Spread with Account for Filtration and Varying Aperture. Tunn Undergr Sp Tech 15(4):353-364. doi: 10.1016/s0886-7798(01)00004-9

Eriksson M, Stille H (2003) A method for measuring and evaluating the penetrability of grouts. In: Proceedings of the 3rd International Conference on Grouting and Ground Treatment, New Orleans, Louisiana, United States, 10-12 February 2003. ASCE:1326-1337. doi: 10.1061/40663(2003)79

Eriksson M, Friedrich M, Vorschulze C (2004) Variation in the rheology and penetrability of cement-based grouts – an experimental study. Cement Concrete Res 34(7):1111–1119. doi: 10.1016/j.cemconres.2003.11.023

Fransson Å (2008) Grouting design based on characterization of the fractured rock, presentation and demonstration of a methodology. In: Technical Report R-08-127. Swedish Nuclear Fuel and Waste Management AB (SKB), Stockholm

Gandais M, Delmas F (1987) High penetration C3S bentonite-cement grouts for finely fissured and porous rock. In: Proceedings of the International Conference on Foundations and Tunnels, London:29-33.

Grøv E, Woldmo O (2012) Modern pre-grouting technology in Norway. In: Proceedings of the 4th International Conference on Grouting and Deep Mixing, New Orleans, Louisiana, United States, 15-18 February 2012. ASCE:805-815. doi: 10.1061/9780784412350.0064

Gustafson G, Stille H (1996) Prediction of Groutability from Grout Properties and Hydrological Data. Tunn Undergr Sp Tech 11(3):325-332. doi:10.1016/0886-7798(96)00027-2

Gustafson G, Stille H (2005) Stop criteria for cement grouting. Felsbau: Zeitschrift für Geomechanik und Ingenieurgeologie im Bauwesen und Bergbau 23(3):62-68

Gustafson G, Claesson J, Fransson Å (2013) Steering parameters for rock grouting. Journal of Applied Mathematics 2013:1-9. doi:10.1155/2013/269594

Hansson P (1995) Filtration Stability of Cement Grouts for Injection of Concrete Structures. IABSE reports = Rapports AIPC = IVBH Berichte 73(1-2):1199-1204. doi: 10.5169/seals-55333

Hjertström S (2001) Microcement-pentration versus particle size and time control. In: Proceedings of the 4th Nordic Rock Grouting Symposium, Stockholm, Sweden, 8 November 2001. SveBeFo Rapport 55:61–71

Houlsby AC (1990) Construction and design of cement grouting: a guide to grouting in rock foundations. John Wiley & Sons.

Håkansson U (1993) Rheology of Fresh Cement-Based Grouts. Dissertation, Royal Institute of Technology

Junwei Z, Zhirong M, Xiaojuan Q (2013) Composite Support System Optimum of Water Transfer Tunnel by TBM[J]. Disaster Advances 6(S2):324-331.

Karol RH (2003) Chemical grouting and soil stabilization, revised and expanded. CRC Press. doi:10.1201/9780203911815

Lombardi G (1985) Some theoretical considerations on cement rock grouting. Lombardi Engineering Ltd.

Lombardi G (2003) Grouting of rock masses. In: Proceedings of the 3th International Conference on Grouting and Ground Treatment, New Orleans, Louisiana, United States, 10-12 February 2003. ASCE:164-197. doi:10.1061/40663(2003)6

Miltiadou-Fezans A, Tassios TP (2012) Fluidity of hydraulic grouts for masonry strengthening. Materials and structures 45(12): 1817-1828. doi:10.1617/s11527-012-9872-8

Mohammed MH, Pusch R, Knutsson S, Hellström G (2014) Rheological Properties of Cement-Based Grouts Determined by Different Techniques. Engineering 06(05): 217-229. doi: 10.4236/eng.2014.65026

Mohammed MH, Pusch R, Knutsson S (2015) Study of cement-grout penetration into fractures under static and oscillatory conditions. Tunn Undergr Sp Tech 45:10-19. doi: 10.1016/j.tust.2014.08.003

Nobuto J, Nishigaki M, Mikake S, Kobayashi S, Sato T (2008) Prevention of clogging phenomenon with high-grouting pressure. Doboku Gakkai Ronbunshuu C 64(4): 813-832 (in Japanese with English abstract). doi:10.2208/jscejc.64.813

Paillere AM, Buil M, Miltiadou A, Guinez R, Serrano JJ (1989) Use of silica fume and superplasticizers in cement grouts for injection of fine cracks. ACI Special Publication 114:1131-1158

Pusch R, Erlström M, Börgesson L (1985) Sealing of rock fractures A survey of potentially useful methods and substances. In: Technical Report TR 85-17. Swedish Nuclear Fuel and Waste Management AB (SKB), Stockholm

Rafi J (2013) Design approaches for grouting of rock fractures; theory and practice. In: BeFo report 124. Rock Engineering Research Foundation (BeFo), Stockholm

Sandberg P (1997) NES-metod för mätning av injekteringsbruk inträngningsförmåga. Svensk Bergs- & Brukstidning 5–6/97.

Schwarz LG (1997) Roles of rheology and chemical filtration on inject ability of micro fine cement grouts. Dissertation, Northwestern University

Stille H, Gustafson G, Hassler L (2012) Application of New Theories and Technology for Grouting of Dams and Foundations on Rock. Geotechnical and Geological Engineering 30(3):603-624. doi: 10.1007/s10706-012-9512-7

Stille H (2015) Rock grouting-theories and applications. BeFo – Rock engineering research foundation, Stockholm

Wakita S, Aoki K, Mito Y, Kurokawa Y, Yamamoto T, Date K (2003) Development of Dynamic Grouting Technique for the Improvement of Low-Permeable Rock Masses. In: Proceedings of the 1th Kyoto International Symposium on Underground Environment. 341–348. doi: 10.1201/NOE9058095565.ch44

Warner J (2004) Practical handbook of grouting: soil, rock and structures. John Wiley & Sons, New York

Weideborg M, Källqvist T, Ødegård KE, Sverdrup LE, Vik EA (2001) Environmental risk assessment of acrylamide and methylolacrylamide from a grouting agent used in the tunnel construction of Romeriksporten, Norway. Water research 35(11): 2645-2652. doi:10.1016/S0043-1354(00)00550-9

White FM (1998) Fluid Mechanics (4 ed.). Mc Graw-Hill, Narragansett, Rhode Island

Widmann R (1996) International society for rock mechanics commision on rock grouting. Int. J. Rock Mech. Min. Sci. & Geomech. 33(8):803-847.doi: 10.1016/S0148-9062(96)00015-0

Yang ZQ, Hou KP, Guo TT (2011) Study on the Effects of Different Water-Cement Ratios on the Flow Pattern Properties of Cement Grouts. Applied Mechanics and Materials 71-78:1264-1267. doi: 10.4028/www.scientific.net/AMM.71-78.1264

Zebovitz S, Krizek R, Atmatzidis D (1989) Injection of Fine Sands with Very Fine Cement Grout. Journal of Geotechnical Engineering 115(12):1717-1733. doi: 10.1061/(ASCE)0733-9410(1989)115:12(1717)

Zhirong M, Shiwei M (2004) The new progress about monitoring technology and dynamic optimizing design of tunnel [J]. China Society and Technology Association.

8. Appendix