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State of the Art Report on Cement Based Grout Properties and Dynamic Grouting

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Master of Science thesis

Department of Civil and Architectural Engineering

Division of Soil and Rock Mechanics

KTH Royal Institute of Technology

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PREFACE

The work presented in this Master of Science thesis has been carried out during 2020-2021 in collaboration between RISE, the Research Institutes of Sweden and Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, KTH Royal Institute of Technology.

The study has been conducted in close collaboration and under the supervision of Dr. Ali Nejad Ghafar to whom I am very grateful for his precious guidance, support, and patience and for providing valuable guidance and encouragement at various difficulties during the progress of this project. I would also like to express my appreciation to the examiner Prof. Stefan Larsson for his support and valuable advice.

2020 was an especially tough year for everyone. Due to the COVID-19, too much uncertainty and restriction have had impacts on everyone’s life. Finally, after overcoming many difficulties, the thesis was finished. For the new year, I hope the pandemic is over soon and I can start my new journey in the Ph.D. program.

Stockholm, January 2021
Bowen Meng

Sammanfattning

Dynamisk injektering i bergmassa har studerats sedan 1985. Önskad tätning av bergmassor med fina sprickor är dock fortfarande en utmaning på grund av osäkerhet och komplexitet i injekteringsprocessen. Detta har uppmärksammats av forskare i olika länder och regioner, särskilt i nordiska länder såsom Sverige. Denna studie presenterar en omfattande granskning av relevant forskning, inklusive faktorer som påverkar penetration, olika utvärderingssystem (utrustning och metoder) och en mängd olika injekteringstekniker.

Filtrering som ett huvudsakligt hinder är en tendens att partiklar av cementsuspensioner gradvis separerar och blockerar flödesbanan, främst i små sprickor. Därför diskuteras effekterna av olika faktorer på filtrering i detalj baserat på tidigare forskning och experiment. Faktorer som temperatur, kornstorlek och vattencementtal har en dominerande påverkan på filtreringsstabilitet och reologi. Detta innebär att reologi och filtrering är starkt kopplade och medför fler svårigheter vid injektering. Därför diskuteras varje faktors påverkan på reologi och filtrering för att hjälpa till att förstå mekanismen i olika injekteringstekniker.

Därefter görs en översyn av dynamiska injekteringsmetoder från 1985 i kronologisk ordning för att hitta begränsningarna för befintlig utrustning och utvärderingsmetoder. Även om det är svårt att avgöra den mest effektiva injekteringsmetoden vid mikrofrakturer, utan den kvantitativa jämförelsen av effektivitet, banar denna översyn vägen för en mer systematisk studie av ny injekteringsutrustning och teknik.

Samtidigt påvisades en motsättning angående påverkan av högfrekvent oscillerande tryck på viskositeten. I stället för en snabb tryckförlust i sprickor introduceras den termiska effekten som orsakas av högfrekvent oscillerande injektering för att förklara dess negativa inverkan på penetration i tunna sprickor (250 och 100μm). Den potentiella orsaken är den snabbare hydratiseringen av injekteringsmedel som beror på den ökade temperaturen och hastigheten på molekylär rörelse. Genom att i slutändan utvärdera fördelarna med olika kombinationer av injekteringsmetoder.

Det har visat sig att metoden med ultraljud för att dispergera injekteringsbruket tillsammans med lågfrekvent rektangulär tryckimpuls påverkar reologin och filtreringsstabiliteten i blandnings- och injekteringsfasen. Med tillämpningen av CDF-simulering kan antagandet om den termiska effekten av högfrekvent oscillerande tryck verifieras bättre i framtida forskning.

ABSTRACT

Dynamic grouting in rock mass has been studied since 1985 while desired penetration in rock masses with fine fractures is still a challenge because of uncertainty and complexity in the grouting process. This has attracted the attention of researchers in different countries and regions, especially in some Nordic countries such as Sweden. This study presents a comprehensive review of grouting relevant research, including factors that influence penetration, different evaluation systems (equipment, and methods), and a variety of grouting techniques.

Filtration as the main obstacle is a tendency that particles of suspensions would gradually separate from the flow and block the flow path. Hence, the effects of various factors on filtration are discussed in detail based on previous research and experiments. Factors such as temperature, grain size, and w/c ratio were found to have a dominant influence on filtration stability and rheology. This means rheology and filtration are highly coupled and brings more difficulties in penetration investigation with dynamic grouting. Therefore, the influence of each factor on rheology and filtration was discussed to help with the understanding of the mechanism in different grouting techniques.

Then a review of dynamic grouting methods from 1985 is made in chronological order to find the limitations on existing equipment and evaluation methods. Even it is difficult to conclude the most efficient grouting method in micro-fractures without the quantitative comparison of efficiency, this review paves the way to a more systematic exploration of novel grouting equipment and techniques.

Meanwhile, a contradiction regarding the influence of high-frequency oscillatory pressure on viscosity was revealed. Rather than rapid dissipation of pressure in the slots, the thermal effect caused by high-frequency oscillatory grouting is introduced to explain its adverse impact on penetration in fractures (250 and 100μm). The potential reason is the faster hydration of grouts resulted from the increased temperature and the speed of molecular motion.

In the end, by evaluating the benefits from different combinations of grouting methods. It was found that the ultrasound dispersing method along with low-frequency rectangular pressure impulse would contribute to the rheology and filtration stability in the mixing and grouting phase respectively. With the application of CDF simulation, this proposal and the assumption of the thermal effect of high-frequency oscillatory pressure can be better verified in future research.

Keywords: Dynamic grouting, filtration, rheology, grouting phase

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LIST OF SYMBOLS

Symbol	Description
μ_B	Viscosity in the Bingham model
μ	Viscosity in the Newtonian model
τ	Shear stress
τ_0	Yield stress
b_{stop}	Width of filter mesh that only allows half amount of grouts to pass
b_{all}	Width of filter mesh size that allows all grouts to go through
$b_{filtration}$	Width of filter mesh sizes causing filtration
D_{50}	The median grain size of grouts
b_{fic}	Fictive aperture in Bergman (1970)
b_{eqv}	Equivalent aperture in (Axelsson and Gustafson, 2007)
S	The specific area of sand in the sand column
n	The porosity of the sand column
K	Permeability of filter
s	Filter’s thickness
k	The coefficient of permeability of sand column
b_{min}	The minimum mesh size that a specific grout cannot penetrate
$b_{critical}$	The minimum mesh size that will not cause filtration
b_{filter}	The aperture in which drips are just pushed out (PenetraCone)
b_{stop}	The aperture that grouts flow just stops (PenetraCone)

1. INTRODUCTION

Among modern construction technologies, the grouting technique is an effective tool to facilitate construction, especially for underground infrastructures in water-abundant environments. In many urban areas, the utilization of underground space has been a good solution to insufficient land surface space, and the focus was put on transportation infrastructures like subways and road tunnels since the 1970s (Kaliampakos, 2008). As one of the critical processes for the construction of these infrastructures, grouting is a popular method to seal the structures against the ingress of ground water thanks to its high efficiency and reliability. On the other hand, sealing with grouts is also used to prevent the leakage of stored materials, such as chemical waste in underground waste repositories, to low the influence on the surrounding environment. Rock grouting in the big category of grouting can be understood as the injection of a mixture of grouting materials, water, and additives into rock joints to seal the fractures.

In terms of grout materials, the ideal materials normally belong to two main categories that are inorganic and organic (Atlas Copco, 1970). The typical inorganic material is cement-based grouts with lower costs and less pollution. The other, due to the great sealing efficiency and better penetrability, chemical grouts are also widely used in the industry (Warner, 2004). However, some chemicals can be toxic and dissolved into the soil and underground water, which limits their application in some countries (Weideborg et al., 2001). Moreover, the raw materials of chemical grouting are limited as a result, the grouting cost would be 10 to 50 times higher than inorganic materials.

Compared with chemical grouts, cement-based grouts have an inherent drawback which is the filtration of cement particles (Draganovic and Stille, 2011; Mohammed et al., 2015; Ghafar. A.N. 2016). Filtration is defined as a separation of particles from suspensions i.e., grouting mixtures, and results in the plugging of cement particles at constrictions (Rushton et al, 2000; Eriksson and Stille 2003). This tendency will stop grouts from penetrating further in the rock joints and small fractures. Apart from filtration tendency, according to Axelsson et al. (2009), the other two mechanisms preventing the penetration of cement-based grouts in rock fractures are clogging and frictional resistance. These two factors were firstly concluded from penetration experiments in sand columns, where clogging is defined as a formation of grains' arch before the entrance of fractures. And frictional resistance from surrounding medium surfaces was found to have an adverse influence on grout spared in the rocks and soils. Sometimes, clogging is also called filtration because it is difficult to observe these two phenomena separately. Addressing these problems mentioned above by using proper grouting methods is a prerequisite for using cement-based materials.

To mitigate the risk of filtration and achieve better penetration, Pusch et al. (1985) proposed a dynamic rock grouting technique with inspiration from sandy silts grouting by the vibration of pressurized grouts. With the beginning of that, this study presents a comprehensive review of the history of grouting techniques with a focus on dynamic approaches since 1985. Meanwhile, before the discussion of the strength and weaknesses of each approach, factors influencing grout spread, and fair comparison of evaluation equipment are summarized.

1.1. Background

Date back to 1802, engineers in France injected the liquid grout into a ground basement to repair a sluice (Aarsleff, 2017). This is a milestone of grouting, where the grouting was first used for ground stabilization by improving the strength and deformation properties of soils. Another two functions of grout, as mentioned before, are prevention of water ingress and rock strengthening. Viewed from history, grouting methods initially started from the gravity-driven filling and evolved into mechanical pressure grouting. Nowadays, with different mechanisms, grouting could be generally classified into three types including penetration grouting/permeation grouting, splitting grouting, and compaction grouting (Yuming Zhong, 2009). Also, they can be divided into rock grouting and soil grouting depending on the mediums in which the grouts are applied. In this study, more attention was paid to rock grouting where grout as a fluid material could only penetrate joints, faults, and fractures with pressure.

One issue in the construction of underground facilities is water ingress. If the spread of grouts did not reach the expectation, accidents such as water inflow might delay the construction and raise the costs of projects quickly. Sometimes in deep mines, the hydraulic pressure in the rock mass is very large, thus water inrush would develop from small defects (shown in Fig.1) and cause casualties. It was reported that more than 100 accidents causing many casualties happened in China because of water inrush (Yong Zhao et al. 2013). However, more effective grouting in fractures around underground facilities could considerably lower the risk.

On the other hand, successive water ingress could lower the groundwater level and consequently cause settlement of ground surface and structures (Ghafar. A.N. 2016). Therefore, in some countries like Singapore, it is outlawed by strict regulations and not accepted because of the huge impacts from the uneven settlement in urban areas containing a high density of structures.

Moreover, in cold regions tunnels without significant spared of grout and exposed to seepage and low-temperature fields tend to suffer hazards, for example hanging ice on the top of the tunnel and frozen water from lateral arch as shown in Fig.2 (Shujuan Zhang et al, 2004). The hanging ice would threaten the vehicles or people passing through the tunnel. Furthermore, a volumetric increase of ice inside the joints could further decrease the strength of the rock which is recognized as frost deterioration.

Apart from the ingress of water in tunnels, in contrast, the leakage of reserved materials in underground waste repositories to the surrounding environment is another issue that needs to be addressed. Krauskopf (1988) showed concerns about the disposal method of putting the waste on or under the ground surface. If the sealing system cannot work properly, the radioactive or toxic waste can easily dissolve into water and be hazardous to the surrounding environment. Using high-performance concrete and sealing the repositories with thick cover would be an effective approach to address this issue.

Take the construction of tunnels as an example, various approaches have been tried in practice in order to reduce water-related hazards. For instance, one of the methods called pre-grouting is widely used. After drilling in the outer perimeter of the tunnel-face, grouts are injected into fractures in order to create a water-tight zone before the next stage of excavation (Mentesidis, 2015). Sometimes, post-grouting is also needed when there is a local high risk of water leakage. In these methods, a variety of parameters contribute to a successful grouting operation, including planning and organization, quality, performance, equipment, grouted cut-off wall, and material (Eklund, 2005). While grouting spread dominates the process and it is the penetrability of grout flow that has a major influence on grout spread.

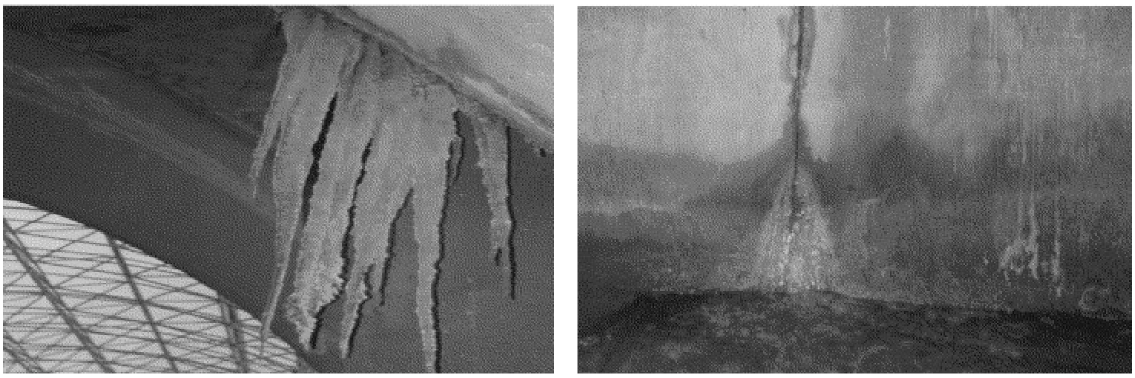
Figure 1. Site conditions of water inrush (Binbin Zhu et al., 2017).

Therefore, in order to gain a high efficiency of grouting with cement-based material, better penetration, more efficient injection, less filtration, and flocculation of cement particles should be achieved. Among those, the most three crucial parameters that can influence penetration in fractures are filtration, rheology, and grouting pressure. Many researchers investigated the mechanisms of filtration and relevant parameters during the last two decades by using different instruments and methods (Ghafar. A.N. 2016).

Meanwhile, grouting pressure is proved to be the other parameter mainly affecting penetrability (Eriksson et al. 1999; Hjertström 2001; Draganovic and Stille 2011; Draganovic and Stille, 2014). Also, grouting pressure was found to be able to influence filtration and rheology in turn.

Whereas some contradictions can be found in some research since their conclusions are drawn based on various assumptions, equipment, experiment methods, and evaluation approaches. Some of the constrictions were discussed later in this study.

In general, static and dynamic grouting are two main topics of previous research regarding grouting pressure. It has been proved that static constant pressure can hardly inject cement-based grouting in fine fractures, though it is effective for grouting in wide joints. The application of increased pressure under static conditions was studied by Nobuto (2008). The results showed a satisfactory improvement of grout spared in the experiments. However, a continuous increase of pressure might end up enlarging the joints and small fractures in the rock mass and even produce new cracks. Given that, more explorations were made on dynamic grouting methods. Using various dynamic pressure and oscillation instead of a simple increase of pressure was considered as a promising direction to obtain deeper penetrability and a more reliable seal of fractures. To validate that, filtration stability is still crucial.



(a) (b)

Figure 2. Disasters inside a tunnel in the cold region: (a) hanging ice from tunnel top; and (b) frozen water from tunnel lateral arch (Shujuan Zhang et al., 2004).

1.2. Problem statement

The root of the filtration issue is in connection with filter cakes (Hansson,1994). In general, the grouts contain solid grains that will gradually bridge in the flow path either at the entrance of a crack aperture or constriction in the fractures (shown in Fig.3) and resulted in the formation of filter cakes. How to slow down the formation of filter cake or erode it would be crucial to improve grout penetrability.

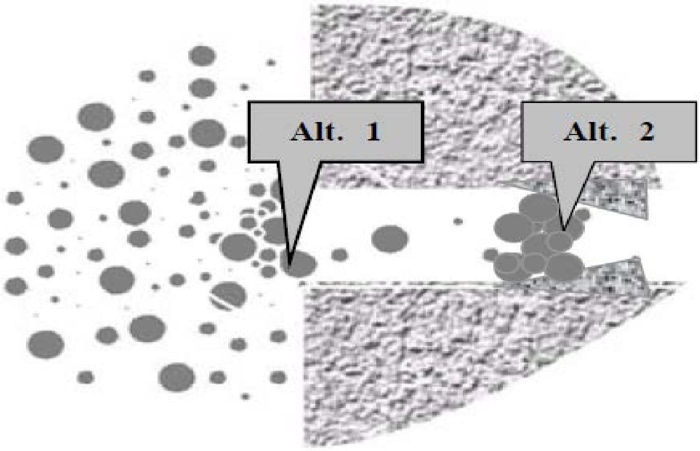


Figure 3. Filtration at the entrance (Alt.1) and constriction (Alt.2) Hansson (1994).

There are many different explanations of mechanisms regarding the growth of filter cakes under various conditions. For example, a great diversity of geometry in the experiment's setup induced differently dominant resistances at constrictions and resulted in clogging(Hansson, 1994). Beyond that, clogging at constrictions could result from flocculation in grouts suspension.

To prevent the formation of filter cakes, some researchers paid a lot of attention to the rheology of grouts. Pusch et al. (1985) has proposed a high-frequency oscillating pressure method to improve penetrability by reducing the viscosity of grout as early as 1985. Following the same fashion, static pressure with a superimposing high frequency proved that oscillating pressure could improve the effects of grouting (Borgesson and Jansson,1990). After that, Mohammed et al. (2015) verified the positive effects of dynamic pressure impulses with high-frequency oscillation on the penetrability of grout by conducting the experiments in aperture sizes of 100-500 µm. Whereas it is the low efficiency of oscillating pressure that limited the wide application in the grouting industry (Ghafar, 2016). Ghafar et al (2015) proposed a method using low-frequency rectangular pressure impulses to erode partially formed filter cakes and reduce the dissipation of oscillation along with fractures.

However, the mechanisms of improvement of grout penetrability in microfractures (<100 µm) are not fully understood because of the involvement of many factors such as cement grain size, water to cement ratio, temperature, and so on. Furthermore, some of these factors are coupled, which leads to more complexity and should be clarified.

Another difficulty in the investigation of grouting methods is from replication of rock fractures. The presence of constrictions within the fractures is of great importance for simulating the real rock fractures, but the geometry of acritical fractures can hardly be the same as fractures in the rock mass. Several types of equipment have been developed to target this issue, including sand column, filter pump, and PentratCone. A decade ago, Draganović and Stille (2011) conducted experiments in a short slot with several constrictions to investigate the formation of filtration. In 2016, a piece of new equipment called Varying Aperture Long Slot (VALS) was developed by Ghafar. A.N. (2016) in order to better simulate variations of fractures in the rock mass.

Even though the instruments and methods of the experiment make the replication of rock grouting possible, it remains unknown which is the most efficient method of grouting.

1.4. Scope of work and objectives

To improve the understanding of rock grouting based on cement material, a comprehensive review of the literature is presented in this thesis. The specific objectives of this study can be summarized as the answers to the below questions:

- How do different factors influence the penetrability of grout?
- Which are the grouting techniques used in rock grouting over time?
- What are the benefits and drawbacks of each technique?
- What do the improvements occur in dynamic grouting over time?
- What are the suggestions for future researches in rock grouting?

The study is mainly divided into three complementary parts based on the questions above. The first part investigates all parameters that might influence the penetrability of grout, and all factors in connection with these parameters were discussed as well. In this subsection, the definition and effects of properties and phenomena like grout rheology and filtration stability are explicitly explained. By reviewing the literature, mechanisms of these parameters, all known factors influencing filtration would be discussed in detail.

The second part introduced a number of instruments and methods that were used to measure penetrability. To clarify the drawbacks and advantages of each instrument with the corresponding method, comparisons between similar methods are necessary.

The last part presented a comprehensive review of the history of dynamic grouting. At the beginning of grouting history, when the technology was limited by instruments, grouting driven by static pressure could fulfill the requirement of sealing. After world history enters the 20th century, higher demands of underground infrastructure construction promoted the developments of grouting technical and equipment. An increment of static pressure is proved to be effective for the prevention of grouting clogging in the crystalline rock by Nobuto et al. (2008). To further improve the penetrability of cement-based grout, many researchers, like Mohammed et al. (2015) and Kim, B et al. (2019), tried to use oscillatory pressure to enhance groutability. Besides, Ghafar et al. (2019) revealed the potential of applying high-frequency oscillation to host rock to have deeper penetration. Having a more realistic instrument for grouting experiments, Ghafar and Fontana (2020) conducted experiments using low-frequency rectangular pressure impulses with VALS. Some of the ongoing researches including ultrasound dispersing of cement-based grout and dynamic grouting based on feedback resonance were studied at the end of this part. Last but not the least, comparisons of each of these methods were discussed in order to investigate the possibility of combinations that could improve the penetrability more than the rest.

1.5. Limitations

The thesis is principally based on the review of previous literature and some reports. Therefore, some limitations must be noted.

Limitations of the scope of studies

The gathered information relevant to grouting technical was mainly based on rock grouting instead of grouting in soil and porous medium, even though there is a huge amount of research investigating the grouting technical in soil. In addition, different grouting materials with disparate properties are widely used in the industry but mainly cement-based materials were studied.

Limitations of the resources

Some research studied in the 1980s is available in reports or books in physical forms and little information can be found on the Internet. Due to this, indirect knowledge from later articles might have a deviation and consequently lead to misunderstanding. Besides, limited information could be obtained for ongoing projects like dynamic grouting based on feedback resonance.

Limitations of the researcher

Lack of knowledge of other languages, for instance, Korean and Japanese, would make some resources unreliable by translating on computers. It was a pity that there were several articles in Korean studying the dynamic grouting that was quite similar to the research from Ghafar (2017) but only the abstract was in English.

Limitations of the feasibility

Based on the advantages and drawbacks of different methods, the possibility and benefits of combining some methods are discussed in this thesis. However, assembling different types of equipment or combining them might cause many small problems that hardly predict in advance and it is questionable if the combined methods could improve grout penetrability without experiments.

2. ROCK GROUTING

2.1. Definition of rock grouting and applicability

In rock engineering, including rock tunnels, rock slopes, and dams founded on rock, many issues are relevant to groundwater during construction and operation periods. The leakage of water under the dam through fractures could cause serious damages to the structures above the ground and even catastrophe. It is therefore of fundamental importance to seal the rock fissures and joints to prevent excess leakage by grouting (Stille, 2017). Similarly, as for tunnel construction in the region where the underground water is rich or for these constructed under rivers, engineers have to cope with the challenges of water inflow. Grouting in rock fractures to seal the water channels is regarded as one effective and economic solution to this problem. Not only that but reduce water ingress also contributes to maintaining groundwater level, and consequently lowers the risk of ground settlement.

However, grouting is not only correlated with geology and material but a wide range of engineering science. According to Nicholson (2019), rock grouting is the injection of mixed material, like cement-based material, into the rock fractures to improve strength or reduce the permeability of the host rock. Sometimes rock grouting can be called fissure grouting because the purpose of rock grouting is to fill the joints and discontinuities in fissured rock with cement-based material.

Fissures and joints widely exist in the rock mass regardless of the quality of rock and the degree of jointing, and weathering have an important influence on the sealing of structures surrounded by rock. By injecting cement suspensions into these fractures, water channels will be plugged if requited grouting spared (Fig.4) is achieved, meanwhile, rock strength tends to be improved by integrating blocks with hardened cement (Verfel, J et al.,1989).

A dramatic increase in the construction of underground infrastructures makes rock grouting develop during the last decade, especially for tunneling construction in urban areas, and is expected to continue because of higher demands on urban space utilization. Rock grouting is considered an effective method to make a permanent barrier for tunnels. Also, it can be used to set up a temporary protective system for next-stage excavation during construction (Johnsen et al., 2012). Nowadays, grouting in rock is also used before the excavation of tunnels in order to mitigate some risks. For example, a watertight zone before the excavation face is created by injecting the grouts in the rock so that the risk of collapse due to water inflow is decreased. Meanwhile, the geotechnical properties of rock masses are improved.

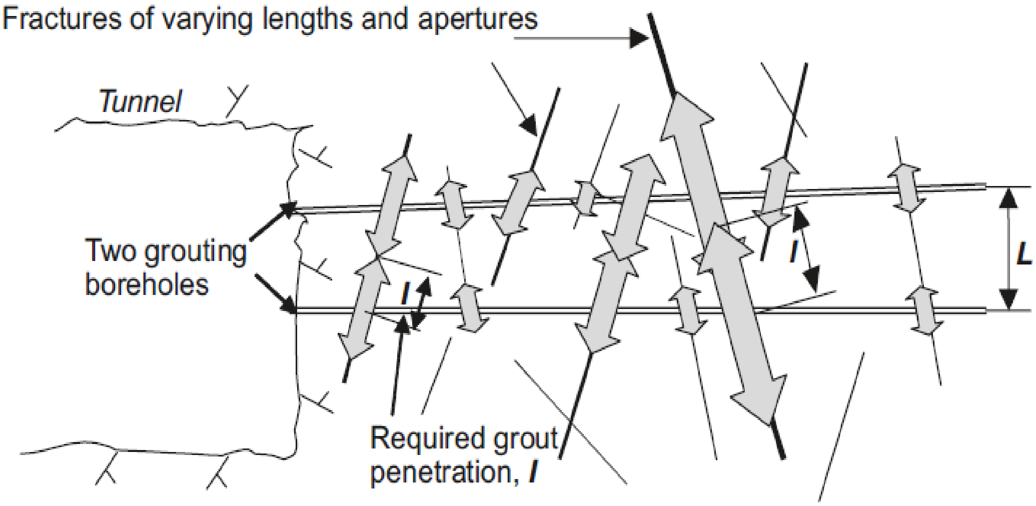


Figure 4. Illustration of required grout penetration length I. (Funehag, 2007)

2.2. Factors influencing the grout spread in rock grouting

2.2.1. Grout rheology (yield stress & viscosity)

Cement suspensions, the same as other fluids, have rheological properties influencing the flow character of grouts in the fractures. However, it is difficult to fully understand the rheological behavior of cement suspensions due to the diversity of components in the grouts (Håkansson, 1993). Besides, the interaction between cement particles and breakdown during shearing makes the rheological properties of cement-based grout even more complicated (Ann Emmelin et al, 2007). According to Banfill (2003), there are some rheological coefficients for cement-based grout and other materials (Shown in Table 1). Many researchers tried to improve grout spread by investigating two governing coefficients, i.e., viscosity and yield stress, by conducting experiments and numerical simulations (Eklund 2005; Banfill 2006; Mohammed et al. 2014).

Table 1. Typical values of rheological properties of the material, Banfill (2003)

Material	Cement paste, Grout	Mortar	Flowing concrete	Self-compacting Concrete	Concrete
Yield stress N/m^2	10-100	80-400	400	50-200	500-2000
Plastic viscosity Pa.s	0.01-1	1-3	20	20-100	50-100
Structural Breakdown	Significant	Slight	None	None	None

In general, cement-based grout can be considered as the non-Newtonian fluid that has variable viscosity under the force, while it could be described by the Bingham model. In the Bingham model two parameters are included, i.e., a yield value (τ_0) and a viscosity value (μ_B), compared with the Newtonian model containing viscosity(μ) only (Shown in Fig.5).

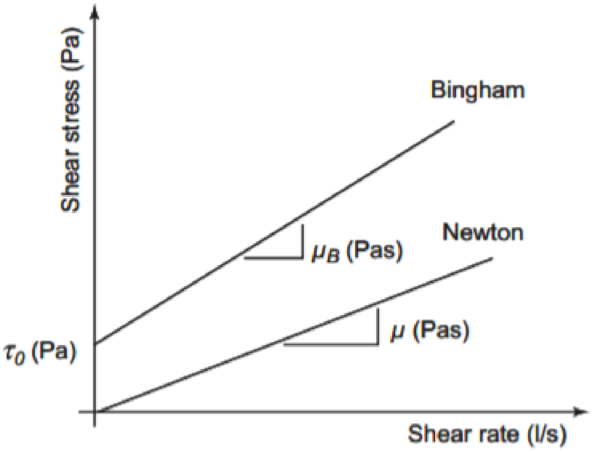


Figure 5. Comparison of Newtonian and Bingham models (Ann Emmelin,2007).

As shown in Fig.5, The Bingham model is expressed as：

$$\tau = \tau_0 + \mu_B \dot{\gamma}$$

where τ is the shear stress, τ_0 is the yield stress, and μ_B is the Bingham viscosity.

There are also many other different rheological behaviors, for instance, Pseudo plastic fluids, Pseudo-plastic fluids, and Dilatant fluids, and more advanced models such as Herschel Bulkley (H-B) model that takes the nonlinear relationship between shear stress and shear rate into consideration. However, due to the ease of understanding and use, the Bingham model tends to be commonly used (Emmelin et al, 2007).

Viscosity, in general, is treated as a measure of workability of grout because it quantifies the internal friction in the grout and is expressed by the force per unit area (Buxbaum, 2011). The factors influencing the viscosity of cement-based grout include the concentration of suspensions, chemical reactions, temperature, and filtration in the fractures. Above all, the smaller the particle concentration, the lower viscosity of grout suspensions. In other words, the water to cement ratio controls the concentration of grouts, and consequently, the viscosity of grout decreases with the increase of the w/c ratio. However, the viscosity difference among high w/c ratio grouts becomes smaller if the critical value is reached. Therefore, it is much more important to use proper types of cement for low w/c ratios instead of using the same type of cement with high w/c ratios (Bohloli, et al., 2019). In terms of chemical reactions, the other dominant factor for cement-based material will generate ettringite (Fig.6) and thaumasite to raise the rigidity of cement as well as viscosity with the progress of time (Kim et al.,2009).

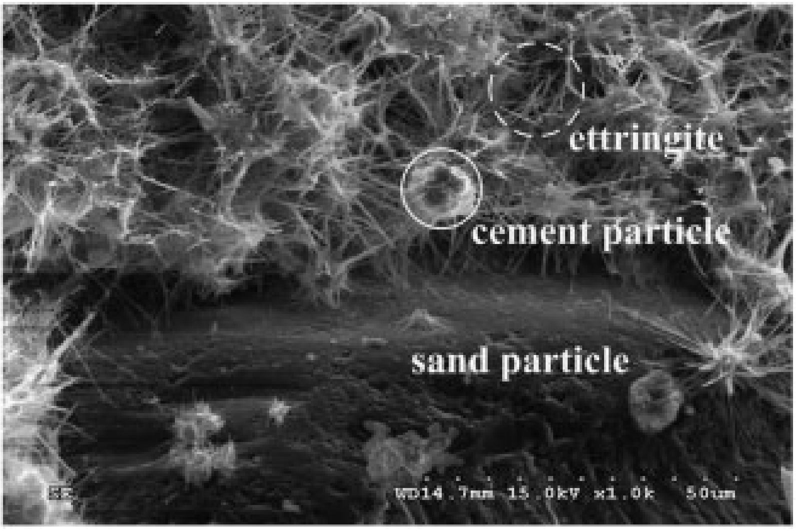
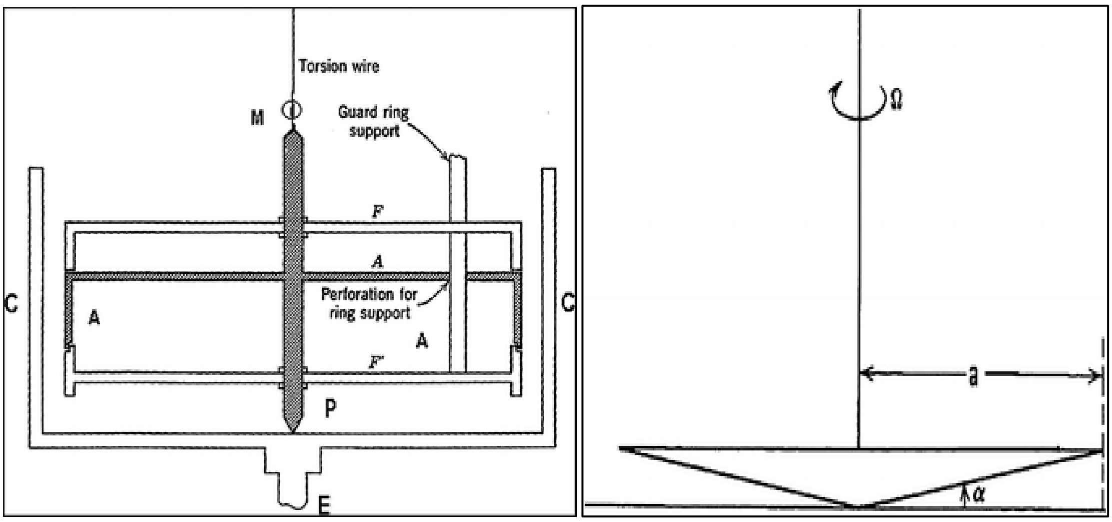


Figure 6. Formation of ettringite in the cement-based grout (Kim et al.,2009).

The other critical factor influencing the rheology of grout and thus the penetrability is yield stress, and according to Rahman (2015), the yield stress could be described as minimum stress turn the solid behavior material into the fluid flow. If the external stress is not enough to overcome the internal force between particles, it would not trigger the transition from solid behavior into fluid behavior. Instead, the external stress below the value of yield stress would only cause deformation inside of the material.

Even though some researchers argued against the existence of yield stress, it still can be considered as an engineering parameter and used as long as it can deduce similar shear rates compared with the measured data (Schurz, 1990). Along the fractures, the shear stress, as well as shear rate, will drop continuously, therefore; the applied stress to the grouts should be larger than yield stress at the frontier of grout flow so that the grout could penetrate further along the fractures.



(a) (b)

Figure 7. Two kinds of viscometer :(a) Couette viscometer and (b) Conical viscometer (Gupta, 2014).

Whereas cement-based grout is a thixotropic material which means its yield stress does not only depend on the shear history but many other conditions (Nguyen et al., 2006). Meanwhile, the type of cement and other rheological parameters could also make yield stress vary in a wide range of numbers.

Håkansson (1993) introduced two different yield stresses, i.e., static yield stress and dynamic yield stress, and the former could be used when the material is at rest and the latter was defined when the cement-based grout was subjected to shear stress in a dynamic state. As a result, the selection of suitable yield stress and measurement equipment, for instance, coaxial cylinders, cone, and plate viscometer (Fig.7), is of great importance before conducting grouting.

2.2.2. Filtration stability

In general, the penetrability of cement-based grout mainly depends on two things, rheology and filtration stability (Eklund, 2003). As mentioned before, filtration refers to a tendency that particles of suspensions would gradually separate from the flow and block the flow path. To deeply understand the stability of filtration, filtration cake as a key concept must be clarified. In fact, there are two kinds of filtration phenomenon according to Svarovsky (1985), including cake filtration and deep bed filtration. Unlike the formation of filter cake, deep filtration describes the process of filtration of grout particles in a porous medium like soil (As shown in Fig.8).

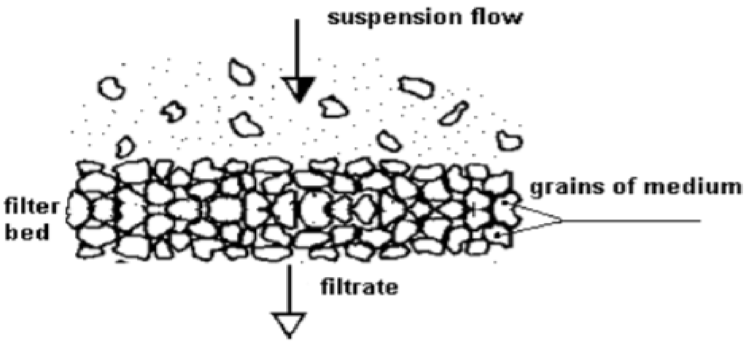


Figure 8. Deep bed filtration (Svarovsky, 1985).

For that reason, deep bed filtration is not the key point of this study, especially for rock grouting. Furthermore, another problem that might be involved in crossflow filtration (shown in Fig.9) occurs when the direction of suspension flow is normal to the filtrate flow (Tien, C.,2006). This phenomenon was also not taken into consideration in this study because the artificial fractures are assumed to be impermeable of water and grout even though it is not true in the rock mass.

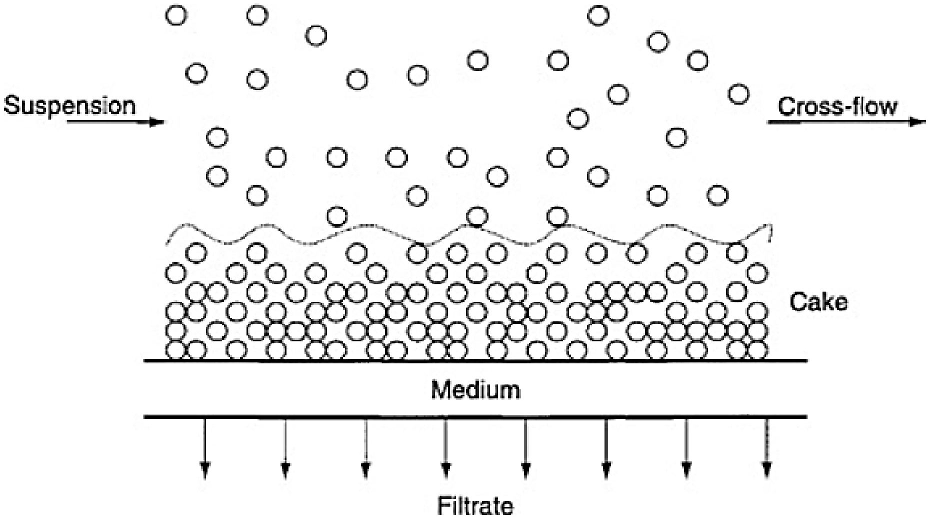


Figure 9. Crossflow filtration (Tien, 2006).

Strictly speaking, cake filtration mentioned in this thesis refers to dead-end filtration happening when the grout flow is parallel to the direction of the filtrate flow. Meanwhile, as for some larger apertures, the formation of the plug is before the formation of filter cake and functions like filter mesh. It is of extreme difficulty to distinguish these two phenomena in the experiments because they cause the same result at the end of grouting and might happen simultaneously. Therefore, in some research plug formation is perceived as filtration, and in this thesis, these two are considered as the same concept.

Several factors can make impacts on the stability of filtration, even their influence is not yet fully investigated, such as maximum grain size, the grain size distribution of cement, and w/c ratio (Hansson, 1995; Eklund, 2003). According to Hansson (1995), some of the parameters and their influence were summarized in Table 2 and three coefficients can be introduced to indicate the filtration stability, i.e., b_{stop}, $b_{filtration}$, and b_{all} (Eklund, 2003). Each of them indicates the filter width allowing different amounts of suspensions to pass the filter (As shown in Fig. 10). b_{stop} means the width of filter mesh that only allows half amount of grouts to pass, and b_{all} is the mesh size that allows all grouts to go through. $b_{filtration}$ is filter width between the other two and causes filtration.

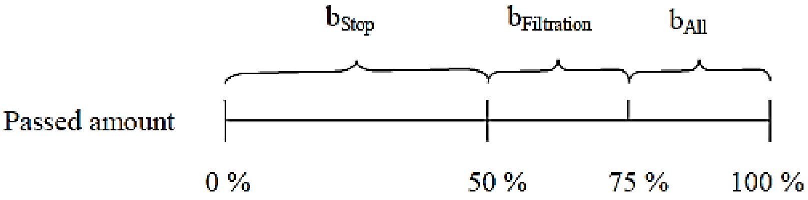
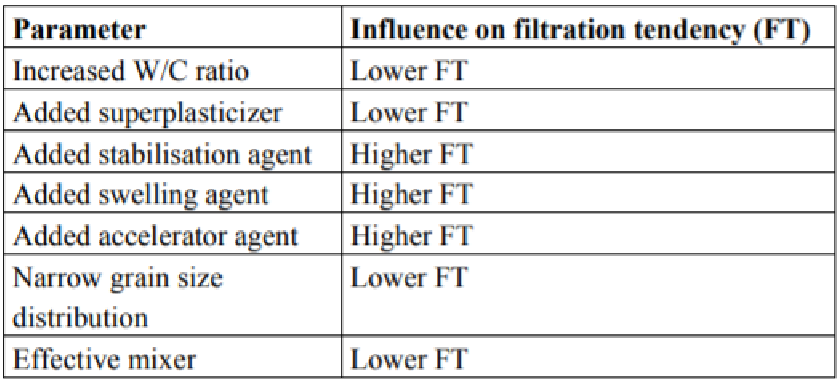


Figure 10. Passed the amount of gout corresponding to coefficients (Eklund, 2003).

Table 2. Parameters influencing filtration (Hansson, 1995).



Parameter	Influence on filtration tendency (FT)
Increased W/C ratio	Lower FT
Added superplasticizer	Lower FT
Added stabilisation agent	Higher FT
Added swelling agent	Higher FT
Added accelerator agent	Higher FT
Narrow grain size distribution	Lower FT
Effective mixer	Lower FT

All in all, a lower filtration tendency representing better filtration stability means no significant filtration occurs during the grouting, and a higher filtration tendency representing adverse filtration stability implies obvious filtration. The detailed investigation of factors influencing filtration is discussed in the next section.

2.2.3. Grouting pressure

The grouting pressure is a decisive factor to achieve the desired penetrability in rock fractures, but its influence on many aspects is complicated, in some cases, even remains controversial (Rafi et al., 2017). Two main aspects regarding grouting pressure are the type of pressure and magnitude of pressure used for injection. As mentioned in the section of grout rheology, cementitious suspension needs minimum pressure to surmount the shear resistance that is relevant to the yield stress of fluids. With the increase of static pressure, not only rheological properties are changed but the filtration tendency would decrease which could result in better penetrability (Eriksson et al, 1999). Higher pressure, before a certain limit, can cause expansion of fractures that facilitates the flow of grouts into small apertures, but in contrast, too much expansion can form new fractures that need extra grouts and will have adverse impacts on the sealing of fractures (Rafi et al., 2017). Hence, more research on dynamic grouting aswas made in order to improve the penetrability of the grout. Pusch et al. (1985) firstly investigated the effects of vibrating grouting on the improvement of penetrability in the Stripa mine. High-frequency oscillations reduced the viscosity of cement suspensions and thus more grout flow could penetrate small fractures. On the other hand, by controlling the magnitude of pressure at peak and rest period, altering of flow pattern due to change of velocity could erode the filter cake at a partially plugged constriction. Ghafar et al. (2016) interpreted the possible mechanism of enrichment from dynamic pressure by using Reynolds-number. Figure 11 illustrated conceptual models of turbulent flow patterns under high pressure and laminar flow patterns under low pressure. For comparison, the flow pattern under static pressure in the slot is also shown in the figure. Major pressure variation, compared with minor pressure variation, caused more rapid variation in the flow pattern and better control on filtration, which effectively improves the grout penetrability.

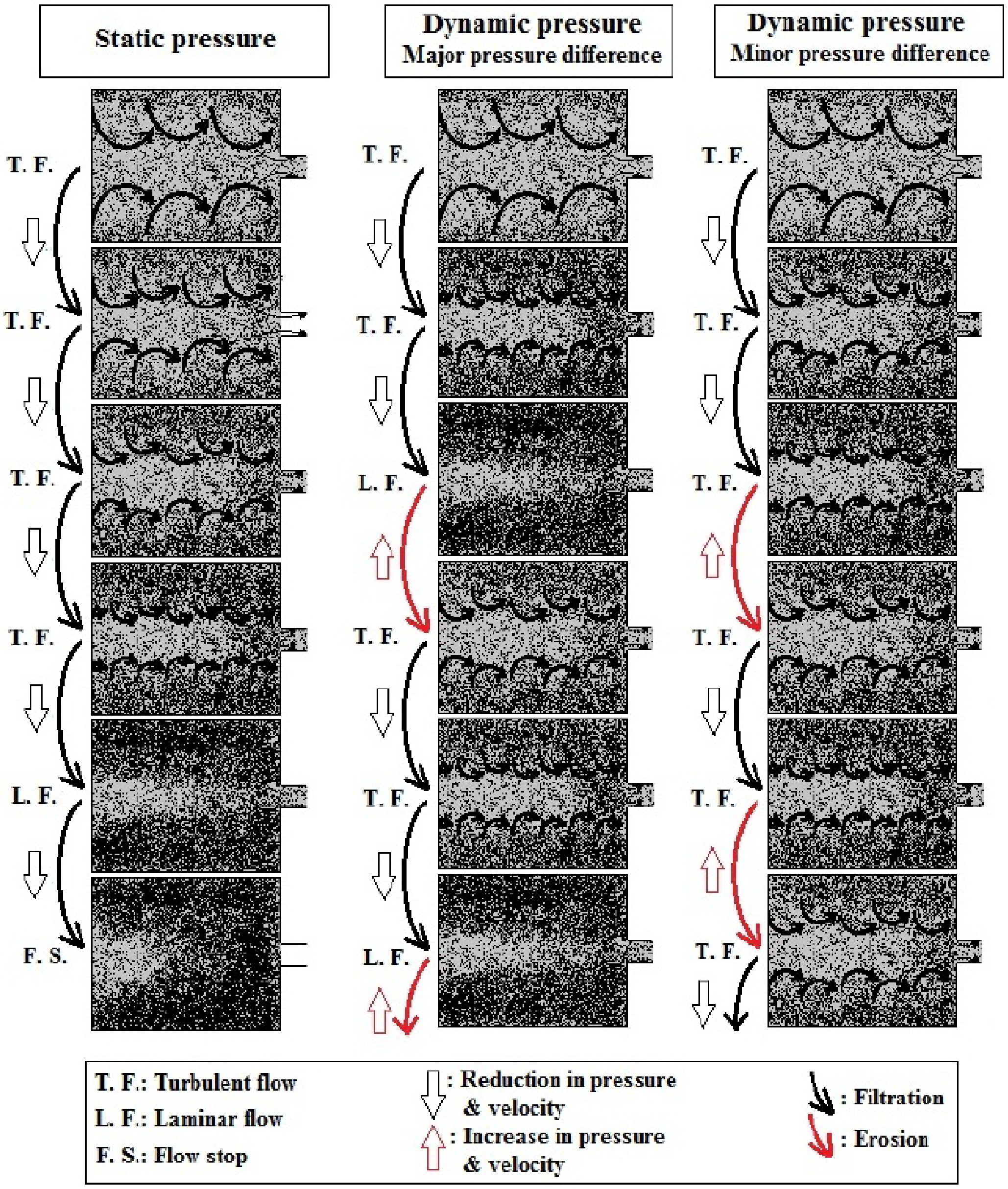


Figure 11. Conceptual model of flow patterns (Ghafar et al., 2016).

2.3. Factors influencing the filtration stability

Apart from the dominating factor, applied pressure, affecting the penetration of grout, there is a wide range of factors that contribute to the grouting efficiency and outcomes. The literature review showed that the mechanism of action of many factors remained unknown as shown in Fig.12, because of the coupling interaction among each factor (Eklund, 2005). Hence, a simple conclusion on a single parameter is not decisive and crucial for dissimilar conditions. To obtain a comprehensive knowledge of rock grouting, several key factors are investigated in this study in connection with two aspects, grout rheology, and filtration stability, that have significant impacts on grout penetrability.

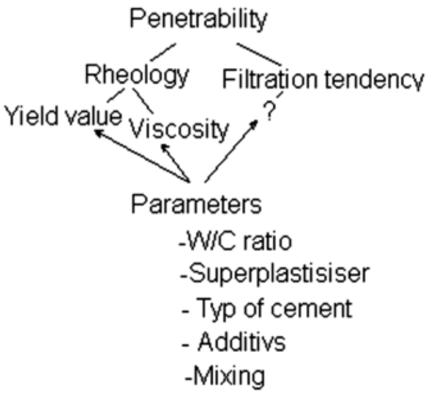


Figure 12. Interactions among parameters affecting penetrability (Eklund, 2005).

2.3.1 Water to cement ratio

Cement-based grout is composed of two main components, i.e., water and certain types of cement, the water to cement ratio thus becomes one critical parameter when better penetrability is expected. According to Håkansson (1993), the w/c ratio is the most important single factor for rheology. Commonly, a higher w/c ratio decreases the possibility of arching through fractures from the perspective of grain concentration. A lower grain concentration means the fewer cement particles passing through constrictions at the same time and the better penetration into the fracture (Draganovic, 2009). On the other hand, the durability of hardened cement should be taken into consideration, where the lower water to cement ratio is beneficial to a longer life cycle for structures (Hansson, 1998). To achieve the lowest possible w/c ratio, the properties of grouting in connection with other factors, such as grain size and superplasticizer, need to be considered.

It is always under discussion that what is an appropriate w/c ratio for grouting. Many researchers advocated using a high w/c ratio to avoid clogging of the particles especially for micro cement whose specific surface is larger than ordinary cement. Houlsby (1990) proposed the use of high water to cement ratio due to the better penetrability benefitting from the positive influence of rheology, where the viscosity and yield stress of grouts were decreased. After that, Graf (1993) revealed that cement particles could pass a constriction one by one under the condition with water to cement ratio 6 by volume. This result can find evidence from the studies of Saucier (1974) who conducted experiments to investigate the median diameter ratio between gravel pack and formation sand in the oil-recovery field. It was observed that thin mixture grout can penetrate further in an injection funnel (Mittag and Sacidis, 2003). Marinet (1998) demonstrated the stability of a three-particle bridge at constriction is better than bridges with more than three particles, which can prove the rule of thumb, i.e., the aperture of fracture should be at least 3 times larger than maximum particle size. However, some literature showed that it seems to likely penetrate these fractures with an aperture close to the maximum particle size by using a higher w/c ratio.

Nowadays, different views about this issue came about in the grouting industry. Some argued against the employment of high w/c ratio grouts. For example, Ewert et al. (2017) investigated the proper value of the water to cement ratio for grouting and gave the recommendation of using “thick” grouts which means the water to cement ratio is smaller than 2. The conclusion was drawn according to the petrological study, where grout stone layers were observed under the condition of thin grouts and thick grouts, and no grout stone was found in finer fractures. Besides, two drawbacks of high-water content grout were given. The first one is the cost of pumping thin slurry is more expensive than thick suspension, and the other is associated with the bleeding issue of high-water content cement. Thanks to the development of superplasticizer, cement-based slurry with a w/c-ratio of around 0.5-0.7 by weight are commonly used for rock grouting by decreasing the viscosity of the suspension. To achieve better penetrability in small apertures, a higher w/c-ratio grout, i.e., 1~2, is used at the beginning of grouting when the thin suspension flows into finer fractures and stops at enough length. The thick grout is then injected so that larger joints can be sealed along with a reasonable consumption of cement (Ewert et al, 2017).

2.3.2. Grain size and grain size distribution in relation to the aperture

In terms of grain size and grain size distribution, it is meaningless to discuss these two parameters without considering the size of apertures, because the way that these two parameters influencing penetrability is mainly associated with filtration or plug phenomena. Commonly, two coefficients that represent the grain size and grain size distribution are maximum particle size and d_{95}, even though there are plenty of ways to describe the grain size distribution. They could be obtained from sieve tests of dry powders where maximum particle indicates the minimum size of aperture allowing all materials to pass through and d_{95} represents the sieve aperture filtering 5 % (by weight) of target mixture.

From the literature review, the mechanism of filtration or plug formation in relation to grain size and grain size distribution could be explained in two aspects, i.e., physical effects and chemical reaction, and the interaction between them is complex. As for physical effects, it could be easily recognized that it would be impossible to penetrate if the size of grains is much larger than the aperture. However, the composition of cement-based grout is not monodispersed (one-grain size), which makes the employment of maximum grain size meaningless to evaluate the tendency of filtration or plug formation. Whereas some authors, like Marinet (1998) using maximum grain size agreed on a conclusion that the maximum grain size needs to be at least three times the apertures to prevent plugging and filtration. Considering the ratio between aperture size and d_{95}, Eklund and Stille (2008) used mesh filters and short slots to measure the filtration tendency and calculate the value of k ($b_{groutable}/d_{95}$). The results showed that the k value varies between 4~10 when the ordinary cement was used in the experiments. The completely same conclusion was drawn by Eklund (2005), from which a large number of experiments were conducted to investigate the influence of grain size and grain size distribution, and the value of d_{95} (cement-based mixture) should between 4~10 times smaller than the size of constriction. Two groups of tests with different materials and one group of scaled-up experiments revealed quite similar results. The first cluster of experiments was executed with inert material in order to exclude the influence of chemistry and the results showed that the d_{95} of particle size should be 3~4 times smaller than aperture so that filtration tendency is not significant. Based on these results, the rule of thumb regarding the proper ratio between aperture and grain size should be described with d_{95} instead of maximum grain size. Besides, the other observation from the experiments' results is that if the d_{95} is similar in two mixtures the steeper shape of grain size curve (not too many fine or too many coarse particles), the better penetrability could be achieved as shown in Fig. 13.

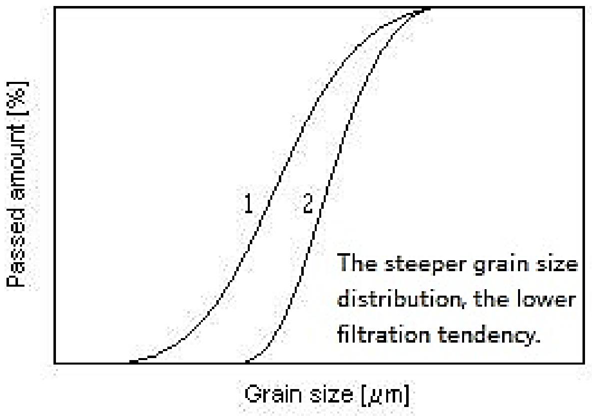


Figure 13. The steepness of the grain size distribution. (Eklund, 2005).

Similar conclusions could be obtained from the performed experiments with cement-based material. However, because of chemical reaction, i.e., the hydration of cement, some experimental data demonstrated that superfine cement had an adverse impact on the filtration even with the same grain size distribution. This was caused by the flocculation of small grains into large clusters in the light of the principle that the larger the specific grain surface, the quicker the chemical reaction. Accordingly, there seems to be a threshold value of d_{95} when the filtration tendency tends to increase with an aperture below that value, which is defined as b_{crit} (4~10 times larger than d_{95}).

In summary, a steep grain distribution curve will contribute to reducing the possibility of filtration, but superfine cement or micro cement might increase the risk of agglomerates and the formation of the plug.

2.3.3. The geometry of constriction and shape of particles

Another issue ignored in many investigations is the influence of the geometry of constrictions. Draganović and Stille (2011) tried to explain the mechanism of plug formation by comparing aperture and maximum grain diameter as illustrated in Fig. 14. Alt. 1, Alt. 2, and Alt. 3 represent three different fractures with a stepwise increase of apertures. As illustrated, the distance between the edge of Alt.1 and the edge of constriction is less than the radius of grain and the possibility of plug formation is low due to the rotation and sliding of grains around the corner. In the case of Alt.2, the first grain in the arches is supported from two sides and consequently, the possibility of arches formation is lower in comparison with the condition with Alt.3.

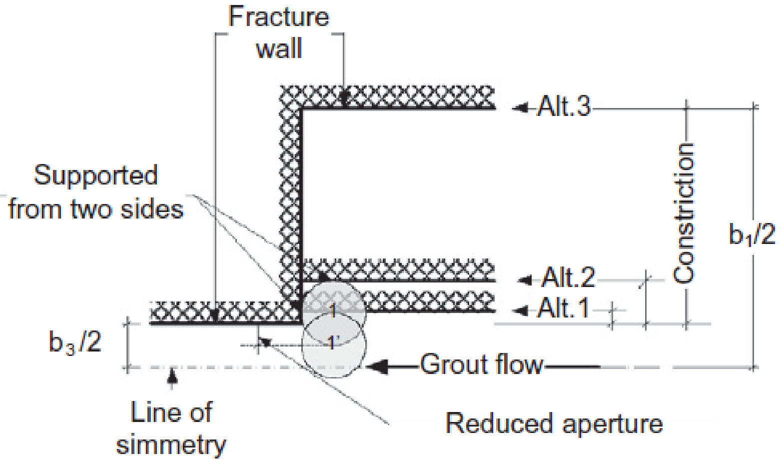


Figure 14. Different apertures compared with maximum grain diameter (Draganović and Stille, 2011).

The difference between the number of grouts passing through mesh filters and slot fractures can be observed even if the aperture and volume of mixtures used are the same (Eklund,2005). The cement-based grout can penetrate deeper in the slot experiments compared to the mesh geometry. The reason behind these differences is largely dependent on the geometry of constriction. The plug can build up in four directions for mesh aperture but only two directions for slot aperture as shown in Fig. 15.

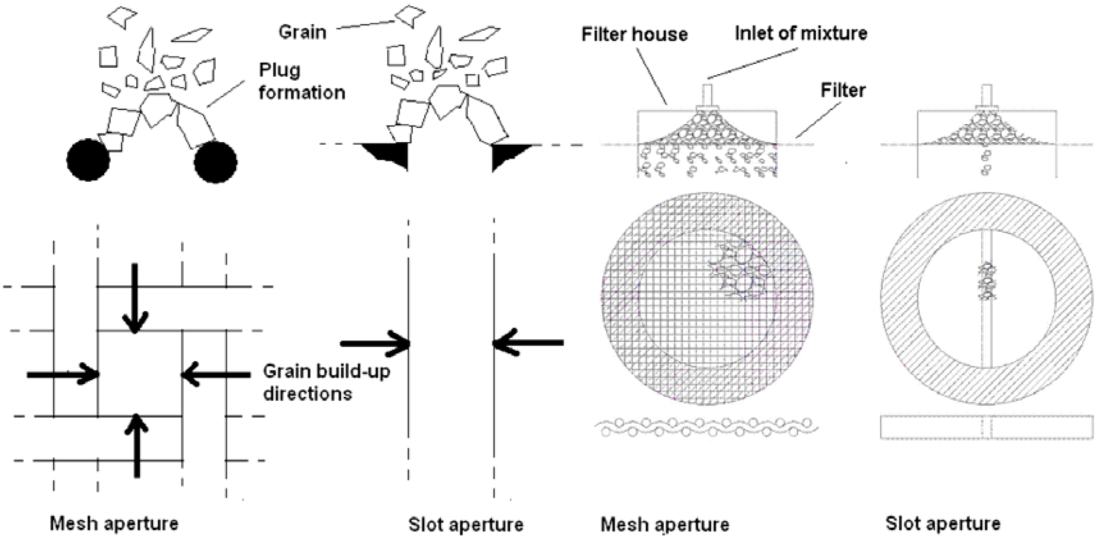


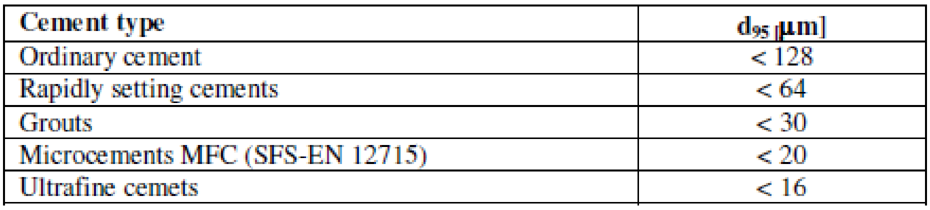
Figure 15. The geometry of mesh aperture and slot aperture (Eklund, 2005).

In addition, Eklund (2005) investigated how grain shape influences filtration by a scaled-up experiment (100:1), where rhombic-shaped grains and spherically shaped grains are marked with black and white colors respective. Theoretically, the shape of grains should make difference in the frictional forces between the particles, especially when the concertation of particles is high. However, there was no significate difference as expected.

2.3.4. Dispersing agents

With the development of cement, the size of particles became finer in order to satisfy different requirements in modern projects and consequently, the specific surface raised dramatically compared with coarse-grained cement i.e., around 300m^2/kg (Holt, 2008). According to Finnish Concrete Association (2006), the cement type can be classified based on the d_{95} of cement as shown in Table.3. In the grouting industry, engineers tried to take advantage of the micro cement to efficiently seal small fractures. However, one issue caused by the increase of specific surface for micro cement (up to 1500 m^2/kg) is how to maintain the workability without adding too much water (Ranta-Kopri, et al, 2008). Therefore, the implementation of dispersing agents becomes inevitable.

Table.3, Categories of the degree of fineness (Finnish Concrete Association, 2006)



Cement type	**d_{95} [µm]**
Ordinary cement	< 128
Rapidly setting cements	< 64
Grouts	< 30
Microcements MFC (SFS-EN 12715)	< 20
Ultrafine cemets	< 16

Dispersing agents are different from additive materials whose main purposes are to lower the heat generation during the hydration and harden the cement paste (Eklund, 2005). The principal function of dispersing agents is to change the properties of grout and optimize the performance of cement suspension. According to Ranta-Kopri, et al. (2008), superplasticizers have become more popular since the 1980s and the gist of this section in this study will incline to the mechanism of superplasticizers, even though there is a wide range of dispersing agents with different functions.

As mentioned before, the rheology of cement suspensions and filtrations may have a major influence on the penetrability of grouts. Satola (2001) revealed that the depth of penetration in the rock fractures correlates with the rheology characteristic of cementitious grouts. On the one hand, remaining workability along with reducing water to cement ratio is the macroscopic expression of the effects of chemical superplasticizer. As for micro cement grouts, the required amount of water would not rise sharply by adding superplasticizers. On the other hand, superplasticizers can decrease the cohesion and viscosity with the same content of water so that the lower grouting pressures would achieve the same penetrability. There are three main types of polymers including naphthalene, melamine and a carboxylic group can be used as active substances for chemical superplasticizers (Ramachandran et al., 1998).

The commonly used cement for grouting is Portland cement whose main raw material is limestone ($CaCO_3$) as well as other mineral compositions like belite C_2S, alit C_3S, aluminate C_3A, and ferrite C_4AF (Houlsby, 1990). It is these chemicals that will associate and then react with water. However, due to the interactions between grains in the suspensions, water molecules could not efficiently contact every single grain. Two principal forces that could flocculate or disperse the grains are London-van der Whale forces and electrostatic forces, of which the former (LvdW) can only make grains attract each other (Eklund, 2005).

Howarth (1986) concluded that electrostatic forces tended to be largely influenced by ion strength in the water but not LvdW forces. Moreover, Eklund (2005) made statements that the LvdW force cannot be manipulated by adding superplasticizer. As a result of that, only repulsive forces from electrostatic interaction might be used to disperse the grains and thus the better rheological properties could be obtained. The surface property of cement particles will be altered because of the adherence of the superplasticizer. More specifically, different surface charges and polarity between the grains tend to be turned into electrostatic stabilization as shown in Fig. 16. to separate the grains. Furthermore, the active substance can create long polymer chains, called steric stabilization, on the surface of cement particles, which also make a positive impact on dispersal (Eklund, 2005).

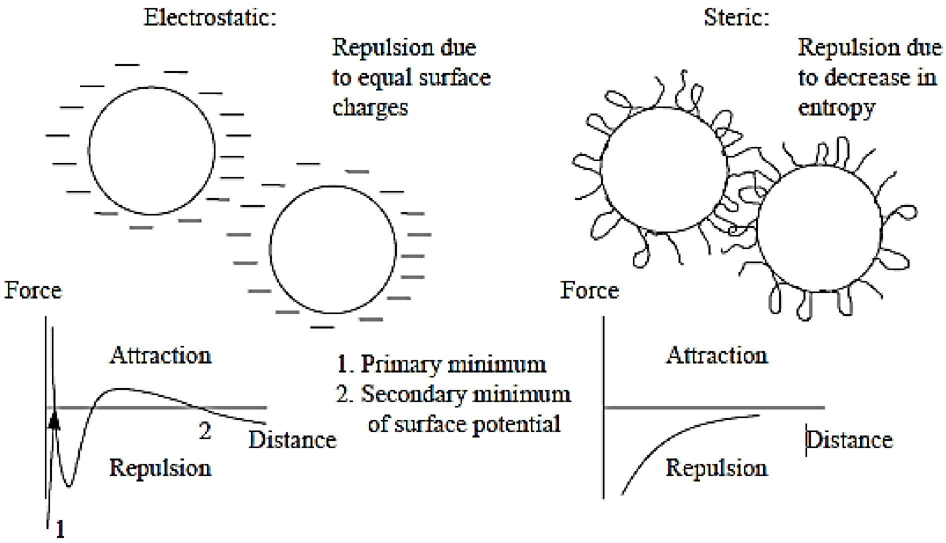


Figure 16. Electrostatic and steric stabilization (Eklund, 2005).

Compared to these two effects caused by superplasticizers, Fjällberg (2003) demonstrated that steric stabilization ought to be more effective to reduce cohesion and viscosity than the other one. It is worth noting that the corresponding superplasticizer and dosage should be selected properly in the light of the type of cement, otherwise; the adverse effects might deteriorate other properties of cement.

2.3.5. Mixer type and mixing time

Before injecting grouting with pressure, cement particles and water need to mix effectively with additives. The mixing methods and time, therefore, have a significant influence on the properties of fresh grout and thereby contribute to the length of penetration (Eriksson et al., 1999). There is a wide range of methods and equipment for mixing cement-based grout, and two commonly used methods, are high turbulence mixer and ultrasonic mixer, which were investigated by comparing the effects of dispersal in the study of Toumbakari et al. (1999). A mechanical turbulence mixer with 2400 rpm was used to mix all material in a dry condition before adding the water and superplasticizers. With a different mix sequence, followed by cement, fine particles were poured into water and ultrasonic mixer at 28 kHz along with a stirring at 300 rpm dispersed all materials. The grouts made of ordinary Portland cement with low C_3A content were utilized to penetrate the sand column at the pressure of 0.8~1 bar after mixing and grouts samples were tested by coaxial viscometer at four moments after mixing (0, 30, 60, and 120 mins) so that the apparent viscosity could be obtained as well as shear stress.

Two batches of cement grouts with silica fume and without silica fume were compared to show the difference in dispersing effects of two dissimilar methods. As shown in Figures 17 and 18, the apparent viscosity of grouts mixed by ultrasonic mixer tended to be around half of the samples in the mechanical turbulence mixer (Toumbakari, et al., 1999).

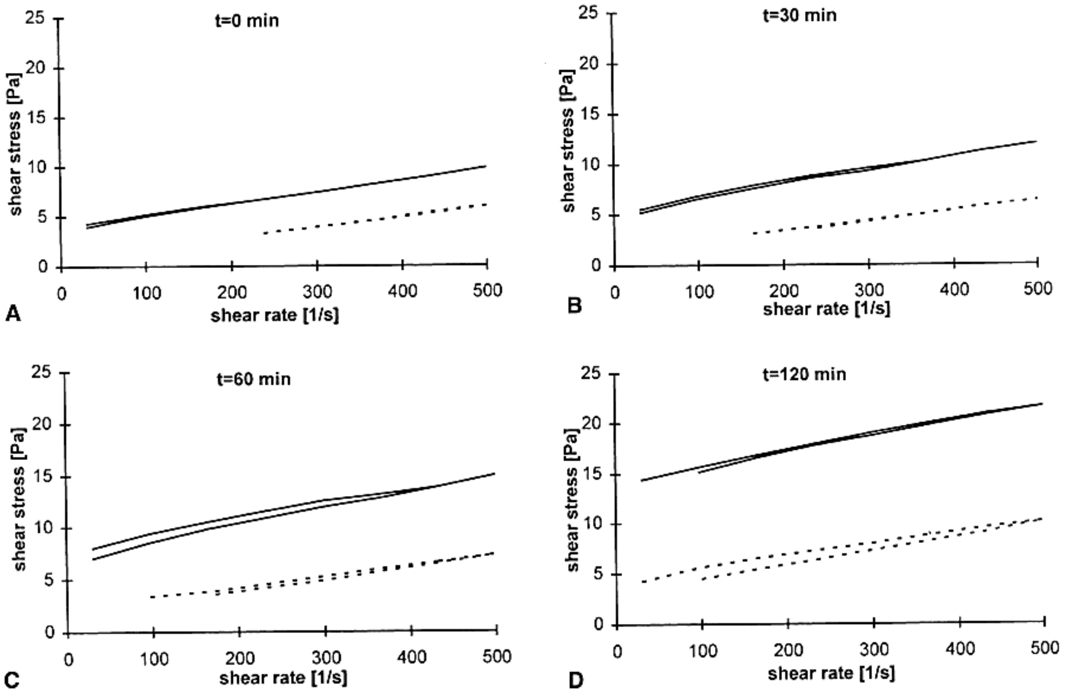


Figure.17, Apparent viscosity of grout without silica fume: HT-mixing (solid line) and US-mixing (dotted line). (A) t=0 min, (B) t=30 min, (C) t=60 min, and (D) t=120 min (Toumbakari, et al., 1999).

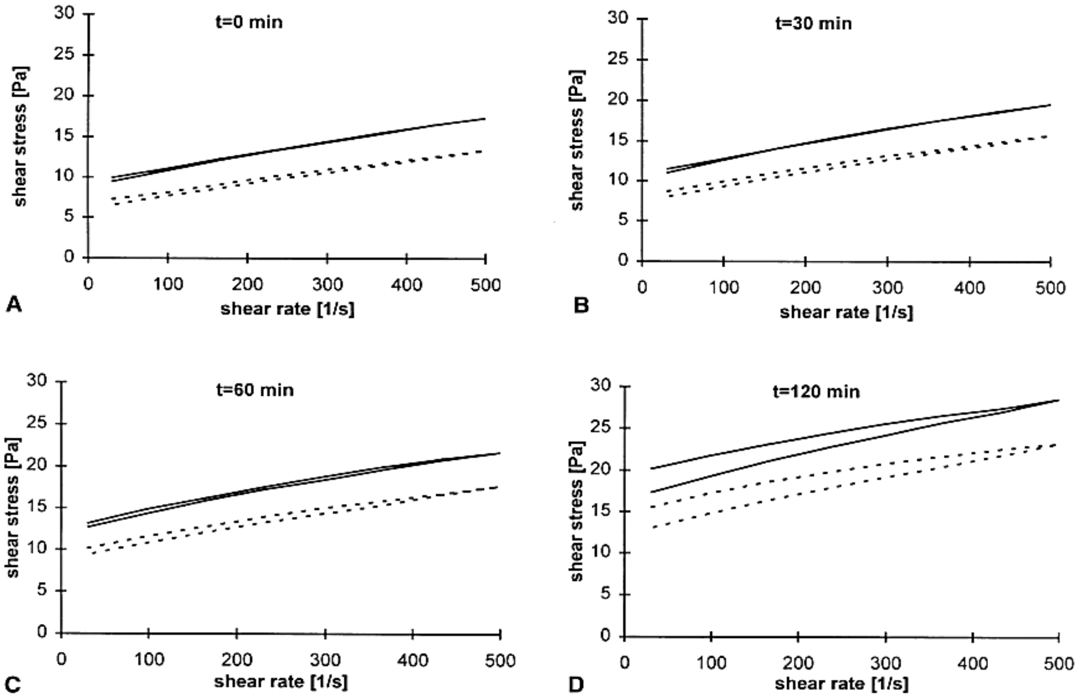


Figure.18, Apparent viscosity of grout with silica fume: HT-mixing (solid line) and US-mixing (dotted line) from Toumbakari, et al., 1999.

Another conclusion drawn by Toumbakari, et al. (1999) is that the apparent viscosity of grout suspensions containing silica fume is unable to inject due to the flocs in the mixture if the mechanical turbulence machine was used. In contrast, an ultrasonic mixer has a stronger dispersion capacity of deflocculating formed flocs without increase the w/c ratio. In summary, mixing with an ultrasonic mixer is advantageous for ordinary cement grouts if penetration into fractures smaller than 0.3 mm is expected (Toumbakari, et al.,1999).

To investigate a similar problem, Eriksson et al. (1999) compared a lab mixer with a field mixer, but the penetration measurement is based on the NES method instead of the sand column. The results of experiments (Fig. 19) showed that cement-based grout (INJ30) tended to have a better penetrability in a lab environment, which probably resulted from rotational speed and other factors such as temperature and storage time of cement.

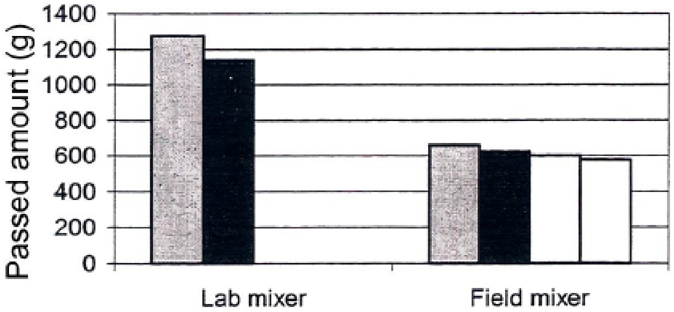


Figure 19. Passed amount of INJ30 with w/c ratio of 0.8 and 0.54% HPM measured with 100μm slot (Eriksson et al., 1999).

According to Hjertström and Petersson (2006), even if the same type of cement and the kind of colloidal mixer were used, the penetrability of cement seemed to be largely influenced by the capacity of equipment as shown in Fig. 20. As for the results from the paddle mixer, the grout mixture could not penetrate the 125µm filter pumps. Besides, another observation from the study is that each type of mixing machine may have different effects on dispersing various cement particles, for example, the traditional paddle mixers are not a good option if the micro cement is the grouting material (Hjertström and Petersson, 2006).

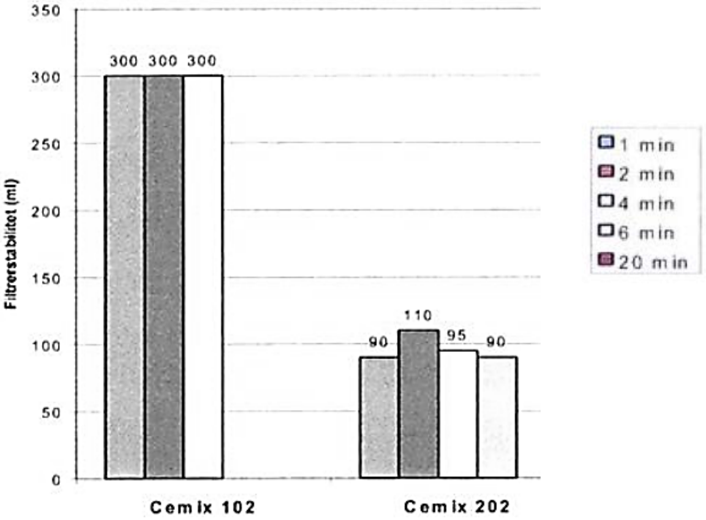


Figure 20. Passed volume measured by a filter pump for different capacity colloidal mixers (Hjertström and Petersson, 2006)

In terms of mixing time, it is also of importance and an unavoidable factor if a better penetration is expected (Eriksson et al.,1999). Simultaneously, the rotational speed (rpm) of the colloidal type of mixers was found vital to the penetrability (Hjertström and Petersson, 2004). Comparison between coarse cement and micro fine cement showed that a longer mixing time was needed if the same penetrability length was expected by using a colloidal mixer (Axelsson and Turesson, 1996).

Ranta-Kopri, et al. (2008) conducted extensive experiments to investigate the influence of mixing time on grouts properties either in lab conditions or in the field. The mixing equipment used for field tests was a colloidal mixer with high turbulence and the experiments were divided into two stages. During the first stage, after 30 seconds of adding water and cement, the samples would be mixed for one minute, two, and three minutes respectively. In the second stage along with additives, it took 45 seconds to pour all materials into the mixing container, and tests were performed with 30, 90, and 180 seconds and 3 minutes of the mixing process. After mixing, the samples would be tested for density by Mud Balance test device and Marsh value by Marsh cone as shown in Fig.21. Accordingly, with the yield values from the rheometer, the viscosity then can be determined.

Figure.21, Mud Balance test device for measurement of the density (left) and Marsh cone (right) for measurement of Marsh value (Ranta-Kopri, et al., 2008).

However, based on the measurements of Marsh value, there was no obvious connection between mixing time and Marsh values. Because the data was scattered, and the trend line could not describe the data with a correlation coefficient as shown in Fig. 22. Nevertheless, the Marsh values were below 43 if the mixing time is long, which might be due to the better viscosity caused by enough mixing.

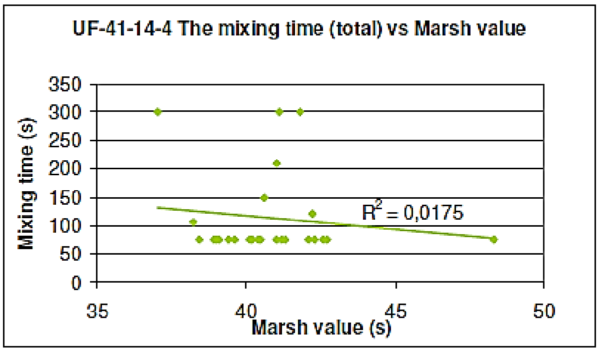


Figure 22. Marsh value vs total mixing time (Ranta-Kopri, et al., 2008)

As for the correlation with time and density, the correlation coefficient R is 0.39 which means poor connection. There is no correlation between density and mixing time as shown in Fig.23.

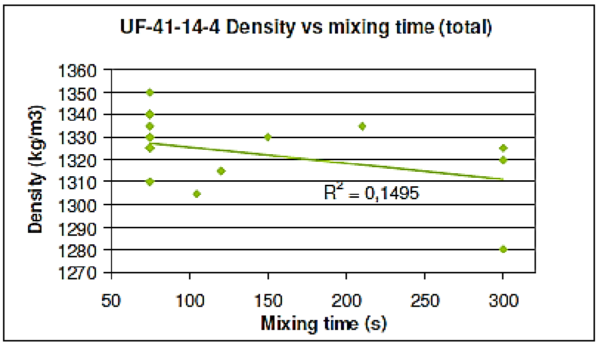


Figure 23. Density vs total mixing time (Ranta-Kopri, et al., 2008)

In conclusion, the mixing time does not have a clear connection with either Marsh values or grouts density. However, the Marsh values are lower when the mixing time is longer than 150s, which can be explained because more air is mixed in the grouts with a longer mixing time. But this variation could not result in obvious fluctuations of properties and a huge influence on penetrability.

Keong (2006) revealed that suitable mixing time was dependent on the volume of mixed grout. Three specimens produced by Portland cement were mixed at 1500 rpm with mixing times of 5,10 and 15 minutes respectively. The viscosity test results as shown in Fig 24. demonstrated that if the volume of grouts did not exceed 200 c.c., 15 minutes was the most suitable time to obtain sufficiently good rheological properties (Keong, 2006). If the volume of cement-based grout is over 200 c.c., the mixing time should be determined by Marsh Cone and mud balance tests so that the viscosity of grouts is constant (Keong, 2006).

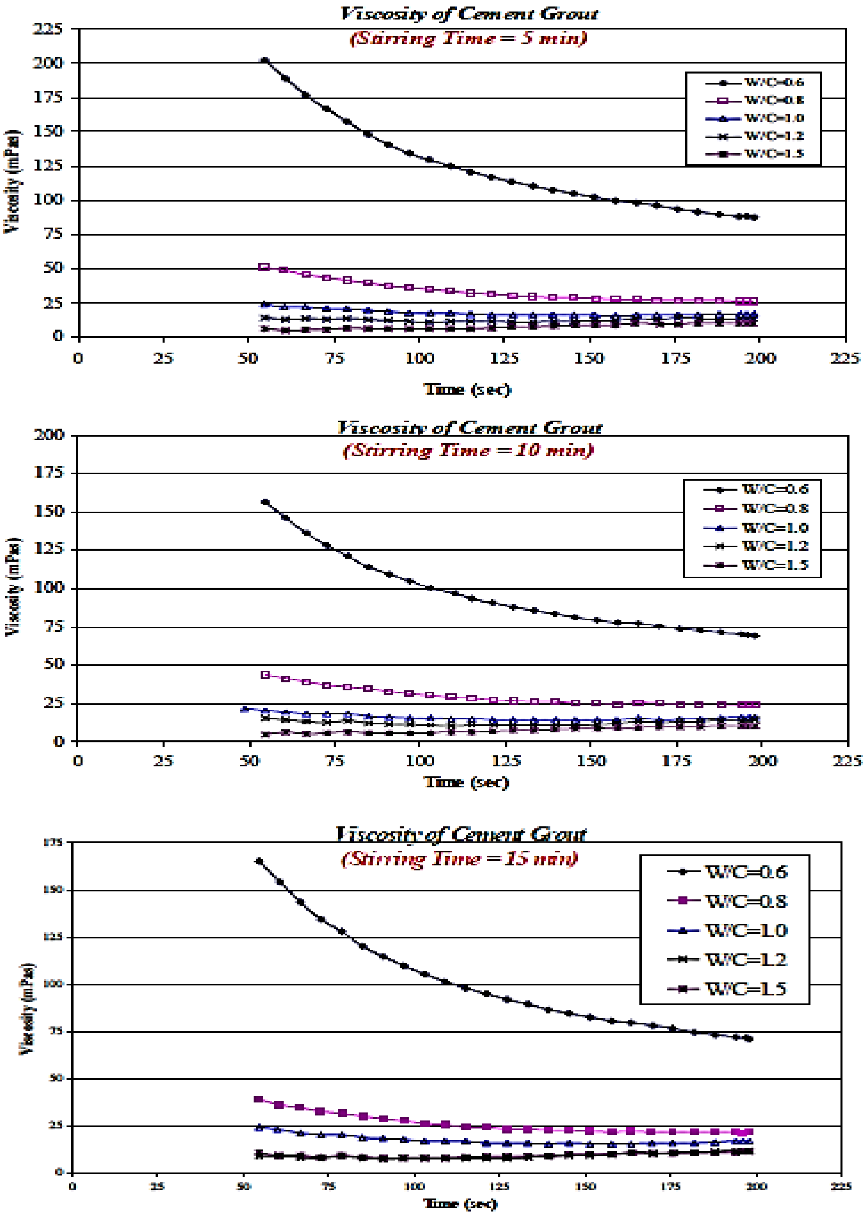
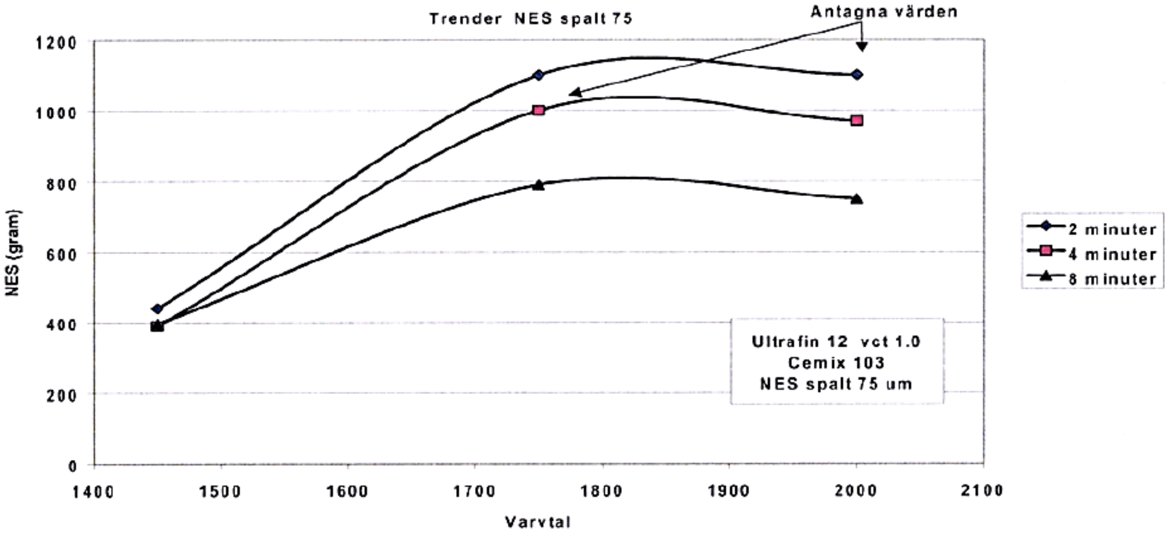


Figure 24. Apparent Viscosity vs time with different mixing times (Keong, 2006)

The conclusion that too long mixing time would decrease the penetrability was underpinned by the research of Hjertström and Petersson (2006). The experiments were performed by the NES method with fine-grained cement, and results from different apertures including 60μm and 75μm are shown in Fig. 25. Under the rotational speed of around 1750 rpm, the duration of mixing for 2 minutes is most suitable to achieve the best penetrability through the 75μm slot.



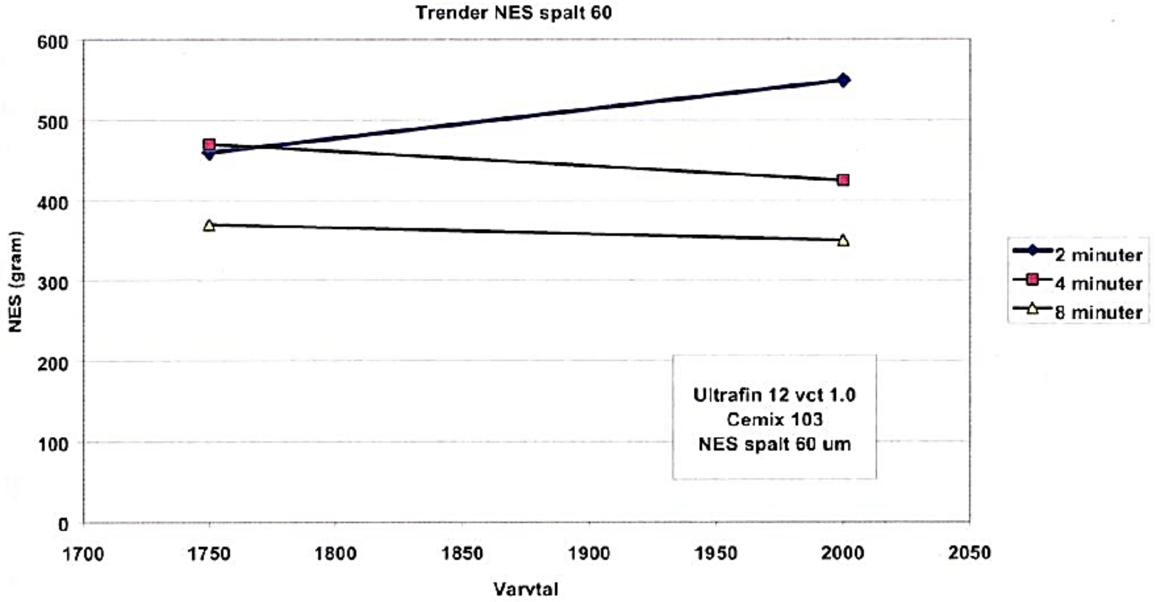


Figure 25. The penetrability of grouts with different mixing times and rotation speed, 75μm slot (upper); 60μm slot (under), (Hjertström and Petersson, 2006)

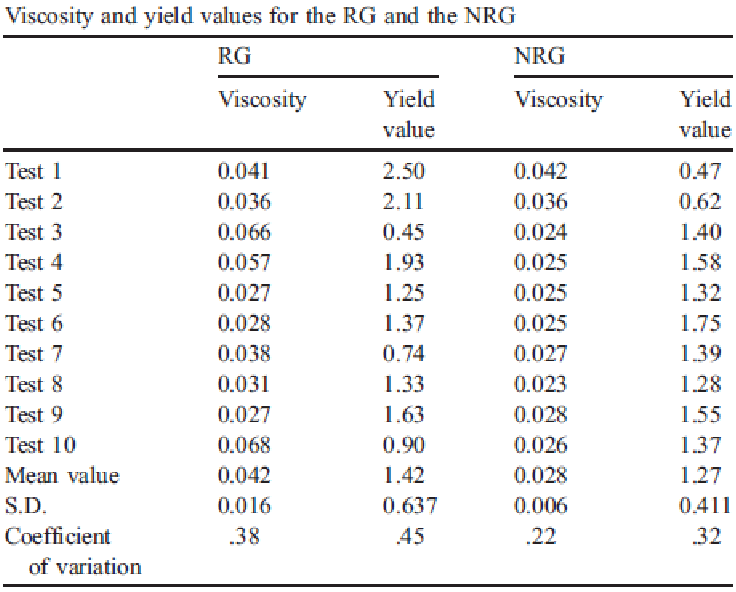
Once the mixing time is over 2 minutes or the rotational speed is below 1750 rpm, the penetrability would slightly decrease. As for the 60μm slot, the suspension could not penetrate further in the fracture if the mixing time is longer than 2 minutes (Hjertström and Petersson, 2006).

2.3.6. Storage time and age of cement

There is not too much information about how storage time impacts the penetrability of cement-based grout from previous studies. But some authors found the indeed influence of storage time on penetrability. For instance, Ranta-Kopri, et al. (2008) revealed that variations of cement properties were partly caused by natural diversities of materials, and partly caused by temperature, storage time, and other factors. Moreover, Mentesidis (2015) demonstrated that longer storage time would exert an influence on the rheology and penetrability of cementitious grouts. Because of local property changes in cement volume, different batches of cement material will present discrepancies over time. These conclusions are supported by the study of Eriksson et al. (2004).

In the study, two batches of cement were both mixed with a w/c ratio of 0.8 and 1% superplasticizer. One batch of cement (40 bags) was stored in a laboratory (20 ° C) for a few weeks before mixing. These types of cement were marked as reference grout (RG). The other batch of cement, marked as new reference grout (NRG), was used right after delivery. In order to obtain the viscosity and yield value results for RG and NRG, a coaxial cylinder viscometer was used. As shown in Table 4, coefficients of variation (standard deviation) for viscosity and yield value are 0.38 and 0.45 respectively in the RG group. These two values are higher than the values in the NRG group, which means a larger spread of the RG results. The reason behind this might be the variation of cement properties. Even though cement materials were stored in a relatively dry condition, the ambient environment in the laboratory still had an impact on cement properties over time (Eriksson et al., 2004).

Table 4. Viscosity and yield values for the RG and the NRG (Eriksson et al., 2004).

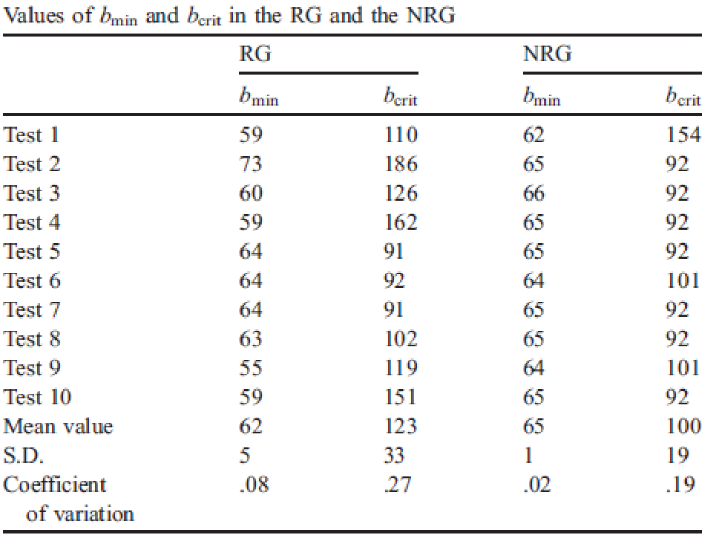


Viscosity and yield values for the RG and the NRG

	RG		NRG	
	Viscosity	Yield value	Viscosity	Yield value
Test 1	0.041	2.50	0.042	0.47
Test 2	0.036	2.11	0.036	0.62
Test 3	0.066	0.45	0.024	1.40
Test 4	0.057	1.93	0.025	1.58
Test 5	0.027	1.25	0.025	1.32
Test 6	0.028	1.37	0.025	1.75
Test 7	0.038	0.74	0.027	1.39
Test 8	0.031	1.33	0.023	1.28
Test 9	0.027	1.63	0.028	1.55
Test 10	0.068	0.90	0.026	1.37
Mean value	0.042	1.42	0.028	1.27
S.D.	0.016	0.637	0.006	0.411
Coefficient of variation	.38	.45	.22	.32

In terms of penetrability, two groups of grouts were tested by Penetrability Meter, and b_{min} along with b_{crit} was obtained and shown in Table 5. The same tendency can be observed. The coefficient of variation for b_{min} and b_{crit} in the RG group is higher compared with the NRG group. The possible reason for the larger variation for older cement is that moisture in the ambient will result in reactions in the cement and influence the properties of fresh grouts (Eriksson et al., 2004). In summary, longer storage time tends to cause variation for both rheology and penetrability of cement-based grout.

Table 5. Penetration tests for the RG and the NRG (Eriksson et al., 2004).



Values of b_{min} and b_{crit} in the RG and the NRG

	RG		NRG	
	b_{min}	b_{crit}	b_{min}	b_{crit}
Test 1	59	110	62	154
Test 2	73	186	65	92
Test 3	60	126	66	92
Test 4	59	162	65	92
Test 5	64	91	65	92
Test 6	64	92	64	101
Test 7	64	91	65	92
Test 8	63	102	65	92
Test 9	55	119	64	101
Test 10	59	151	65	92
Mean value	62	123	65	100
S.D.	5	33	1	19
Coefficient of variation	.08	.27	.02	.19

Besides, some research only focuses on the effects of storage time on cement rheological properties, which can also be helpful to understand the correlation between storage time and penetrability. Ramge et al. (2013) elaborated on the effect of the storage time on early properties of cement suspensions. All samples were taken from a single cement batch and then stored in defined conditions with different durations. Except for a reference group packed airtight, all specimens were stored in open plastic boxes and exposed to the corresponding environment. With a concentration on the effects of storage time, the results from three groups of cement with the same storage climate but different storage duration (14 days, 28 days, and 56 days) are presented in Fig.26.

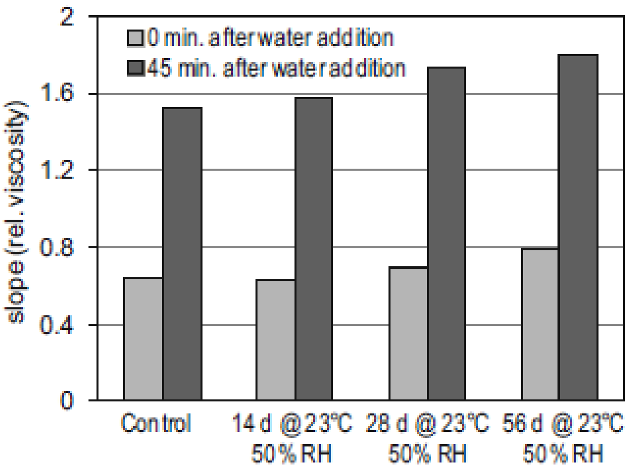


Figure 26. Change in viscosity for different storage times (Ramge et al., 2013).

It can be observed that the longer storage time, the bigger value of viscosity even under the same climate condition. Besides, an ideal correlation between the mass increase rate of dry cement and relative humidity was recorded during experiments. Therefore, based on these two observations mechanism of the effects of storage time on properties can be determined. Due to the hygroscopic nature of dry cement, water molecules in the ambient environment will be adsorbed and leads to hydration reactions on the surface of the cement. It is this pre-hydration that deteriorates the properties of cementitious grout according to Ramge et al. (2013). Accordingly, one can infer that cement materials exposed to climate for a longer duration would not have the same penetrability as those with short storage time.

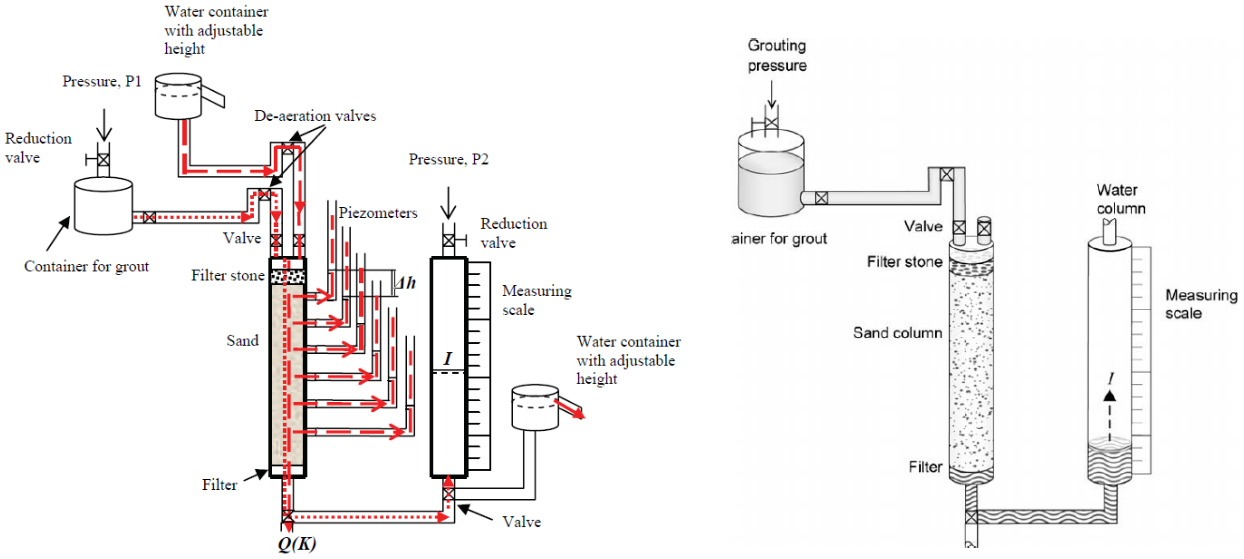
2.4. Equipment and methods used to measure grout penetrability

The involved complexity of grouting operations makes it extremely difficult to deeply understand the different effects of factors without experiments. Many researchers have managed to approach penetrability and filtration tendency by developing testing equipment and methods since the 1970s. These equipment and methods have been continuously improved in order to further investigate and measure penetration from various perspectives. Some equipment and methods are used to investigate grout penetration in a porous medium. For example, Sand Column is commonly utilized when grouting penetrability is tested in soil and sand. However, methods like NES and Short Slot are designed for better simulation of grouting operations in rock joints and fractures.

Cross-examination of several dominant factors influencing grouting penetrability is observed among different methods, but there is a discrepancy between results due to the characteristics of each method. Sometimes, results from distinct literature are contradictory (Ghafar, 2017). This might be caused by diverse assumptions, testing apparatus, evaluation approaches, and induced new parameters (Mentesidis, 2015). Therefore, this section will study all developed methodologies and their advantages and disadvantages in detail.

2.4.1. Sand column

According to Eriksson, (2002), Sand Column is the oldest method for measurement of penetrability and is recommended in standards and norms in some countries. For instance, the French standard (NF 18-891, n.d.) prescribes the use of Sand columns. This method has become very popular in researchers, Bergman (1970), Arenzana (1989), Zebovitz et al. (1989), Hansson (1995), Perret et al. (1997), Schwarz (1998), Toumbakan et al. (1999), Sanatagata (2003), Dalmalm (2004), Funehag (2005), Dupla et al. (2005), Ranta-Korpi et al. (2008), Axelsson et al. (2009) and Zhou et al. (2019) conducted a lot of experiments with the sand column to investigate penetration and flirtation tendency. The experiment apparatus used in these investigations might slightly differ, depending on how grout penetrability is evaluated. Nevertheless, instruments of the sand column are commonly comprised of three main parts, including a grouting container, a transparent column filled with sand, and a water column. As shown in Fig 27, Axelsson et al. (2007) presented a layout of the Sand column, and then, in 2009, they modified the experiment apparatus. In picture (a), penetration is measured based on water volume in the water column as grout material is injected into the sand column and pressure loss would be measured by piezometers along the sand column at constant water pressure. After simplification, penetration can be evaluated either by measuring the water height in the water column with the saturated sand column or by measuring the total volume of injected grouts under unsaturated conditions. Another method to determine penetration length in the sand column is visual inspection after grouting (Ghafar, 2017).



(a) (b)

Figure 27. Layout of Sand column. (a) Water saturation in column (Axelsson et al., 2007). (b) Modified after Funehag (2005) and Axelsson et al. (2009).

For this method, predefined sands should be filled in a transparent column in order to simulate pores in soil or channel systems in rock. Accordingly, the grain size distribution and grain shape are controlled to get proper porosity of sand and thus determinate aperture in the sand column. However, this aperture is only a theoretical value and could be related to rock fractures.

Bergman (1970) proposed that median grain size (D_{50}) could be utilized to describe the value of fictive aperture b_{fic} in rock joint:

$$b_{fic} = 0.15 D_{50}$$

This equitation is derived from dividing total volume between the sand grains with half of the sand surface and it is correct in spherical unsorted grains for a Newtonian fluid (Axelsson & Gustafson, 2007).

As mentioned before, cementitious grouting is commonly treated as Bingham fluid. Therefore, another equation based on Bingham fluid in a granular material can be obtained:

$$b_{eqv} = \frac{8}{\pi \cdot S \cdot (1-n)}$$

where S is the specific area of sand in the column and n is the porosity of the sand column (Axelsson and Gustafson, 2007).

However, the accuracy of these equations is under discussion. Axelsson et al. (2009) performed experiments with two inert grouts in three different sand columns to investigate grout penetrability in different conditions. Whereas, conducted experiments show that it is difficult to relate grout penetration in the sand column to penetration rock fractures. The reason is that filtration in porous media is not the same as that in rock joins and this difference is not taken into consideration as the derivation for b_{eqv}.

Even though many researchers tried to relate grout flow in sand medium to that in rock fractures, it is proved to be extremely difficult. Therefore, the Sand Column might not be the best method if the target of the investigation is to improve grouting penetration in rock fractures.

2.4.2. Pressure chamber or filter press

To further study the filtration tendency of cement-based grout and penetrability, another method called Pressure chamber or Filter press was put forward by Gandais and Delmas (1987). The experiment rig designed for this method comprises a main chamber, some filtering materials, and an effluent container. A schematic of the Pressure chamber (Fig. 28) was shown in the study of Widmann (1996), where compressed air exerted from the top is marked with 1, grouting suspensions with 2, contact surface with 3, a sheet with 4, and predefined filtering materials with 5. Similar to the Sand column, the penetrability of filtering materials is controlled by using various materials such as paper, fine sand, soft rock, standard porous stone, etc.

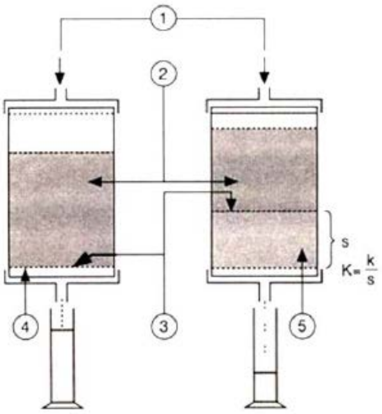


Figure 28. Schematic view of the Pressure chamber (Widmann, 1996).

As shown in the above figure, the permeability of filter (K) is based on two parameters:

$$K = \frac{k}{s}$$

One is the filter's thickness *(s)* and the other is the coefficient of permeability *(k)*. During experiments, bentonite-cement grout was tested while the filter in the pressure chamber simulated fine apertures in fracture walls instead of apertures in soil or rock, which means this type of filtration belongs to surface filtration. Gandais and Delmas (1987) presented the mechanism of this filtration as the formation of pasty deposits when some water in grout suspension penetrates micro-cracks in the walls and this would result in an eventual plug-in flow channel. A depiction of this procedure is shown in Fig. 29.

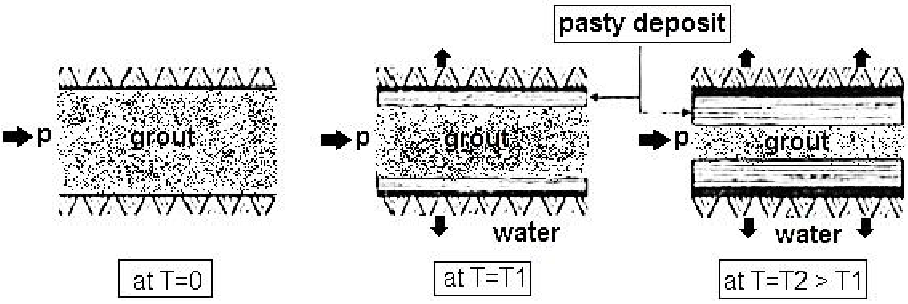


Figure 29. Formation of pasty deposit as time passes (Gandais and Delmas, 1987).

An observation from conducted experiments is that the density of deposit at the contact surface of filter material is a linear function of depth and has a positive correlation with the volume of filtered water. However, this observation is not valid for rock fractures, even though there are micro-cracks in the rock matrix. Draganovic (2009) draw this conclusion and stated that surface filtration is not relevant in impermeable fractures such as artificial fractures.

2.4.3. Filter pump

Another commonly used equipment, the Filter pump, was developed by Hansson (1995), it is specifically designed to evaluate the filtration stability of cement-based grouts. It has advantages such as simplicity of application and good portability compared with other equipment. The general depiction of this method can be found in Hansson (1995) and is also shown in Fig. 30. It consists of three main components including a metal tube, a piston rod, and woven metal wire cloth. By pulling out the handle, grout mix is sucked into a metal tube through a woven metal mesh filter with a certain size (32, 45, 75, 100, or 125 μm). Based on the volume of grouts collected in a metal tube, the filtration stability of grout under a specific mesh size can be measured.

According to Hansson (1995), the formation of filter cake in rock fractures, especially at the entrance of fractures, can be replicated by filter cake building in the filter pump. This process is illustrated in Fig.31. In the same research, measurements from filter pumps were compared with the results from concrete cracks, and column, and smooth slots. It seems that results from the filter pump have a relation with those data from the sand column but not concrete crack when the grout mix is close to a kind of Newtonian fluid.

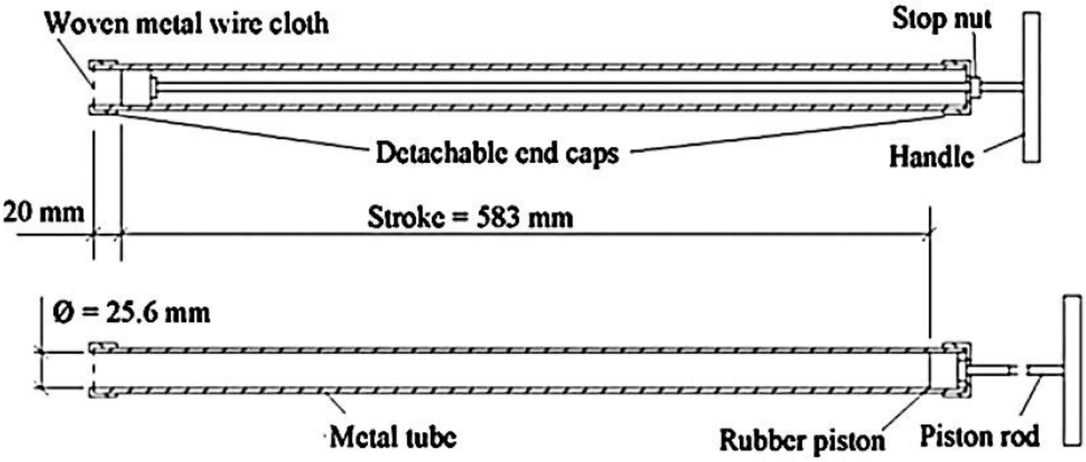


Figure 30. Schematic view of Filter Pump (Hansson, 1995).

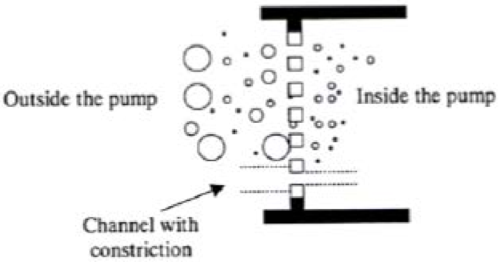


Figure 31. The illustration of grout mix passing filter mesh in filter pump (Eriksson et al, 2000).

In general, the filter pump can be used to find suitable grouts that can be injected into a certain fracture, in another word, a type of grout mix with the least filtration should be selected for given mesh size. In contrast, Eriksson et al. (2000) tried to measure the filtration of one grout with different mesh sizes and defined two parameters to describe the properties of grout penetrability. Tests start with the minimum mesh size and the mesh size is successively increased until the collected grout mix reaches 300 ml. During the test procedure, the volume of passed grouts for each mesh size is recorded and drew against mesh size (As shown in Fig.32).

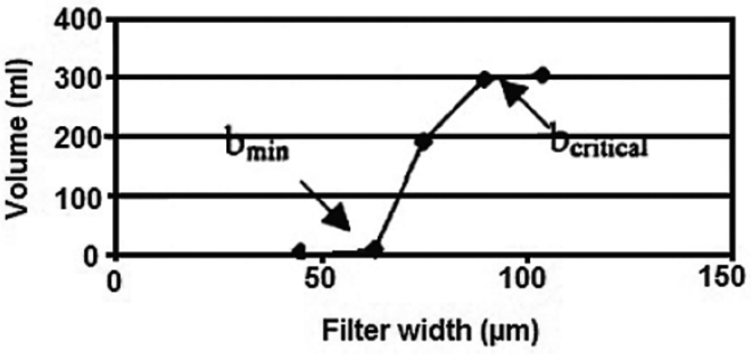


Figure 32. Depiction of b_{min} and $b_{critical}$ (Eriksson et al, 2000).

As illustrated in the above figure, b_{min} is the minimum mesh size that a specific grout cannot penetrate, which means the cement particles cannot flow into apertures smaller than this value. In terms of $b_{critical}$, it is the minimum mesh size that will not cause filtration, and all 300 ml grout mix can pass through the filter. As for the mesh size between these two values, the grout is partially filtered.

There are three drawbacks to the filter pump. The first problem with repeatability is due to the variable applied pressure in each test. The second one is the relatively low pressure produced by pulling pistons. This pressure can only reach 0.3-0.8 MPa which is much smaller than the pressure used in the field. Besides, the limited capacity of the metal tube (300ml) has a huge influence on the value of $b_{critical}$.

2.4.4. Penetrability meter

By using the same concept as the filter pump, a mesh filter is also used in another method, called the penetrability meter, for measuring filtration tendency and penetrability. This method, developed by Eriksson and Stille (2003), is an improvement of filter pump but with a different instrument. As shown in Fig. 33, a small metal tube in the filter pump is replaced by a bigger grout container with a one-liter capacity, and one bar constant pressure is applied on the top of the grout container. Compared with the filter pump, the pressure produced by the pump in this method is more stable and thus replication of the test is improved. At the bottom of the grout container, an outlet valve is connected to the container and a tube with a mesh filter is attached at the end. During each test, grout is pushed out through various sizes of mesh filters and collected to measure the volume of passed grout mix.

Figure 33. Penetrability meter (Eriksson and Stille, 2003).

Based on the same method of valuation in the filter pump, the volume of collected grout mix in the penetrability meter is measured and drew in a diagram with mesh size. Accordingly, two parameters (b_{min} *and* $b_{critical}$) are determined in light of the abovementioned diagram.

On top of that, Eklund and Stille (2008) carried out a series of tests with a penetrability meter in order to investigate the difference of plug formation between mesh geometry and slot geometry. As shown in Fig. 15, grout particles can bridge the plugin in two directions under mesh conditions, while the filter cake can only build in one direction if grouts are injected into slot apertures.

The experiments conducted with inert material prove that penetrability is better in slot geometry than in mesh geometry, which also means that filtration of grouts measured with mesh filters is overestimated. Besides, Eklund and Stille (2008) introduced a new coefficient k which is a slot aperture divided by d_{95}. At the same time, due to a larger amount of grouts in a container, b_{crit} replaced $b_{critical}$ when k is used to determine critical aperture. According to Eklund and Stille (2008), grout mix based on coarser inert material have a k closer to 2 but this value is closer to 16 when fine cement is used.

2.4.5. The NES method

To better evaluate the penetrability of grouts in rock fractures, the NES-method was developed by Sandberg (1997) with slot geometry, and it can emulate the real grouting process in rock fracture system according to the author. Figure.34 illustrates the instruments used in the NES method. There are five main components, including a pressurized gas tank, a steel frame, a load scale, a grouting container, and two parallel steel plates. To start the test, constant pressure which is up to 20 bars will push grouts in the grouting container into the slot (50 µm) between two steel plates through a 25 mm “borehole”. At the same time, the weight of the grouting container would be recorded over time as well as pressure variations during the injection.

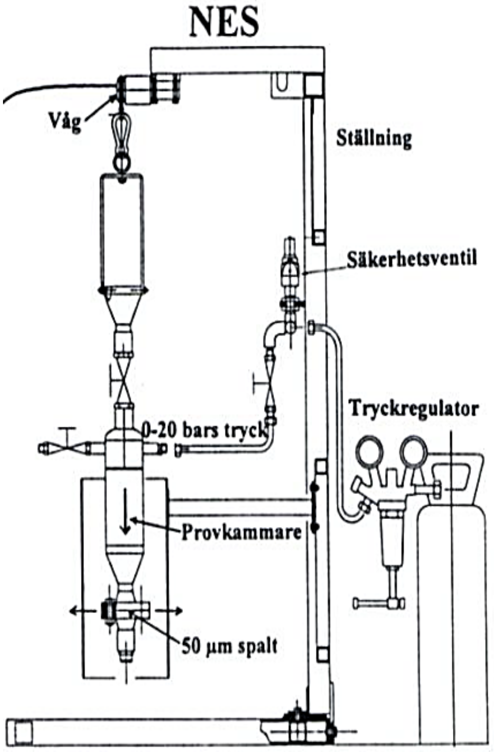


Figure 34. Setup of NES method (Sandberg, 1997).

By measuring the decrease in weight of the grouting container, injected grouts can be known. Meanwhile, the penetration rate can be obtained by this method as well. Experiments conducted by Sandberg (1997) with three different size grouts and water shows a remarkable discrepancy in penetrability. As expected, water has the best penetrability and the fastest penetration rate. The filtration becomes stronger with the increase of cement size if the w/c ratio is 3.0, which means plug formation has more influence on the penetrability of fine-grained cement with a bigger size. This seems to be contradictory to some research. The possible reason is that using high water content and additives yields the proper velocity of grout suspension without flocculation.

This method has been used by many researchers, such as Eriksson et al (1999) and Hjertström and Petersson (2006), to investigate various factors influencing the penetrability of cement-based grouts, and then it is modified by Nobuto et al (2008).

In the modified method, four outflow paths created by two steel plates, as shown in Fig. 35, would be injected with stepwise increasing pressure from 0 to 50 bars, and field equipment is used for mixing and injecting continuously. By applying stepwise increasing pressure, Nobuto et al (2008) concluded that clogging of thick grouts can be prevented effectively. The mechanism of this improvement is explained as continuous erosion of filter cake by the increase of pressure as shown in Fig. 36.

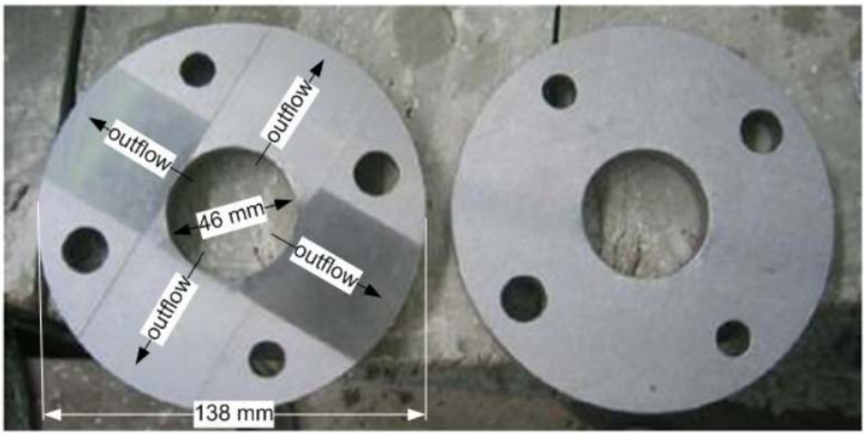
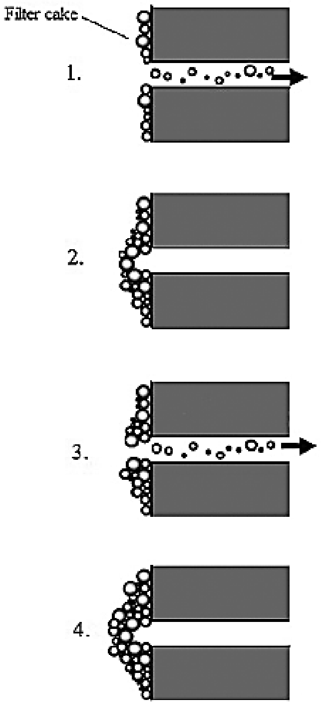


Figure 35. Modified Steel parallel in NES method



1. Grout penetrates into the channel.
2. Grout mounds over the channel and only water can penetrate (filter cake grows).
3. Filter cake brakes partially by increase of pressure and grout penetrates again.
4. Grout mounds over the channel again and the flow stop occurs due to the clog formation.

Figure 36. Filter cake erosion by stepwise increasing pressure.

2.4.6. PenetraCone

According to Axelsson et al (2009), a new method, called PenetraCone (Fig.37), is introduced to measure the penetrability of cement-based grout in the field. The author demonstrated that using a slit geometry can better simulate the flow of grouts in rock fractures compared with mesh geometry and theoretical analysis would better predict penetration conducted with this instrument. Therefore, two conical cylinders comprise a main component of PenetraCone, where a constant aperture is formed between the outer and inner cylinders. Subsequently, the aperture is adjusted by controlling the position of the inner cylinder.

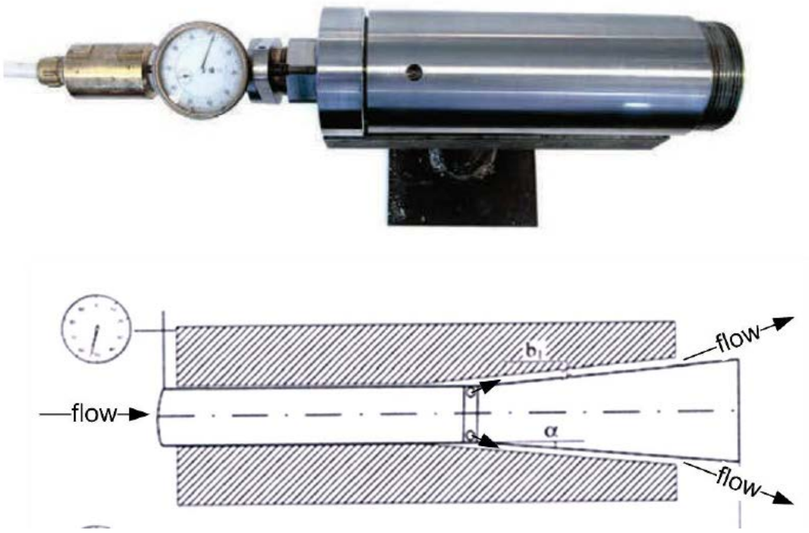


Figure 37. PenetraCone and cross-section (Axelsson et al, 2009)

As shown in the above figure, the gap between the two cylinders creates a flow path for the grout mix. At the beginning of the test, a relatively large aperture is used for the first test and then decreases constantly until the continuous flowing of grouts turns into dripping. To evaluate the penetrability of grout, one parameter, b_{filter}, is defined at the time when drips are pushed out from the gap. After reopening the aperture to its initial size, the gap is reduced again until the flow of grout stops. Accordingly, the other parameter, called b_{stop}, is determined from the corresponding aperture.

An enlargement of the cross-section of the PenetraCone (Fig.38) shows the entrance of the aperture where cement particles plug the flow path and eventually stop the penetration.

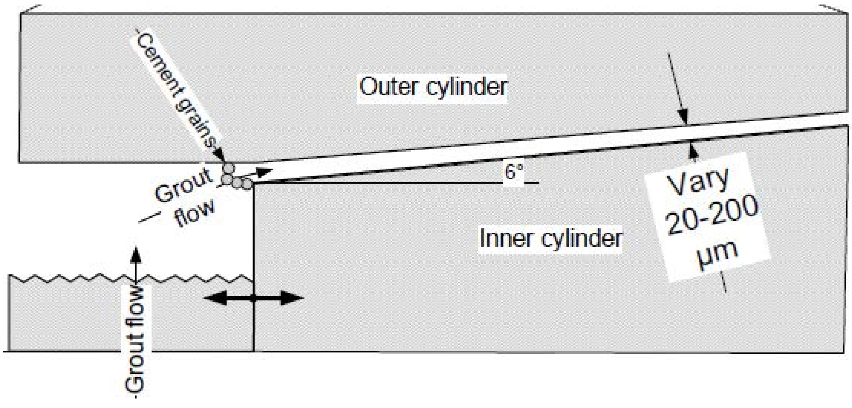


Figure 38. Enlargement of the inflow to the aperture (Draganovic, 2009).

It is different from the geometry in the NES method where filtration happens between the borehole and fracture. Besides, compared with NES and other methods, the PenetraCone test needs judgment from the operator when b_{filter} is determined. This is a drawback of this method (Draganovic, 2009).

2.4.7. Short Slot

Draganovic and Stille (2011) further developed the artificial fracture used in the NES method. A new short slot with two channels of penetration was formed by two bolted steel plates and there are two constrictions before the outlet of each channel as shown in Fig. 39. This means that the position that filtration occurs in a short slot will be different in the NES method. As mentioned in the NES method, grout grains tend to bridge between the borehole and fracture, whereas filtration will be expected in the constrictions of the short slot, which is more similar to that in rock fractures (Draganovic and Stille, 2011). As illustrated in Fig. 40, the assumed mechanism of filtration in the short slot is that grout particles would gradually arch from fracture walls at the reduction of width and eventually plug the flow path (filter cake).

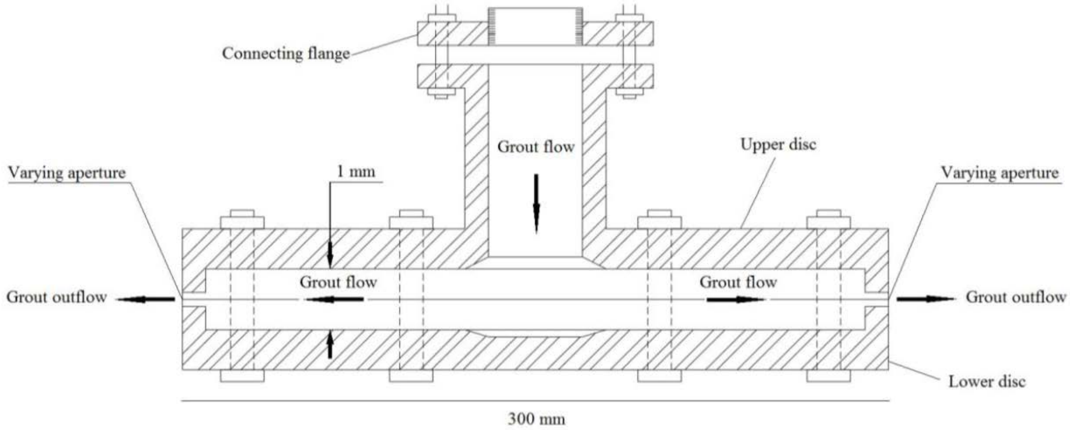


Figure 39. Cross-section of Shot slot (Mentesidis, 2015).

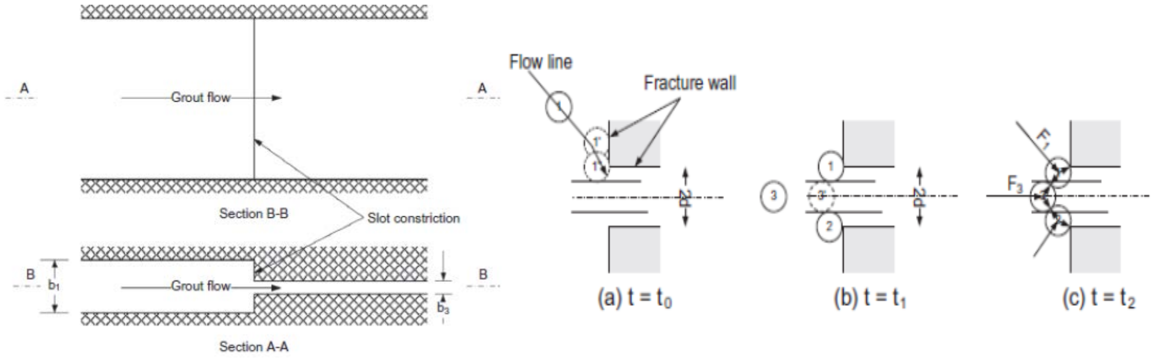


Figure 40. Formation of filter cake at constriction (Draganovic and Stille, 2011)

The rest of the components of the Short slot are the same as those in the NES method. The pressurized gas in a gas tank is used to push grouts from a grout container into the short slot. The grout container has a 2.6 l capacity and hangs on a load scale so that weight changes of the grout mix will be measured over time.

In the study of Draganovic and Stille (2011), three general parameters including b_{crit}, b_{min}, and k were used to evaluate the penetrability of grouts. Besides, they also indicated that filtration tendency can be distinguished from the time-weight diagram. The stable gradient in the diagram of time-weight suggests continuous grouting without filtration, while the non-linear relation between time and weight means variations of penetration rate, which could be caused by filtration (Draganovic and Stille, 2011).

2.4.8. Long Slot

Based on the idea of measuring penetrability with slot geometry, the Long Slot, developed by Draganovic and Stille (2014), was used to investigate the filtration tendency of cement-based grout in the same fashion as Short slot. This instrument is aiming to improve a shortcoming that the Short Slot method contains. As motioned in the last subsection, Short Slot designed with a constriction close to the outlet would simulate plug-formation in the fracture, but the length of the reduced aperture is relatively short compared with the distance from the borehole to constriction. To better simulate filtration tendency in rock joints, a much longer slot with 4 m length and 10 cm width is tested and compared with Short Slot and Penetrability Meter (Draganovic and Stille, 2014). As shown in Fig. 41 (a), before the reduced aperture (75μm) there is a two-meter slot with an aperture of 0.5 mm and a 30 mm long aperture (1 mm) which is to maintain a similar geometry to the short slot.

As for other equipment for testing including a gas container with a pressure regulator, a grout container, and four pressure gauges. After starting the experiment, a constant pressure of 1.5 MPa provided by compress nitrogen gas will press grout mix from the grout container into the slot so that grout flow can penetrate the slot and the magnitude of pressures are recorded along the slot (Draganovic and Stille, 2014).

The mechanism of plug formation or filtration in a long slot is almost the same as that in a short slot. Fig. 41b illustrates plug-building that occurs just before the constriction and stats at the edges of the slot. Meanwhile, plug formation will bring about a climb of pressure in front of it or a drop of pressure behind it. On the contrary, a decreased pressure before the plug or an increased pressure after the plug indicates an erosion of the partially built plug (Draganovic and Stille, 2014). Therefore, pressure variances measured before and after the constriction can be plotted against time during grouting and indicate the formation and erosion of the plug. For example, P2 and P3, located in front of and behind the constriction, will keep constant without filtration in the slot and fluctuate with filtration as shown in Fig.41 c & d. Meanwhile, the parameters used in the short slot (b_{crit} &b_{min}) is also a method to evaluate the penetrability of grouts.

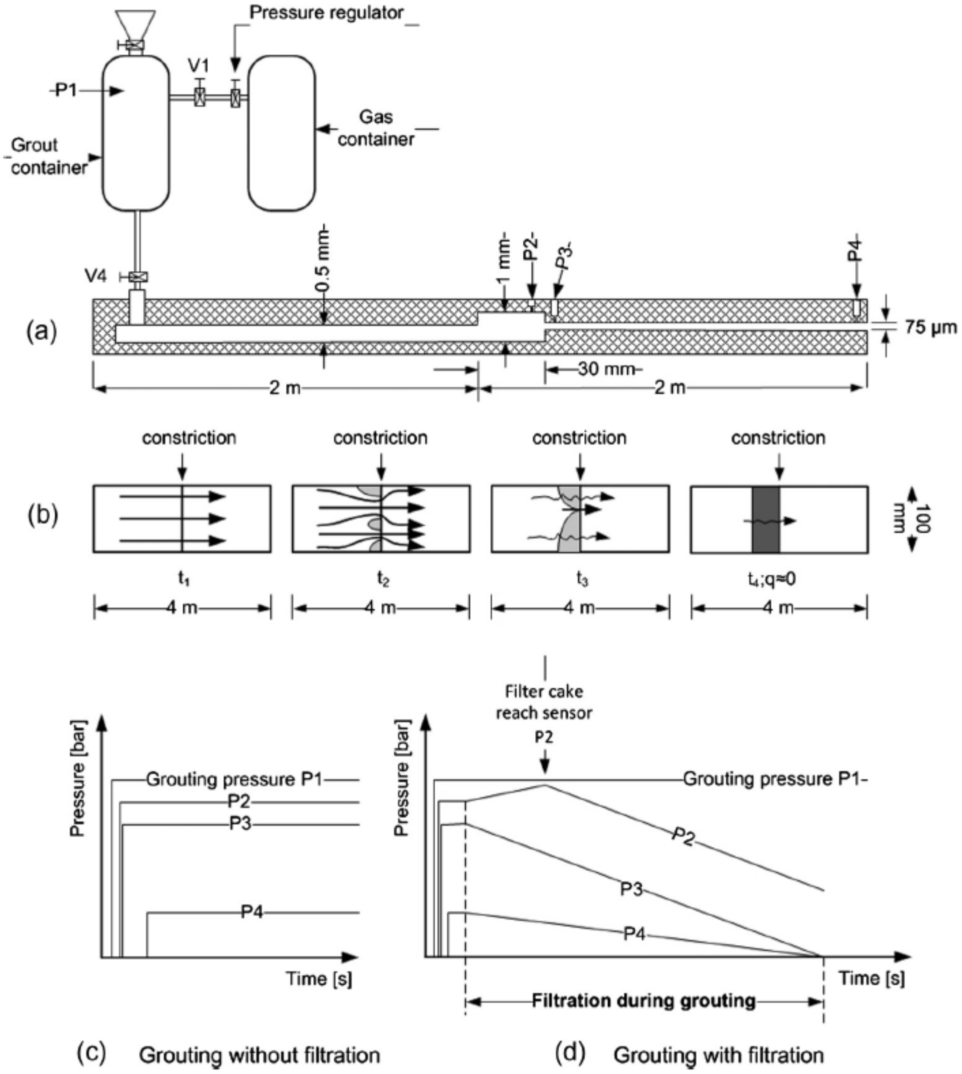


Figure 41. Long Slot section (a) plug formation (b), pressure variance along the slot (c) &(d) (Draganovic and Stille, 2014).

According to Draganovic and Stille (2014), grouts can more easily penetrate in the long slot compared with the short slot and penetrability meter. The short slot gives conservative results and the Penetrability Meter significantly overestimates the filtration tendency of grouts. Even though the Long Slot may not be suitable for daily measurements due to its complexity of instruments, the Long Slot probably gives the closest results to the truth (Draganovic and Stille, 2014).

2.4.9. Varying Aperture Long Slot (VALS)

In the light of the literature review, a newly developed method called varying aperture long slot (VALS) gives another alternative to investigate filtration tendency or penetrability of the grout. This method was proposed by Ghafar et al. (2017b) after further improvement of the Long Slot. Both instruments and evaluation methods have been refined compared with these in the Long Slot. Fig.42 presents an overview of the experimental setup.

As shown in the figure, the test apparatus mainly includes three parts. The first part is the pressure source, which is provided by nitrogen gas (2 MPa) in a container and controlled to remain constant (1.5 MPa) with a regulator during the grouting process. The second part is to supply grouting materials for tests. Connected with a nitrogen gas container, a grout tank with a capacity of 2.6 l is suspended from a load cell so that the weights of injected grout can be registered over time. Lastly, the VALS is an artificial fracture with the same dimension as the Long Slot but there are 11 constrictions in the slot. These varying apertures of 230-10µm are uniformly distributed along the slot and there is a 500µm chamber with an outlet (30 mm) before each constriction.

Besides, to monitor plug formation and erosion processes, 23 holes are drilled on the top plate. For each aperture, there is a hole before and one after the constriction. Therefore, the variations of pressure in front of and behind the constriction can be measured by pressure transducers in these holes, thus the filtration process can be distinguished. Without pressure transducer allocation, these holes are plugged with steel caps.

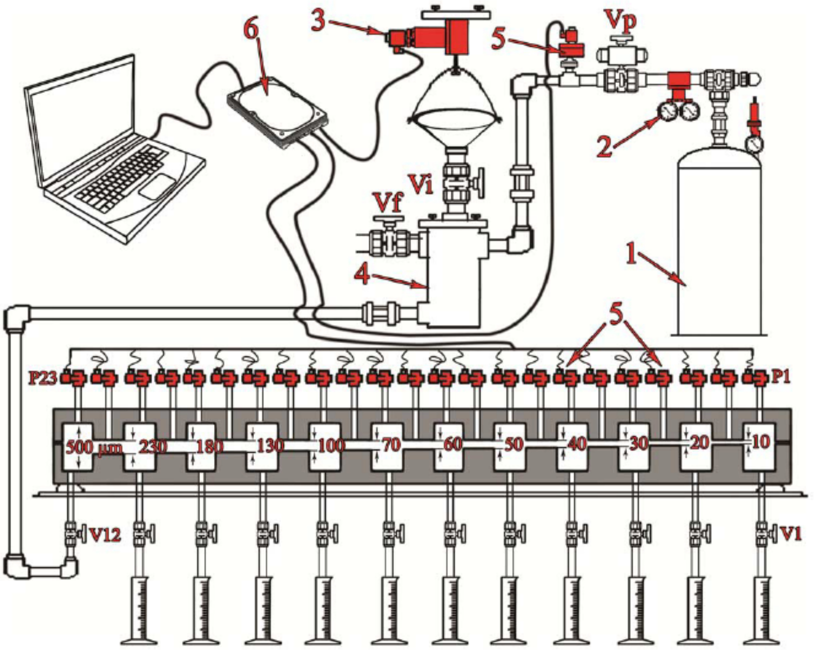


Figure 42. Depiction of the experimental setup (Ghafar et al., 2017b).

Apart from determining the filtration process by pressure variations close to apertures, the other two methods are simultaneously utilized to distinguish plug formation and penetrability of the grout.

The first method is to define filtration based on a weight-time gradient that represents the injection rate as shown in Figure 65. Linear relation meaning constant injection rate suggests no filtration and varying gradient implies plug formation or erosion. When the gradient tends towards zero, it indicates the stop of penetration. However, this method is only a guide during the test.

The other method uses b_{crit} and b_{min} to determine the penetrability of different grouts. At the beginning of the test, only V12 and V1 acting as inlet and outlet respectively are opened. Then the next valve (V2) is opened after the last outlet (V1) is closed. Follow the same procedure until finding the outlet in which the first drip of grout mix is collected. Hence the aperture just before the outlet is b_{min}. Similarly, the procedure is continued until no filtration is observed in a valve (stable gradient of the weight-time diagram), hence the constriction size before the valve represents b_{crit}.

Some advantages of VALS should be noted, for example, both constant and dynamic pressure can be applied for grouting in the test. Meanwhile, all outlets on the bottom of each chamber can be set as an inlet by controlling corresponding valves to be opened or closed. In addition, the VALS is able to determine the penetrability of grout with only one test using the same batch of materials, which makes it replicated and robust. Whereas the capacity of the gout tank and roughness of the slot (Ghafar et al., 2017b). are the two points that can be improved for better replication of rock grouting in the field.

2.5. Other grout properties important in rock grouting

2.5.1. Bleeding

There are various statements on the definition of bleeding but most of them express a similar meaning which is the separation of solid particles from the fluid. In most cases, water would be the fluid in grouts. The reason for separation is that cement particles in grouts are 3 times heavier than water (Lagerblad &Fjällberg, 1998), and these particles sink to the bottom of grouts due to gravity.

According to the height of clear water at the surface of the grout, bleeding is estimated. In general, the height of clear water is measured after a certain time and calculated by comparing the initial height of the grout. A method mentioned in the research of Widmann (1996) follows the same principle of which bleeding is measured by the percentage of ΔH (height of clear water)/ H (initial height of grout). The specific test setup is shown in Fig. 43 (a). One cylinder with a diameter of 60 mm is used for measuring the bleeding of different grouts with a volume of one liter. In another word, the initial height of the grout should be 353 mm. After a given time, the height of clear water is measured, and bleeding is calculated subsequently. This method is widely used in the industry thanks to its effectiveness and efficiency. However, more research is trying to determine whether the results measured by this method have relevance to bleeding in small fractures in the rock. For example, in Draganovic (2012) tests performed with a long slot, and the cylinder method is compared to investigate the correlation between these two methods.

Bleeding can be divided into two processes, sedimentation and consolidation, that happen at the same time (Powers, 1939; Tan et al., 1997). Sedimentation is a process when solid particles sink due to gravity and consolidation is a process when pore water is pushed out from space between particles due to overloads from later settled particles (Neubauer, et al, 1998). In addition, the extent of the bleeding is dependent on steric and repulsive forces between particles. Two factors contributing to attractive forces between particles and the formation of clumps or flocks in grouts are hydration and flocculation.

As one of the common phenomena occurring before concrete hardening, bleeding of concrete grouts is easily observed and could influence grouts' properties such as rheology and workability. Grouting is subsequently under influence of an increase of rheology at the bottom of grouts.

Cambefort (1977) explained how bleeding during grouting causes constrictions and blocks the flow path of grout in fractures as illustrated in Fig. 43(b). It is believed that sedimentation would be the main reason for bleeding and have an adverse impact on a horizontal flow of grout. Besides, Angelis & Mancini (1997) found that bleeding caused by sedimentation is more evident in a low-velocity flow than in a high-speed flow.

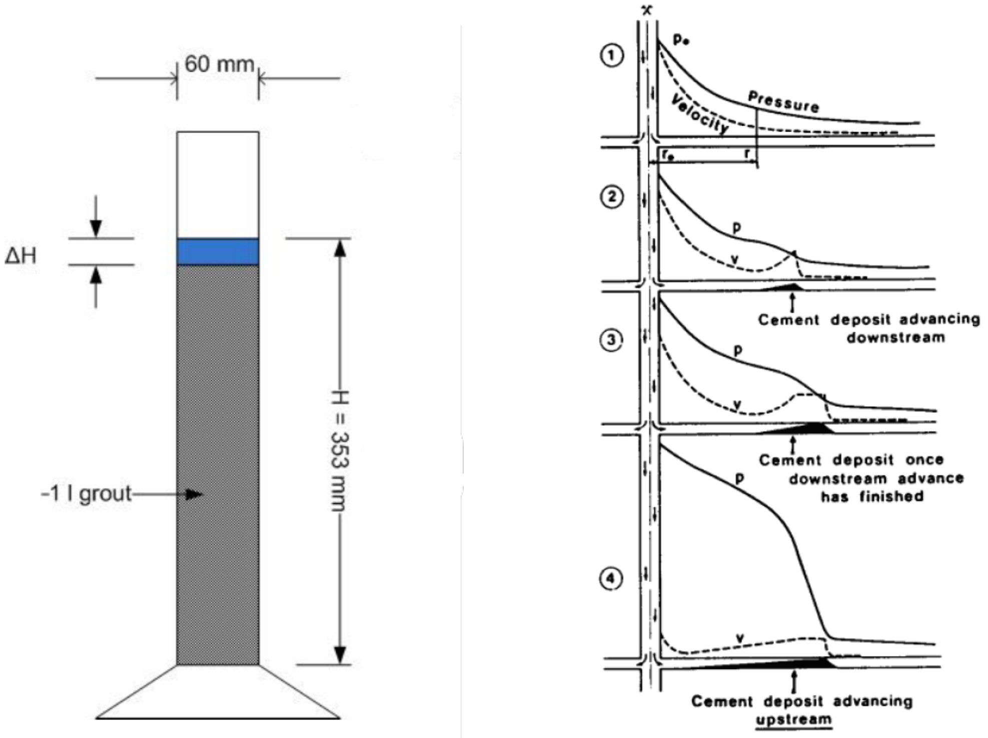


Figure. 43(a) Figure. 43(b)

Figure 43. (a) Formation of constrictions due to bleeding during grouting (Cambefort, 1977); (b) Bleeding test method according to Widmann (1996).

On the other hand, bleeding could also result in open voids in the flow path even after the desired penetration is achieved. This will reduce the sealing effect of grouts. Whereas, in the study of Draganovic (2012), bleeding is measured both in a long slot and a cylinder. The voids in the fractures caused by bleeding have been proved to be at least partially refilled during grouting. Lastly, another conclusion dawned from performed tests is that high bleeding tends to be impossible in small vertical fractures due to the resistance from arching and hydration (Draganovic, 2012).

In summary, even though bleeding is an unavoidable phenomenon during rock grouting, the bleeding is considerably less in rock fractures.

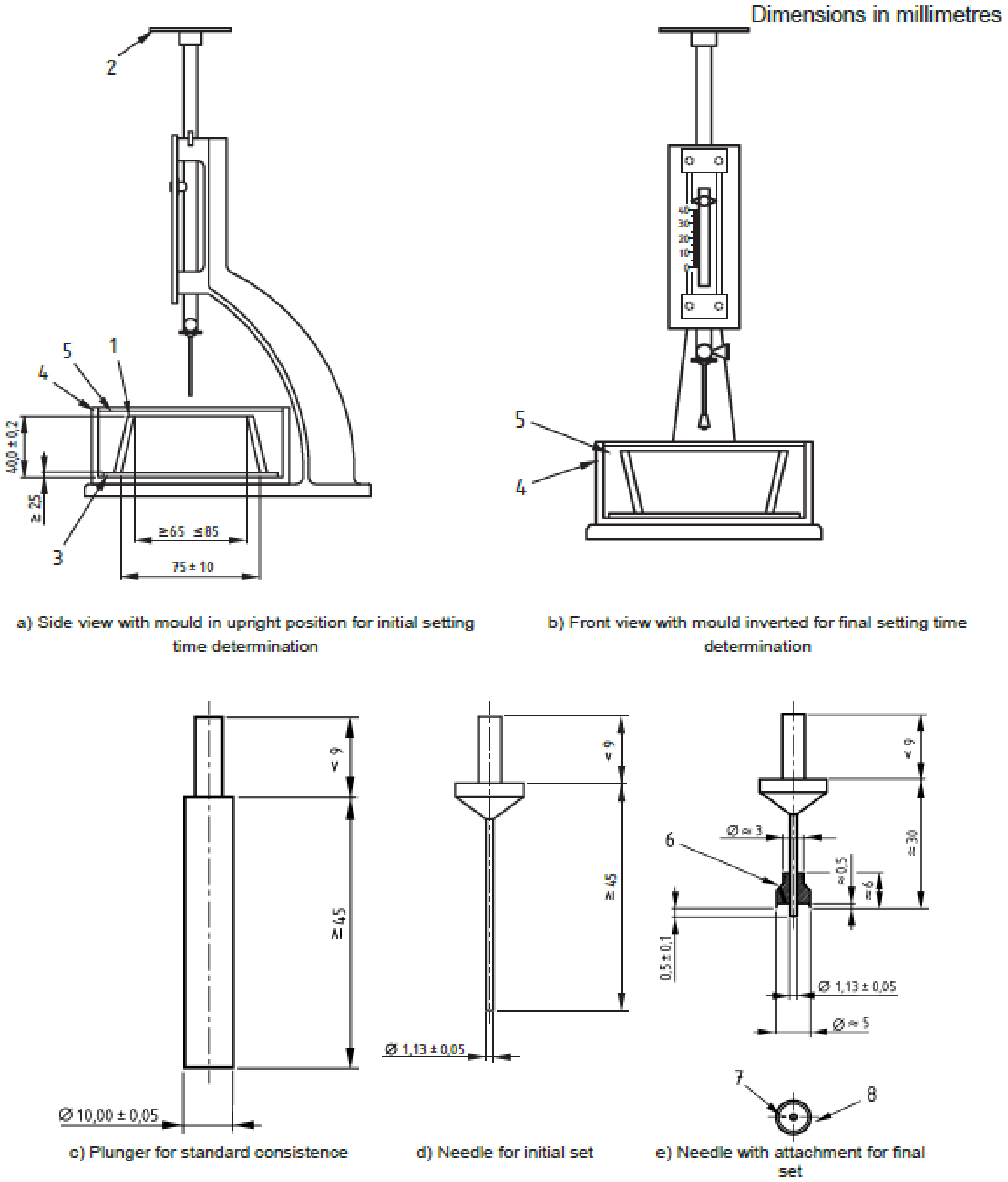
2.5.2. Setting time

Cement-based grout is an intermediate state in which mixed cement has just turned into fluids from solid particles after the addition of water but still doesn’t become concrete. The period between the addition of water and the initial hardening of cement is called the setting time of cement or the setting time of concrete. During the setting of cement, there are three main stages with different chemical reactions, including hydrolysis and hydration of cement compounds, colloidisation of hydration products, and crystallization of most compounds in the grouts. Accordingly, setting time is divided into two phrases depending on the degree of chemical reactions and workability of cement.

The two phrases include initial setting time and final setting time. Typically, the setting time is measured by the penetration resistance of grouts that change with time. Two testing methods, Vicat Needle and Proctor Penetration Resistance are standardized in EN 196-3:2005 and ASTM C 403-88 respective. They share the same principle but with different specifications and procedures. In this thesis, the apparatus for Vicat Needle testing is shown in Fig. 44. With that, the setting time is measured with fixed intervals from the addition of water until the penetration of a needle into cement paste reaches a stipulated value. For the initial setting time, it is measured from the addiction of water until the needle has a distance (around 6 mm) from the base plate. And the final setting time is the period elapsing between the time when water is added and the time when the needle first penetrates only 0.5 mm into the specimen according to EN 196-3:2005 and BS EN 196-3:2005.

There are more methods proposed by different researchers with the development of computer technologies. For example, impact-echo methods, ultrasonic pulse velocity methods, and wave reflection methods can be used to measure the setting time of cement and have the advantage of continuous monitoring, which is tiresome for the Vicat Needle test (Trtnik et al., 2008).

From the rheological point of view, the initial setting time is the time when the workability and plasticity of grout paste start decreasing. Meanwhile, viscosity and yield stress will increase dramatically until the grout pastes completely lose its plasticity and workability at the final setting time. As motioned in the section of grout rheology, penetration of grouting highly depends on grout viscosity and yield stress. More specifically, high viscosity and yield stress have an adverse impact on grout’s penetration into small fractures because filtration is more likely to happen with larger clusters in grout and the head of grout needs more pressure to move forward. Therefore, the initial setting time of cement is of extreme importance for rock grouting. If a better penetrability is expected, more time before the beginning of dramatic changes of rheology in grout paste is required. In another word, the longer initial setting time is preferable. In terms of final setting time, most types of cement have measured values of over hundreds of minutes, which is considerable compared with grouting time. So, the final setting time doesn't have too much influence on the penetrability of cement-based grout.



a) Side view with mould in upright position for initial setting time determination

b) Front view with mould inverted for final setting time determination

c) Plunger for standard consistence

d) Needle for initial set

e) Needle with attachment for final set

Key
1 Mould
2 Correcting weights
3 Base plate
4 Container
5 Water
6 Air vent (Ø ≈ 1,5)
7 Air vent
8 View from below needle with attachment for determining final setting time

Figure 44. Vicat Needle apparatus for determination of setting time (BS EN 196-3:2005).

2.5.3. Temperature

The temperature has been demonstrated to be another factor that can influence rock grouting on rheology, filtration stability, setting time, and bleeding of grouts. On the other hand, taking temperature into account for rock grouting is because the changes in temperature in different seasons and areas can be considerable. For example, in Nordic countries, the tunneling environment has a temperature of 8 °C to 20 °C (Bohloli et al., 2019). Compared with the indoor temperature, around 20 °C, grouts will be exposed to a relatively cold environment in tunnels. However, the temperature in the rock mass increases with the depth below the ground surface and can reach 45 °C in the depth of 1500 m where the mine tunnels are constructed and sealing of rock fractures is extremely crucial (Xu et al.,2020). Therefore, investigation of the influence of temperature on grouting would be the basis of practical work.

As mentioned in the previous subsection of rheology, viscosity, and yield stress are two parameters that could be employed to characterize the rheological properties of grouts. Accordingly, the influence of temperature on rheology could be investigated based on the research of relations between temperature and these two parameters. Xu et al. (2020) conducted a series of experiments with the same type of cement mixing with various amounts of water at 12°C, 25°C, 35°C, and 45°C, respectively. To determine viscosity by the ratio of shear stress to shear rate, a rotary viscometer is utilized to measure the shear stress with torque at a given shear rate. The experimental results show that an increase in temperature has more distinct impacts on thick grouts ($w/c \leq 0.8$) than thinner grouts ($w/c \geq 1.0$). In other words, the viscosity variation of thick grouts is more pronounced. In general, the viscosity of thick grouts ($w/c \leq 0.8$) would increase with temperature, and a similar trend is observed from yield stress. Nevertheless, for grouts with $w/c \geq 1.2$, measured viscosity decreases when the temperature goes up to 45 °C. A possible explanation is that temperature increases the average kinetic energy of the molecules in the grouts. The greater average kinetic energy of the molecules more easily overcomes the attractive forces that tend to hold the molecules together.

The same question has been studied by Bohloli et al. (2019). By comparing three different types of cement mixed with w/c ratios of 0.6, 0.8, 1.0, 1.2, the viscosity of these grouts at both 8 °C and 20 °C was measured. In accordance with results from Marsh cone, rheometer, and Spread ring, a consistent trend that cement grouts have lower viscosity at 8 °C than those at 20 °C was revealed. This agrees with the results from Xu et al. (2020). One of the possible reasons is that surface hydration of thick grouts at lower temperatures maintains at a low extent so that the workability of thick grouts is better in a colder environment.

Bohloli et al. (2018) also performed a systematic laboratory study to compare the filtration of cement-based grouts with different w/c ratios in both indoor and outdoor environments. The grout recipe and temperature setting used in this study were the same as in Bohloli et al. (2019). Whereas the API filter press test method (shown in Fig. 45) was employed instead of using a filter pump. Even though these two methods share a similar principle and evaluation approach, the author advocates filter press has better control of pressure. From experiments, the difference of filtration for all cement grouts at 8 °C and 20 °C is hard to observe. In contrast, the w/c ratio and grain size distribution were found to impact filtration considerably.

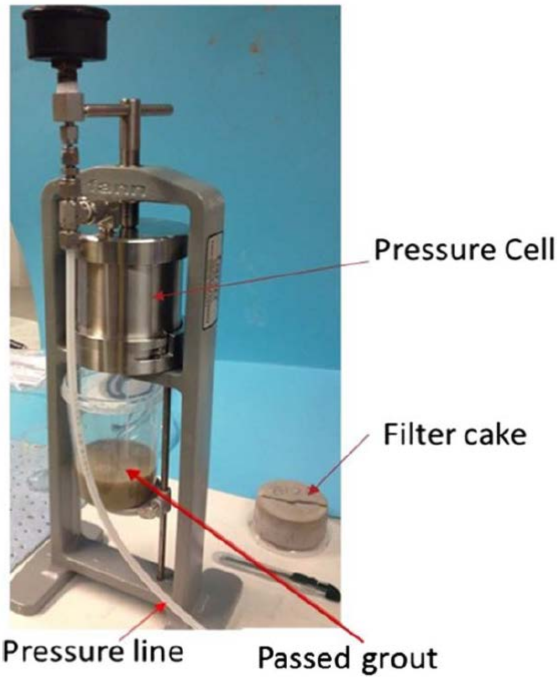


Figure 45. An API low pressure 300 filter press apparatus (Bohloli et al., 2018)

Regarding the impact of temperature on setting time, the discussion is more inclined to initial setting time, and some research related to that is summarized here. For example, experimental results from Bohloli et al. (2019) revealed a negative relation between setting time and temperature. Grouts mixed and cured at the temperature of 20 °C set faster than those at the temperature of 8°C, even though the differences of setting time in the two environments could vary depending on cement types. However, in this study setting time was estimated by an index called significant temperature increase, which is not accurate as Vicat needle. In addition, Wang et al. (2015) also investigated the relationship between setting time and temperature in four different scenarios. Both the initial and final setting times of cement-based grouts decrease with a temperature rise. Especially for the grout with a temperature below 8°C, a dramatic change of setting time can be observed when the temperature increased. Again, this agrees with the conclusion from Bohloli et al. (2019). Therefore, the adverse impact of the tunnel environment on setting time should be taken into consideration when the better penetrability and early strength of the grouted mass are essential.

In fact, the extent of bleeding of grout mainly depends on the speed of hydration. Subsequently, the temperature will make an impact on the hydration of grouts. Wang et al. (2015) used cement-based grout to measure the bleeding extent under the temperature of 2°C, 8°C, 15°C, and 22°C and found that grouts at lower temperatures show more bleeding than these in the hotter environment. This means the low temperature in tunnels contributes to harder control of bleeding. However, according to the previous investigation in the subsection of bleeding, it is considerably less in rock fractures. As a result, the penetrability of grout should not be largely influenced by changes in bleeding due to lower temperatures.

3. HISTORY OF DYNAMIC GROUTING

After finding the limitation of static pressure grouting, researchers turned their attention to other injection methods to gain a better penetrability of grouts in apertures smaller than 0.1 mm. In order to achieve that objective, it requires a very low viscosity and yield stress of the substance during grouting operation. Inspired by a technique that is based on the vibration of pressurized grouts for sandy silts, a rock grouting technique called dynamic injection was proposed by Pusch et al. (1985).

They assumed that by combining constant pressure and superimposed shear waves, the viscosity will be reduced, and grouting material could penetrate further in fractures. Thus, several tests were performed to verify this hypothesis. After a comprehensive series of viscosity tests on various materials, the main components of grouting materials are determined as bentonite, quartz powder with a grain size smaller than 50 µm (called filler in the study), and a low alkali cement with particles size smaller than 75 µm.

Meanwhile, joints and fractures in rock can be simplified as plane slots and this can be simulated by constant aperture between two plates (as shown in Fig.46). Pusch et al. (1985) used two bolted concrete slabs together with small ring-shaped foils to keep the distance. Different foils in different tests yielded the desired fracture's size and a 20 mm pipe was cast in the center of the upper slab, where the grout was injected.

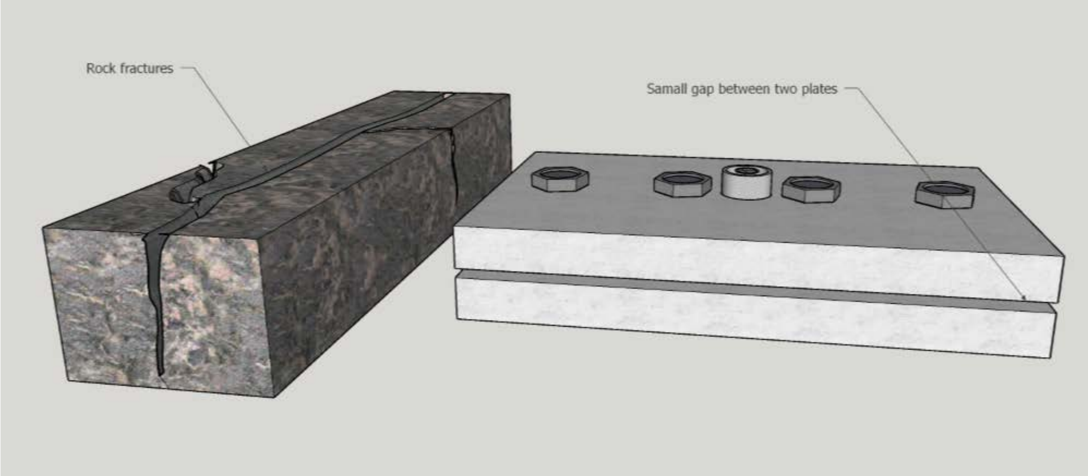


Figure 46. Simplification of rock fractures and joints with concrete slabs

As for experimental equipment, shows in Fig. 47, a hydraulic jack with a tightly fitting piston was utilized to provide static pressure (0.7-0.8 MPa) through compressed air and dynamic pressure was produced by a TEX-50 percussion machine. According to the authors, the percussion machine has a frequency of 1170 blows per minute, which can be translated into around 20 Hz. The steel cylinder was connected to a grout container in which the slurry was applied, and then to the pipe in the concrete slab. By pulling the piston, the cylinder can be filled when valve 1 is opened and valve 2 is closed. And during the injection process, valve 1 was closed and a free passage opened to the injection point. Afterward, static and dynamic pressures were imposed on the back of the piston so that grout flows into the slot. Lastly, the injection pressure is measured by a piezoresistive transducer after valve 2. After each test, concrete slabs would be separated and penetration depth would be measured.

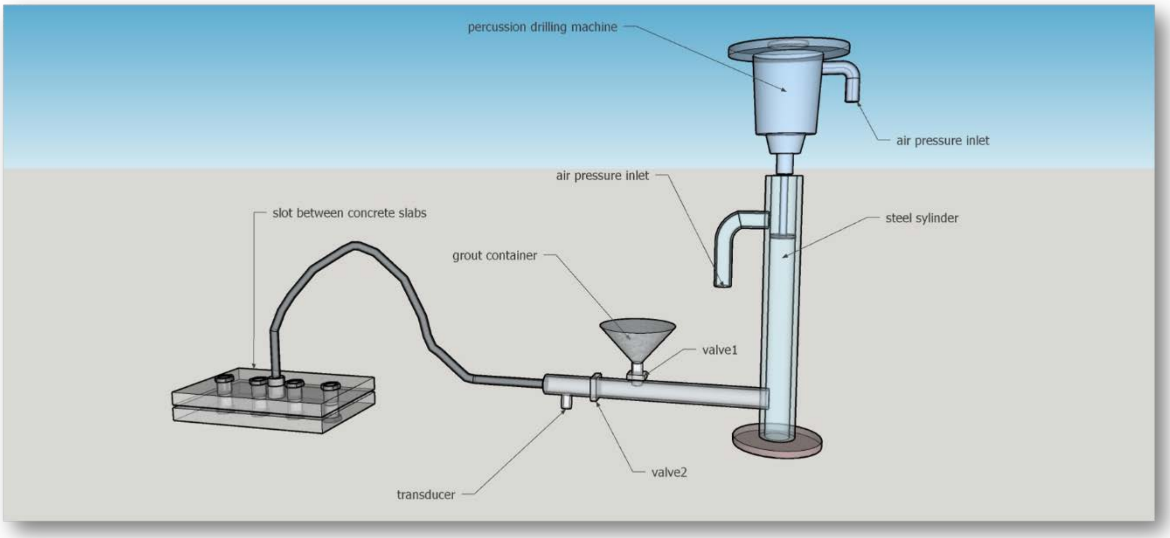


Figure 47. Configuration of experiment equipment according to Pusch et al. (1985).

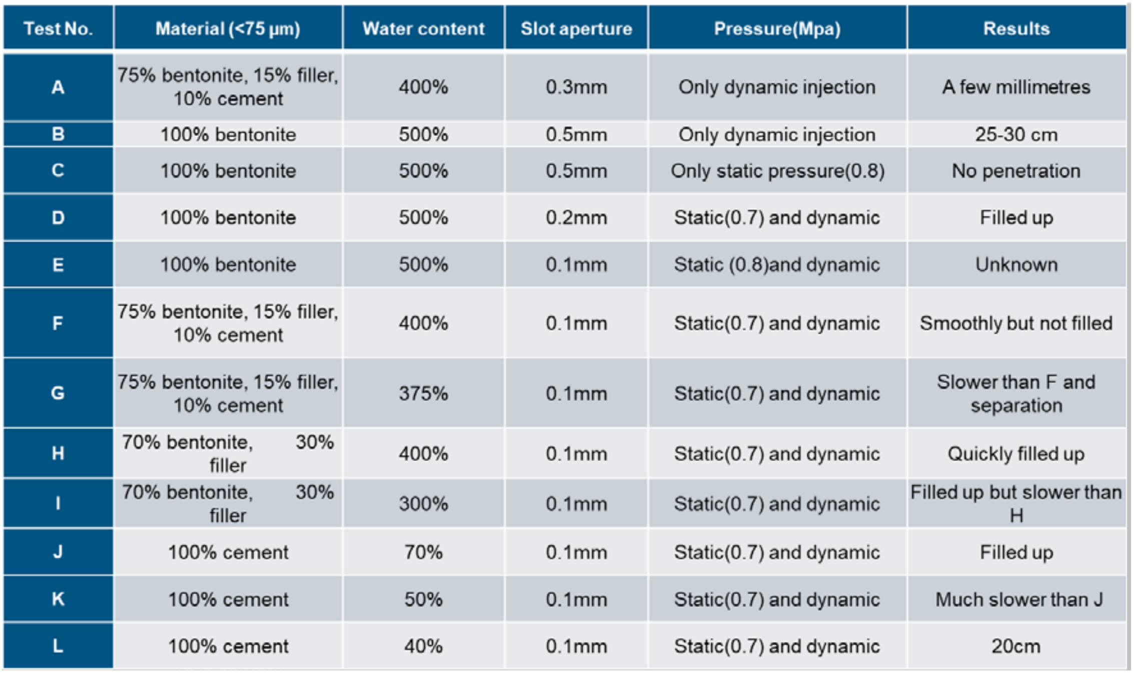
In this investigation, twelve tests were made (Table 6). For the first two tests, A and B, no static pressure was applied, only the percussion was in operation with 0.7 MPa air pressure. And both results showed insignificant penetration of grouts under this condition. The possible reason is that the pressure waves induced by the percussion did not seem to reach through to the injection point and the energy input was insufficient to make the slurry move deep into the slot. In test C, only static pressure was applied but no penetration was observed.

Therefore, to transfer dynamic pressure further in the slot, an attempt to combine hammering operation with constant pressure was tried in test D and the effect was very good. The slurry filled up and flowed out of the slot within a few seconds. In test E, a smaller slot aperture was planned to further investigate the effect of this method, however, the result was not presented in the report.

As for tests F and G, the same mixture with different water content was injected into 0.1 mm fracture and the grout behaved as mixtures in test E. However, due to lack of prepared mixture, the injection was shortly terminated which makes additional injection after pause impossible. Besides, it was observed that lower water content would result in slower penetration and even separation of components in the grouting slurry. The same tendency can be observed in tests H and I.

The last three tests were purely based on cement material, and the water content was reduced from 70% to 40 % in order to investigate penetration limitation when static and dynamic pressure was imposed. For cement with 70 % water content, grouts filled up the slot as expected. Whereas the penetration rate drops quickly with a decrease in water content until the penetration limitation was reached and only about 20cm penetration was able to achieve even a larger percussion machine was used.

Table 6. Summary of injection tests performed by Pusch et al. (1985).



Test No.	Material (<75 µm)	Water content	Slot aperture	Pressure(Mpa)	Results
A	75% bentonite, 15% filler, 10% cement	400%	0.3mm	Only dynamic injection	A few millimetres
B	100% bentonite	500%	0.5mm	Only dynamic injection	25-30 cm
C	100% bentonite	500%	0.5mm	Only static pressure(0.8)	No penetration
D	100% bentonite	500%	0.2mm	Static(0.7) and dynamic	Filled up
E	100% bentonite	500%	0.1mm	Static (0.8)and dynamic	Unknown
F	75% bentonite, 15% filler, 10% cement	400%	0.1mm	Static(0.7) and dynamic	Smoothly but not filled
G	75% bentonite, 15% filler, 10% cement	375%	0.1mm	Static(0.7) and dynamic	Slower than F and separation
H	70% bentonite, 30% filler	400%	0.1mm	Static(0.7) and dynamic	Quickly filled up
I	70% bentonite, 30% filler	300%	0.1mm	Static(0.7) and dynamic	Filled up but slower than H
J	100% cement	70%	0.1mm	Static(0.7) and dynamic	Filled up
K	100% cement	50%	0.1mm	Static(0.7) and dynamic	Much slower than J
L	100% cement	40%	0.1mm	Static(0.7) and dynamic	20cm

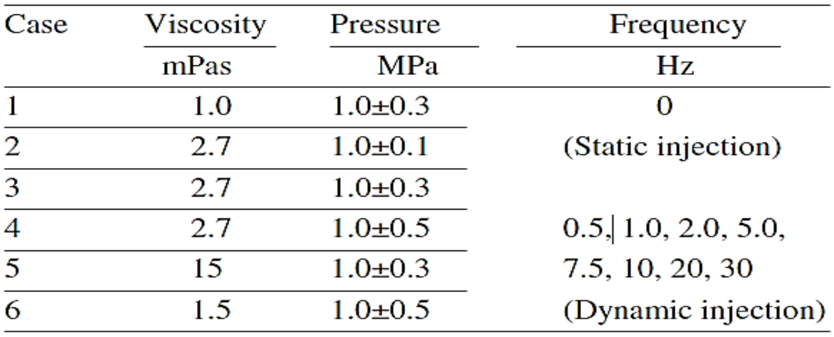
Besides, it can be observed from disassembled concrete slabs that the degree of filling is very high and uniform because of the changing viscosity of the grouts under dynamic pressure (Pusch et al.1985). At the same time, dynamic injection increases the aperture of the fracture temporarily, and the rebound of the rock after pressure release is expected to distribute and consolidate the grouting over the entire cross-section.

In summary, all tests have primarily validated the effects of dynamic injection to improve the penetration of grouts in narrow fractures. Nevertheless, additional research is required, particularly with respect to the efficiency of the grouting equipment and the composition of the grouts. A percussion machine with higher or lower frequency should be tested and much research remains to be done in order to test the longevity of the filling substances.

Wakita et al. (2003) conducted a series of laboratory and field tests to investigate the effect of dynamic grouting in low permeable rock masses. The mechanism of improvement of penetration, oscillating pressure can reduce the viscosity of grouts and prevent the formation of clogging, was proposed in this paper.

A new test apparatus together with grouting equipment were applied in the laboratory tests. A single slot (100μm) with a 2m length was created by two stainless steel plates and 8 pressure gauges were installed on the top to measure the dissipation along the flow direction. The static pressure (1 MPa) generated by the air cylinder was superimposed to oscillating pressure from a servo-cylinder. Different amplitude and frequencies were applied to investigate their effects on penetration. The detailed test plan is shown in Table 7.

Table 7. Test cases in Wakita et al. (2003)



Case	Viscosity	Pressure	Frequency
	mPas	MPa	Hz
1	1.0	1.0±0.3	0
2	2.7	1.0±0.1	(Static injection)
3	2.7	1.0±0.3	
4	2.7	1.0±0.5	0.5, 1.0, 2.0, 5.0,
5	15	1.0±0.3	7.5, 10, 20, 30
6	1.5	1.0±0.5	(Dynamic injection)

Meanwhile, to study the effect of viscosity on penetration rate and depth, cellulose solution with fixed viscosity and water (1mPas) were compared with super fine cement grouts.

From the results of the tests (Fig.48), a large improvement of flow rate was observed when high viscosity material or big amplitude oscillating pressure is used. Also, it was found that higher frequency oscillating pressure would result in faster dissipation along the slot.

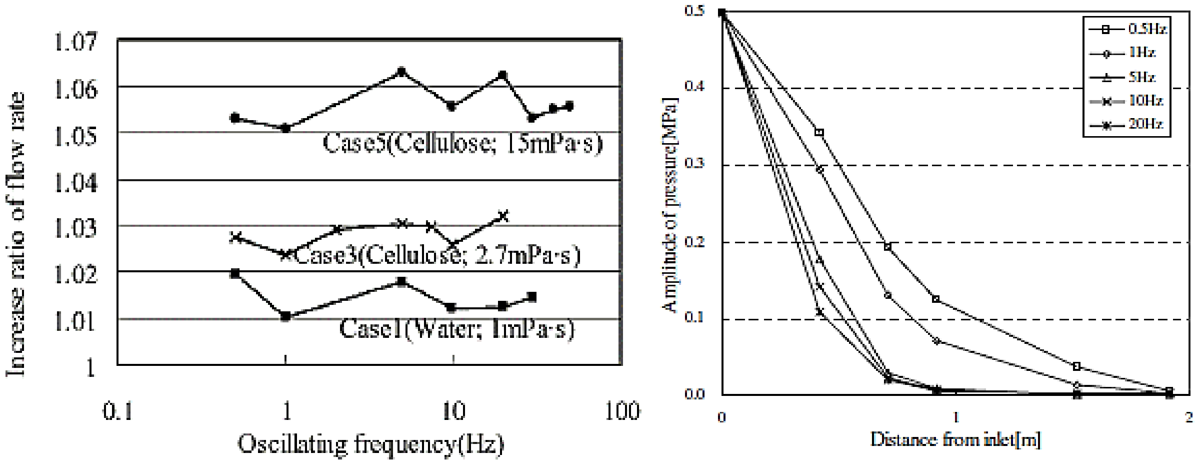
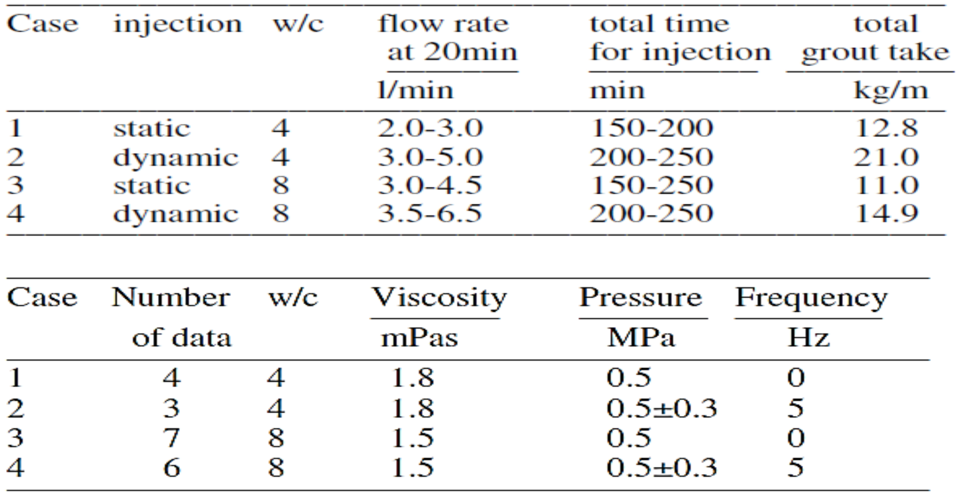


Figure 48. Laboratory test results from Wakita et al. (2003)

In the second stage, Wakita et al. (2003) verified the results obtained in the laboratory with more field tests in low-permeable rock masses. The test plan and results are shown in Table 8.

Table 8. Field test plan (upper) and injection results (lower) Wakita et al. (2003).



Case	injection	w/c	flow rate at 20min	total time for injection	total grout take
			l/min	min	kg/m
1	static	4	2.0-3.0	150-200	12.8
2	dynamic	4	3.0-5.0	200-250	21.0
3	static	8	3.0-4.5	150-250	11.0
4	dynamic	8	3.5-6.5	200-250	14.9

Case	Number of data	w/c	Viscosity	Pressure	Frequency
			mPas	MPa	Hz
1	4	4	1.8	0.5	0
2	3	4	1.8	0.5±0.3	5
3	7	8	1.5	0.5	0
4	6	8	1.5	0.5±0.3	5

A comparison between static and dynamic grouting pressure was made in the flow rate and total grout take. The flow rate with w/c of 4 under dynamic conditions is 135 % larger than static pressure, and the injection time is 120 % longer. As a result, the total grout take was largely improved from 12.8kg/m to 21 kg/m. To better demonstrate the improvement of grout take during injection, the averaged grout take in unite time against time was plotted (Fig 49).

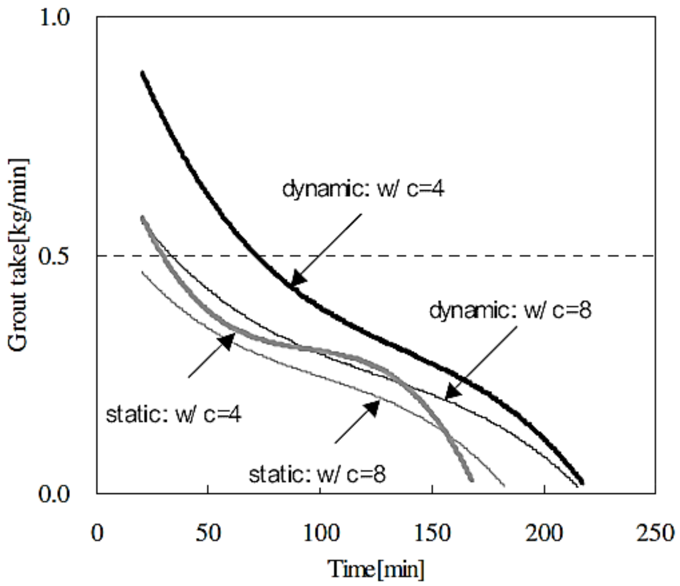


Figure 49. Average grout take in a unit time (Wakita et al., 2003)

In conclusion, dynamic grouting not only improves the penetration rate but also the volume of grouts, which means more efficient and effective than static pressure (Wakita et al., 2003).

3.1 M1-High frequency oscillatory pressure

In 2015, Mohammed et al. (2015) followed the research of Pusch et al. (1985) and tried to solve the remaining questions from previous experiments of dynamic grouting. Their study investigated the composition and performance of low-pH cement-based grouts in laboratory experiments through new slot equipment.

The objective of the study was to achieve better sealing of rock fractures around highly radioactive waste cans. Therefore, it is very important to consider the longevity of grouts at least 100 years and select proper grouting materials different from Portland cement. Thus, Merit 5000 low-pH cement together with quartz powders and milled talc are utilized as the main components for the grout in the study. Two recipes, named R1 and R2, were prepared for the experiment and the water content of R2 differentiated it from R2 (Mohammed et al., 2013).

Following the same principle of equipment (concrete slabs) used for investigating the improvement of grouting in Pusch et al. (1985), a new artificial fracture was made. As Fig. 50 illustrates, two stiff plexiglass discs with 0.5 m diameter were bolted together so that a space between them was created by using thin rings. The author prepared 3 different rings so that apertures of 100, 250, and 500 μm are created. One advantage of this equipment is that the penetration process of grouts in the slot can be directly observed with bare eyes, even though variations of aperture and mineral coatings in the real fractures are not able to be replicated by this equipment.

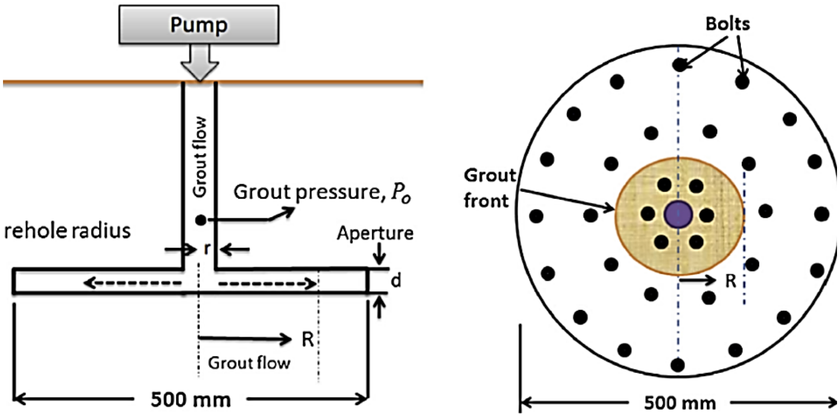


Figure 50. The geometry of the artificial fracture (Mohammed et al., 2015)

The configuration of experimental equipment is shown in Fig. 51. The static pressure can reach 500 kPa with additional dynamic pressures up to 1.5 MPa. A more detailed description of the experimental setup can be found in Mohammed et al. (2015).

Before the beginning of the grouting experiment, a series of tests were conducted to determine the rheological properties of grouts. A rotational viscosimeter was used to measure the rheological properties of grout material under static and dynamic conditions. Without vibration, test results show that the grout R2 has a lower viscosity (0.31Pas) compared with R1 (0.92Pas).

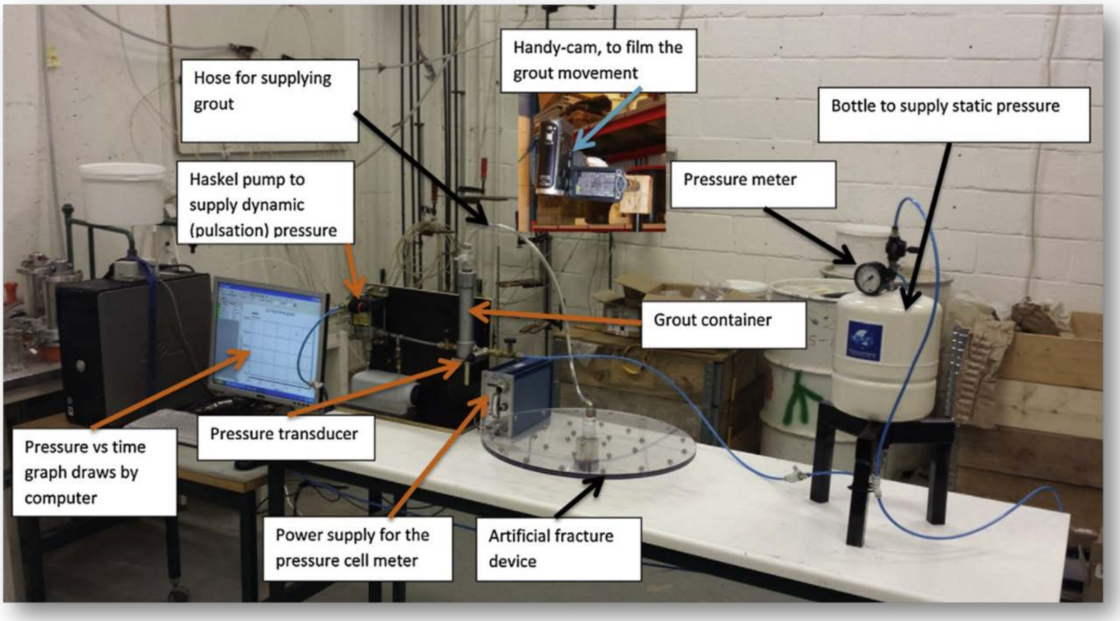


Figure 51. Configuration of experimental equipment (Mohammed et al., 2015).

However, under the vibrations with a frequency of 14-17Hz, the shear stress of R1 and R2 still increased linearly with the shear rate but the yield stress of grouts dropped down to around zero, which means that grouts R1 and R2 turned into Newtonian materials from Bingham. On the other hand, the viscosity of R1 and R2 increased to 2.4 Pas and 0.96 Pas. These implied that oscillation could contribute to lower yield stress of grout.

During the tests, two grouts, R1 and R2, were injected into 3 different apertures respectively. 300 kPa pressure was applied in static tests for 30 s, and a dynamic pressure with a frequency of 10-50 Hz was imposed on static pressure during dynamic injection. A pressure transducer would, during each test, record the pressure changes.

Make a comparison of the penetrability of grouts between two injection methods, it was shown that the grouts penetrated faster when dynamic pressure was imposed. Two pictures (Fig. 52) taken by the camera above fracture showed two distinct penetration depths of grout R1 with different injection methods. The picture on the left showed a much larger and axisymmetric penetration pattern in the 100 μm fracture. However, the author did not mention the specific frequency of dynamic pressure used in the experiment.

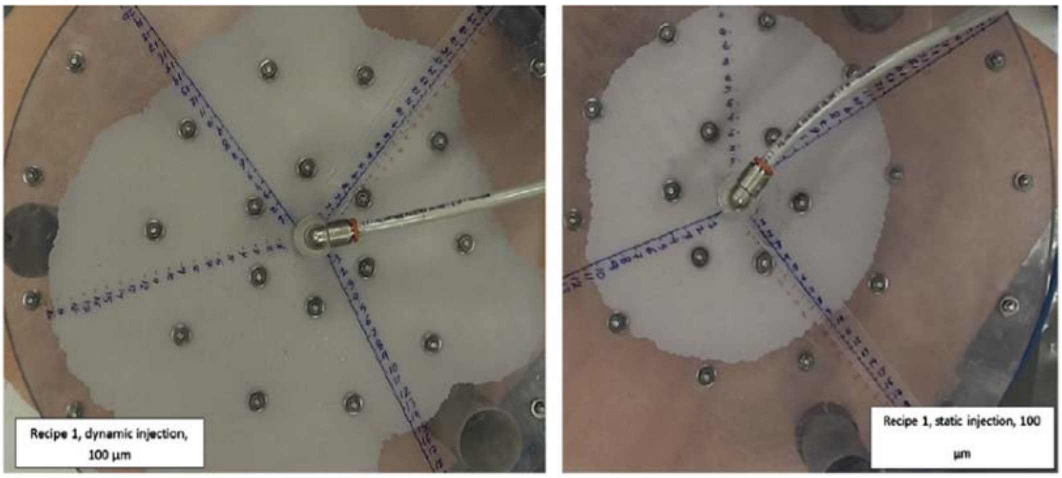


Figure 52. Penetration pattern of R1 with two different methods (Mohammed et al., 2015).

In Table 9, all detailed test results of penetration in different slots are demonstrated. There are several interesting findings. Within the first 25 s, dynamic grouting as expected gave faster grout flow than static pressure for all apertures and made a deeper penetration in the aperture of 500 µm. Nevertheless, as for the grouts in 100 µm and 250 µm, static pressure gave a better injection range than dynamic pressure after 35s. This made the author conclude that static pressure is preferable if the fracture is smaller than 100 µm and dynamic grouting should be applied at the early stage of injection for the apertures between 100 -500 µm. However, the author did mention the possible reason.

Table 9. Comparison of penetration depth between dynamic and static grouting (Mohammed et al., 2015).

Time (s)	Radial front movement of the grout (m) with differences ratio (%)								
	100 µm			250 µm			500 µm		
	Static	Dynamic	%	Static	Dynamic	%	Static	Dynamic	%
5	0.075	0.117	56	0.109	0.133	22	0.093	0.139	49.4
10	0.113	0.156	38	0.131	0.163	24	0.128	0.168	31.2
15	0.137	0.172	26	0.160	0.185	17	0.159	0.197	24.0
20	0.156	0.181	16	0.189	0.205	8.4	0.187	0.226	21.0
25	0.173	0.188	8.6	0.217	0.224	3.2	0.213	0.253	18.7
30	0.186	0.194	4.3	0.243	0.242	−0.4	0.238	0.279	17.2
35	0.198	0.200	1.0	0.267	0.259	−3.0	0.262	0.304	16.0
40	0.208	0.205	−1.4	0.290	0.276	−4.8	0.284	0.328	15.5
45	0.216	0.211	−2.3	0.312	0.293	−6.0	0.305	0.352	15.4
50	0.224	0.215	−4.0	0.332	0.309	−7.0	0.326	0.375	15.0

Apart from dissipation in narrow fractures, another potential reason could be the faster hydration caused by the increased temperature in the grouting. With consideration of molecular dynamics, high-frequency oscillation will bring energy to the molecules and increase the speed of molecular motion (Prausnitz et al.,1999). As a result, more heat is produced from friction in this process even though the temperature might not go up depending on the heat conduction of the environment. Therefore, after starting the grouting for a while, the heat produced by high-frequency oscillation could induce the increase of viscosity and thus adverse impacts on penetration, especially in narrow factures with less volume of grout suspension and heat exchange. This is a good answer to the reason why the high frequency of oscillation seems more efficient at first 25s in narrow slots, compared with static pressure, and then starts having adverse impacts on penetration.

Therefore, finding a suitable frequency of oscillatory is critical for further investigation.

3.2 M2-Low-frequency rectangular pressure impulses

Apart from high-frequency oscillation pressure, grouting with low frequency, in contrast, might be effective to reduce the clogging of particles or filtrations in fine fractures. Ghafar et al. (2016) firstly investigated the effect of low frequency instantaneous variable pressure (shown in Fig. 53) on grouting penetration with laboratory tests.

Different from the mechanism of improvement of grouting penetration by reducing the viscosity of grouts, low-frequency pressure with longer cycle periods i.e., longer peak or rest periods, could change flow pattern and velocity of grout and contribute to the efficiency of grouting (Ghafar, 2016).

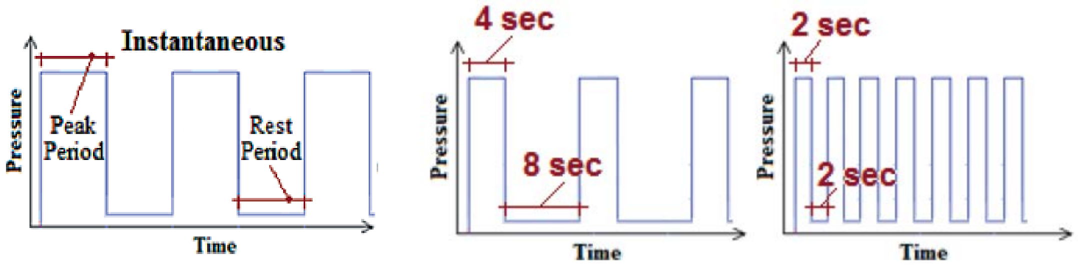


Figure 53. Instantaneous variable pressures from Ghafar et al. (2016).

In this study, the test apparatus is based on the modified NES method, while two constriction sizes of 30 µm and 43 µm were created by disc-shaped parallel plates. In addition, a pressure control system was programmed to obtain different peak and rest times.

Tests have been divided into two groups, C and V groups, representing grouting with static pressure and dynamic pressure respective and the maximum pressure for both groups is 15 bars. In the dynamic pressure condition, 4s/8s peak and rest periods of pressure were tested in V1 and V2 while the dynamic pressure with 2s/2s peak and rest periods were tested in V3 and V4. The grout is comprised of cement of INJ30 (d_{95}=30 µm) with w/c of 0.8 and 0.5% concentration of superplasticizer.

To evaluate the penetrability of grout under different types of pressure, other than the measurement of the total weight of injected grout against time, the other two new methods were proposed in this study. For instance, a polyline formed by connecting the peak point of each rest period in all cycles was called the min-pressure envelope. From the pressure envelope (Fig.54), an upwards trend along this polyline represents the development of filter cake or vice versa. Because clogging of constrictions will reduce grout flow and magnitude of the pressure drop in the subsequent cycles and thus minimum pressure has an upwards trend in the pressure-time diagram.

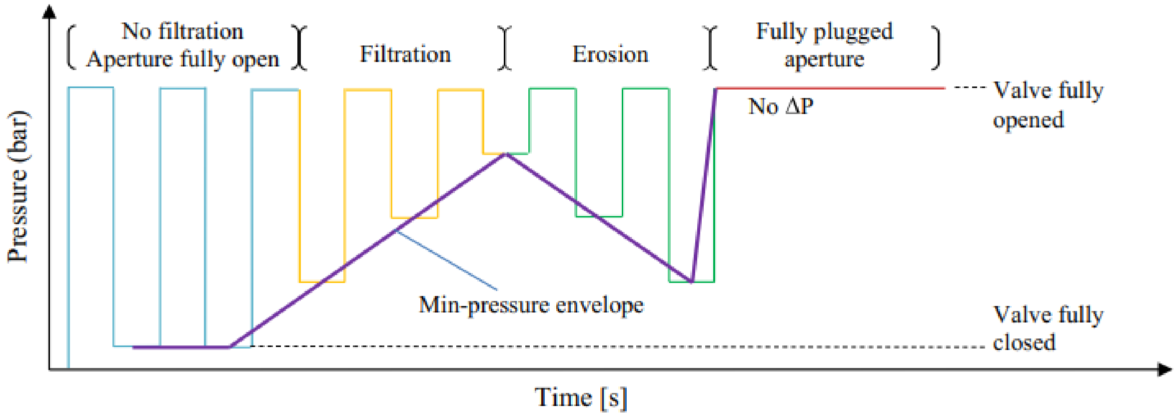


Figure 54. Illustration of the min pressure envelope (Ghafar et al.,2016).

The other parameter is called the Cycle Mean Flow Rate. It can be calculated as a ratio between the volume of injected grout during each cycle and the duration of one cycle. The larger value of the cycle mean flow rate, the less filtration, and the more effective injection.

Collected data from the load cell showed the weight of injected grouts in different groups. Table 10 compared the average weight of passed grout in test groups C2, V2, and V4 when a 30 µm slot was applied. Compared with the test applying static pressure, about 2.6- and 11-times improvement were observed from group V2 and V4 respectively.

Table 10. Weight of passed grout in 30 µm slot (Ghafar et al., 2016).

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

On the other hand, tests result obtained from the min-pressure envelope explained the improvement in group V4. It can be seen from the diagrams below that before reaching the maximum pressure of around 15 bars, the test group V4 took a longer time. Moreover, random downwards trends appeared in the right diagram, which means erosion and re-opening of clogging constriction.

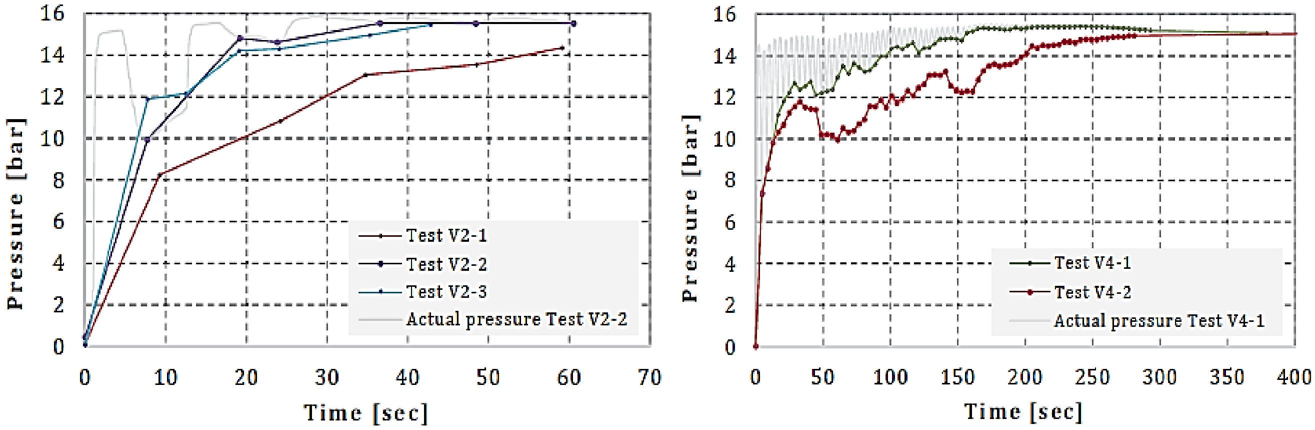


Figure 55. Min-pressure envelopes of test groups V2 (left) and V4 (Ghafar et al., 2016).

To quantify these improvements and differences resulting from the various peak and rest periods, the Cycle Mean Flow Rate (CMFR) histogram below was presented. In general, the values of CMFR for the tests with peak/rest period of 4s/8s were lower than those in the group employing 2s/2s dynamic pressure, even though the first cycle in the V4 group showed a relatively large value. Also, this gave a piece of evidence that filtration in the latter case was lower.

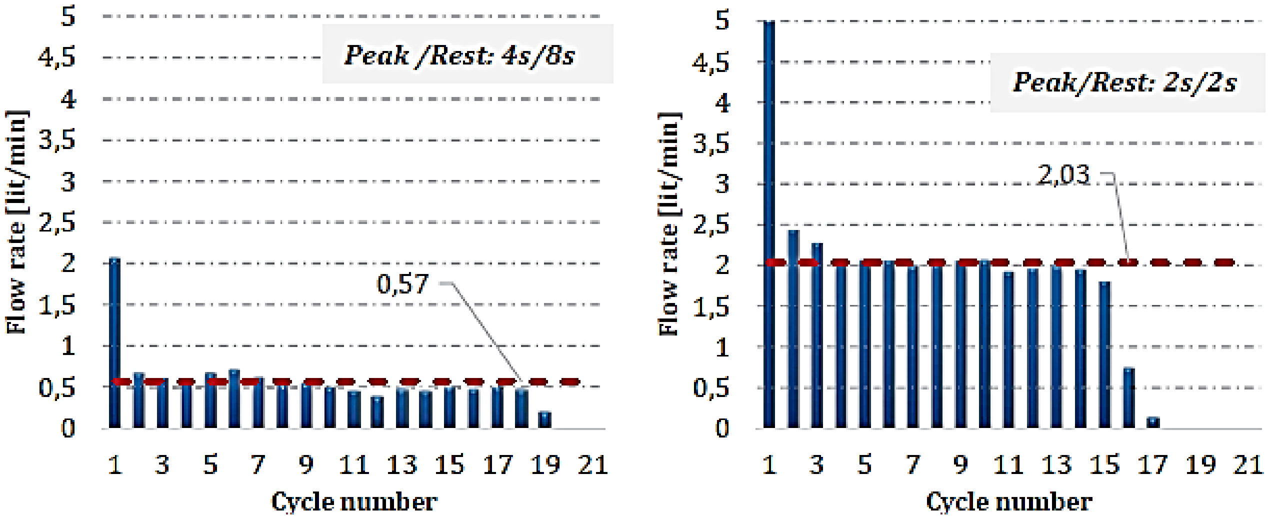


Figure 56. Cycle Mean Flow Rate (CMFR) histogram for V2 (left) and V4 (Ghafar et al., 2016).

In conclusion, a considerable improvement in penetrability can be observed when frequency instantaneous variable pressure was applied, especially with the pressure with a peak/rest period of 2s/2s.

Promising results from experimental tests with low-frequency rectangular pressure led to the continuation of the study using the same grouting method. Nejad Ghafar, A. (2017) did a further investigation on the dissipation of the oscillation along a varying aperture long slot (VALS) to verify the potential of this method to improve penetration in real rock fractures.

The recipe of grout used in this study and grouting pressure (15 bar) were the same as in the last research and the values of b_{min} and b_{crit} were around 40 and 60 µm respective. However, the VALS and related experimental setup replaced the old apparatus as shown in Fig 57.

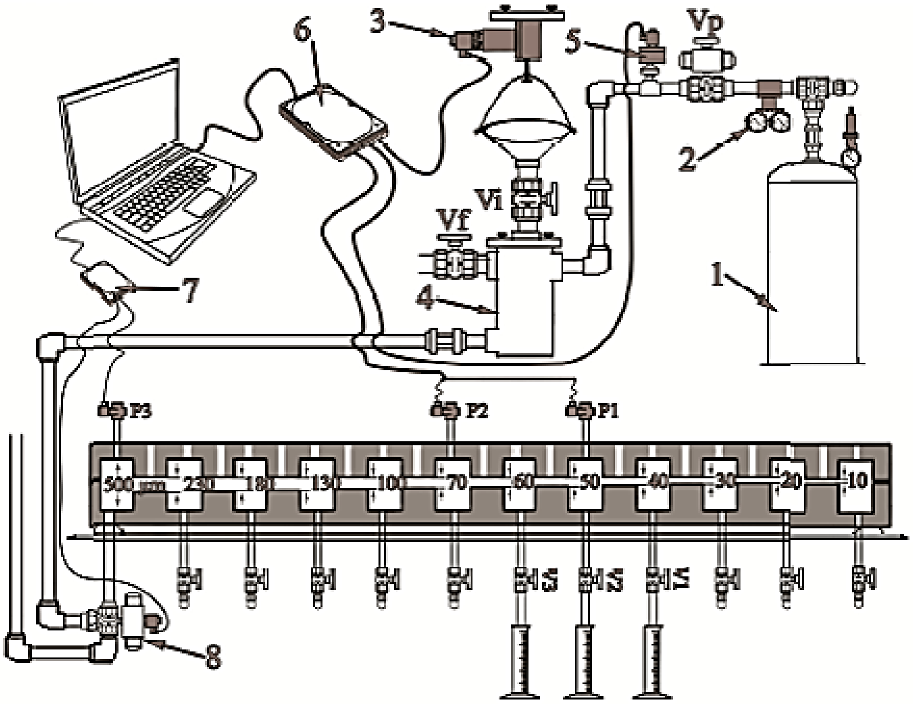


Figure 57. Test setup: 1. Gas tank (200 bar) 2. Pressure regulator 3. Load cell 4. Grout tank (2.6 L) 5. Pressure sensor 6. DAQ-data acquisition system 7. The PID-control unite 8. A three-way ball valve

There were three pressure transducers installed in the VALS. P3 was placed at the beginning of the slot. P2 and P1 were located before 60 µm and 40 µm constriction respectively in order to measure the pressure dissipation along the slot. Besides, a three-way pneumatic driven ball valve was installed at the inlet of the slot so that either the grout could flow from the tank toward the VALS or the internal pressure of the VALS can drop down to the atmospheric pressure.

Two groups of tests were performed with grouting material of tap water and cement-based grout. The peak/rest period of pressure is 2s/2s according to previous research.

Firstly, the results from the water test showed the dissipation of pressure along the slot. As Fig.58 illustrated, after stabilization of grouting 40% and 70% loss of pressure amplitude were measured at the position of pressure transducers P2 and P1.

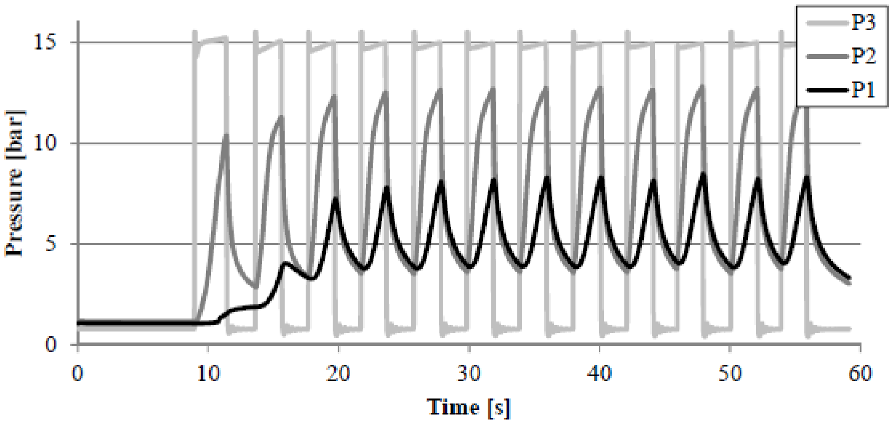


Figure 58. Variations of pressure at P1, P2, and P3 against time during water test (Nejad Ghafar, A., 2017)

Similar test results as shown in Fig. 59 from cement-based grout revealed that 54% and 75% dissipation of pressure amplitude occurred at P2 and P1. Nevertheless, due to the significant loss of grout from the three-way valve during the reduction of pressure in the VALS, the stoppage of outflow from V2 was not able to be observed until the grout tank was empty.

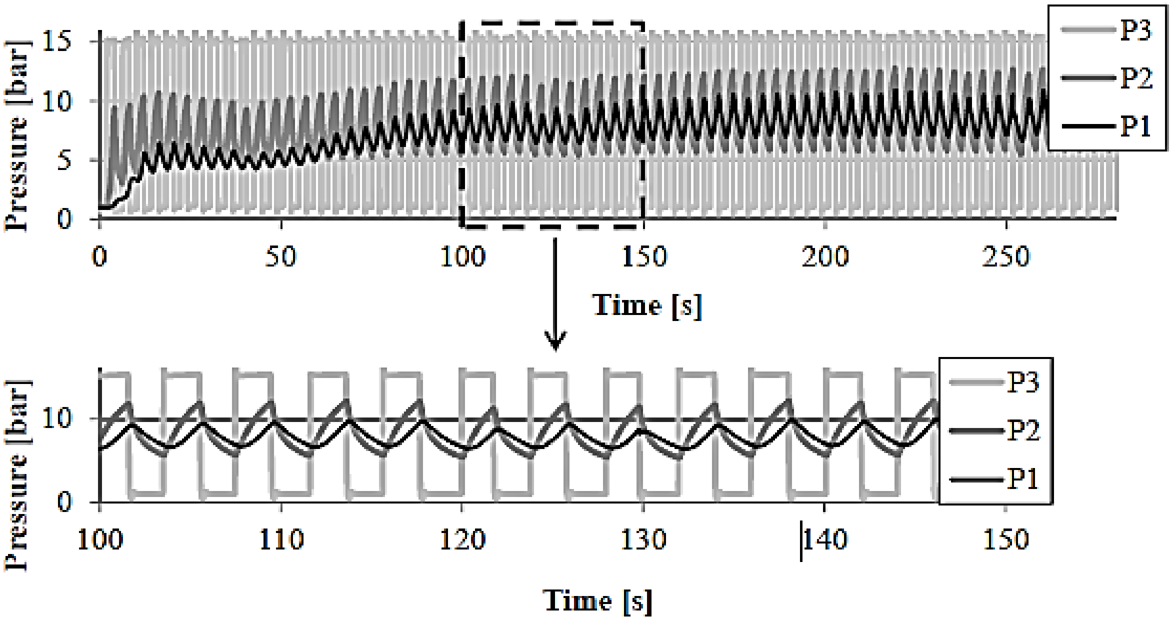


Figure 59. Variations of pressure at P1, P2, and P3 against time during cement grout test (Nejad Ghafar, A., 2017)

Also, the author used a similar analysis method called max-pressure envelope to evaluate the development of filtrations. This method shares the same principle with the min-pressure envelope whereas the polyline of the max-pressure envelope was created by connecting the highest point of peak time in each cycle.

From the diagram in Fig. 60, three phases with a downwards trend followed by an upward trend can be seen, which means an erosion of filter cake occurred from time to time. Above all, this study revealed that the dissipation of pressure impulse under a maximum pressure of 15 bar and 2s/2s peak/rest period was not critical to erode the filter cake.

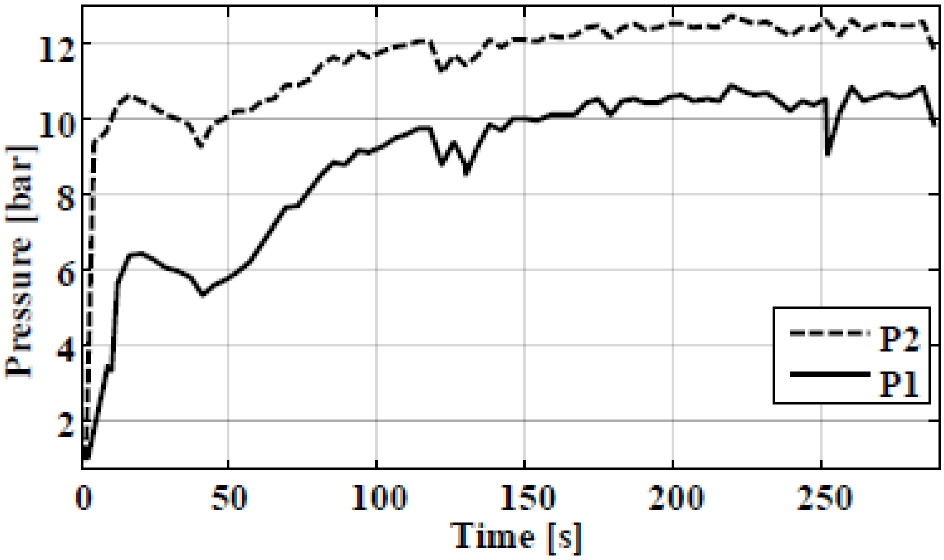


Figure 60. The max-pressure envelopes using P1 and P2 in grout test with 2s/2s peak/rest period (Nejad Ghafar, A., 2017)

To address the limitation caused by test equipment in the last research, Ghafar et al. (2019a) elaborated dissipation of low-frequency oscillations along the slot based on modified experimental setups. This research was divided into two steps.

In the first step of the experiment, all other components of the apparatus remained the same as these in the last study but the three-way ball valve with a control system was replaced by two coupled two-way ball valves as shown in Fig. 61. This device included: 1) ball-values, 2) Pneumatic actuators, 3) Solenoid valve, 4) Asymmetrical recycler timers.

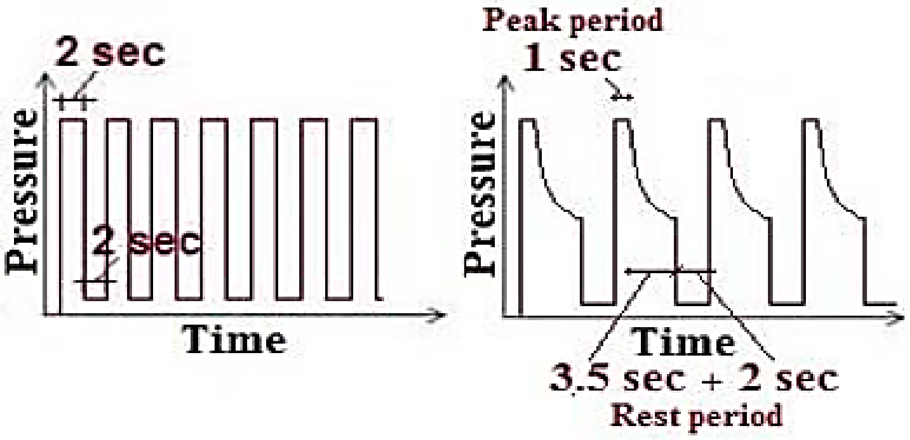


Figure 61. Illustration of the new valve system for turning static pressure into dynamic pressure (Ghafar et al., 2019a).

With this device, the loss of grout from the valve in each cycle can be reduced. The recipe of grout, mixing of grout, maximum grouting pressure, and location of three pressure transducers in VALS was the same as the last study. However, to further improve the penetration of grouts in VALS, another frequency pressure with a peak/rest period of 1s/5.5s (shown in Fig. 62) was compared with static pressure as well. Because the authors wanted to decrease the formation of filtration during peak time and rise the potential of erosion by increase the rest period in each cycle.

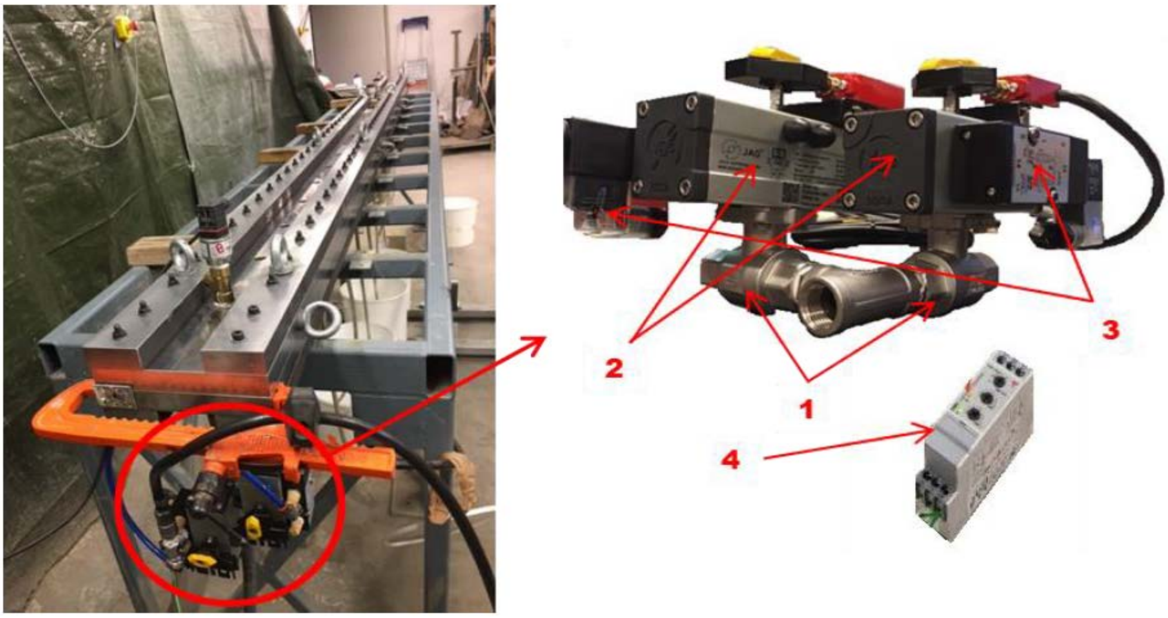


Figure 62. The peak and rest periods of 2s/2s and 1s/5.5s (Ghafar et al., 2019a).

The weight of grouts under static and dynamic conditions is summarized in Table 11, where the average weight of grouts in test group D2 (with peak/rest period of 1/5.5s) was 10 times that in the static pressure test group. Whereas the results of group D1 were not presented.

Table 11. Comparison of grout spread in test group C and D2 (Ghafar et al., 2019a).

Test group	Test No.	Peak/Rest period [sec]	Weight of the passed grout [g]					Improvement of grout spread in apertures < 70 µm
			V1 (40 µm)	V2 (50 µm)	V3 (60 µm)	V4 (70 µm)	Average (40-70) µm	
C (Static)	1	-	84	60	0	0	102	-
	2	-	0	0	44	16		
D2 (Dynamic)	1	1 s/5.5 s	0	120	880	-	1020	10.0
	2	1 s/5.5 s	0	76	964	-		

Meanwhile, the dissipation of pressures along the VALS is shown in Fig. 63. For the group applying pressure with 2s/2s peak/rest period, 31% and 22% of pressure amplitude remained at the position of transducers P2 and P1 respective. While in the test group D2 (with 1/5.5s peak/rest period), 30% remaining amplitude at P2 was observed.

Even though the new valve system has been used, there was considerable loss of grout when the pressure was released in each cycle, which led to the empty of the gas tank before the stoppage of outflow from the VALS. Therefore, to better address this issue a screw pump was employed as the pressure source in the second step of this study. Subsequently, a bigger grout tank with a capacity of 20 L was connected to the screw pump and thus an agitator was used to prevent the settlement of cement particles during grouting. Also, a backflow from VALS to the grout tank recycled leaked grout during the rest period. The schematic of the test apparatus is shown in Fig.64.

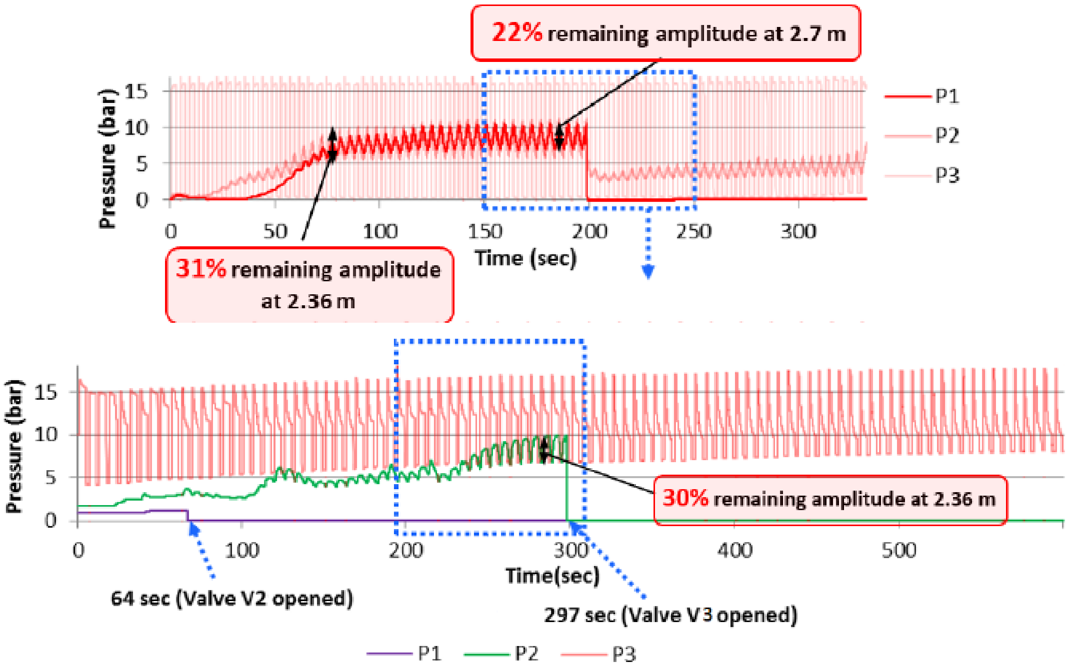


Figure 63. Dissipation of dynamic impulses along the VALS registered by P1, P2, and P3 in tests group D1 (upper) and D2 (Ghafar et al., 2019a).

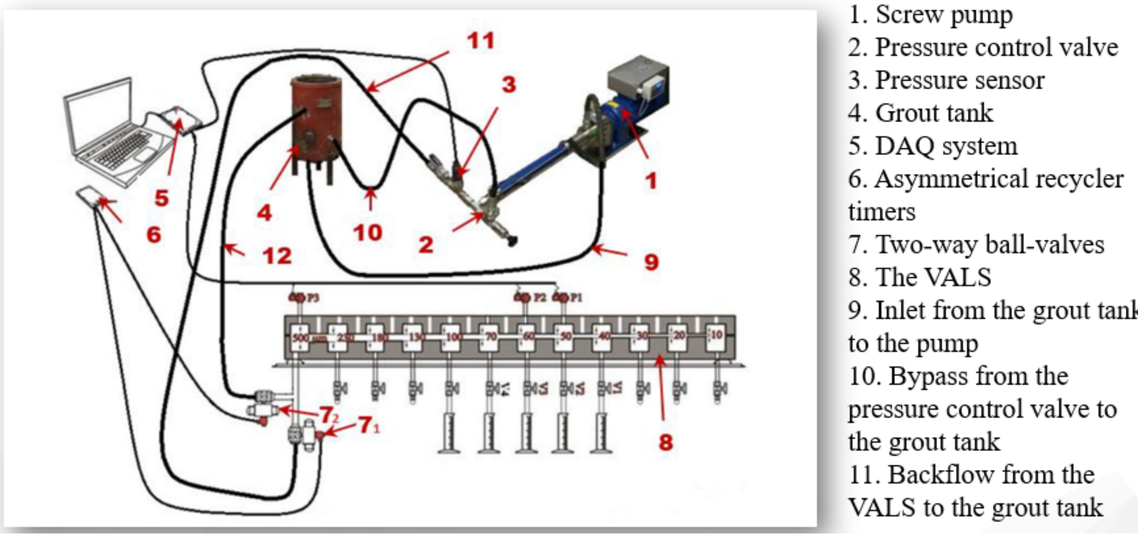


Figure 64. New test apparatus with a screw pump and bigger grout tank (Ghafar et al., 2019a).

Again, the tests were performed both under static and dynamic conditions. Due to the damage of the pressure control valve, the weights of injected grout in apertures (40-70 µm) in the new test apparatus were compared with the results in step 1 (in Table 12).

One can find that the average weight of grout under static pressure in step 2 was almost 4 times larger than the corresponding value in step 1. This was also caused by the fluctuation from a damaged valve. Hence, the improvement of grout spread from test group D_{S2} was evaluated based on the average grout weight of the static group in step 1, where the passed grout in group D_{S2} was 8 times larger than that in S_{S1}.

Table 12. Comparison of the total amount of grout passed through 40-70µm apertures between tests Step 1 and Step 2 (Ghafar et al., 2019a).

Pressure sourse	Test group	Test No.	Peak/rest period	Weight of the passed grout (g)					Improvement of grout spread in apertures < 70 µm	
				V1=40 (µm)	V2=50 (µm)	V3=60 (µm)	V4=70 (µm)	Average of 40-70 (µm)		
Gas (Step 1)	S_{S1}	1	-	84	60	0	0	102	$D2_{S1}/S_{S1}$=10.0	D_{S2}/S_{S1}=8.09
		2	-	0	0	44	16			
	$D2_{S1}$	1	1 s/5.5 s	0	120	880	-	1020		
		2	1 s/5.5 s	0	76	964	-			
Pump (Step 2)	S_{S2}	1	-	0	64	290	16	491	D_{S2}/S_{S2}=1.68	
		2	-	0	60	532	20			
	D_{S2}	1	2 s/2 s	0	206	344	0	825		
		2	2 s/2 s	0	192	908	0			

Fig. 65 presents the dissipation of pressures along the VALS at the position of pressure transducers P1, P2, and P3 during the dynamic tests in step. 70 % remaining amplitude of initial pressure can be observed at pressure transducer P2 which is 2.7 m far away from the inlet of the slot. Compared with the value (22%) from the same position in step 1, it was a significant improvement which means more energy can be transferred to the same position in the VALS. Nevertheless, the damage of the pressure valve after 272 s of injection resulted in a dramatic drop of pressure in the VALS.

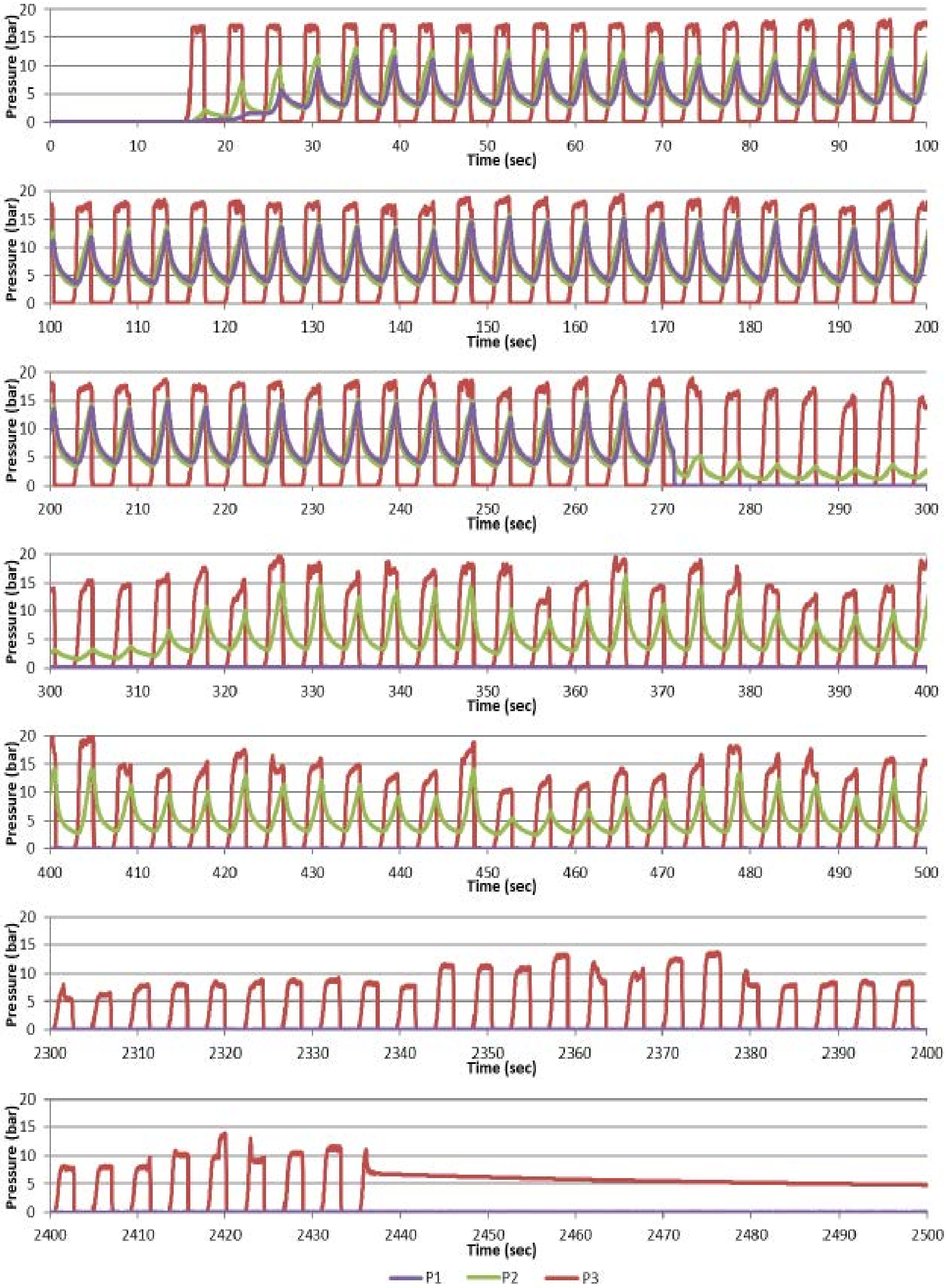


Figure 65. Dissipation of dynamic impulses along the VALS registered by P1, P2, and P3 in dynamic test 2 (with 2s/2s peak/rest period) between 0-500 sec and 2300-2500 sec (Ghafar et al., 2019a).

3.3. M3-Grouting in the vibratory host rock

Another interesting study regarding the dynamic grouting technique was done by Ghafar et al. (2019b). This study was based on laboratory tests and investigated how vibrations in host rock influence penetration of cement-based grout in microfractures. Inspired by previous research of applying oscillation to the grout, the author assumed that improvement of penetration could also be achieved by injecting grout into vibratory host rock and less attenuation of the oscillation along a fracture was expected.

It has been proved that the application of high-frequency oscillating pressure would bring the grout into smaller fractures and achieve a better spread of grout, because of favorable rheological properties result from vibration. However, there are still many remaining questions to be addressed. For example, the oscillating pressure generated by the pump drops quickly along the grout hose and slot so the only limited length of fracture can be penetrated. On the other hand, previous tests performed in uniform apertures cannot simulate variations in real rock fractures. Therefore, Ghafar et al. (2019b) presented a pilot effect to address the above questions.

To stimulate vibration of the rock mass, an electrical rotary motor (marked as 7) was attached on an artificial varying aperture long slot (the VALS), which is the same as that in Ghafar et al (2016). This motor can adjust the frequency imposed on the slot from 0 to 100 Hz and its masses are changeable. Moreover, the location of the vibrator is just before 50µm constriction (as shown in Fig.66), because filtration tends to occur at the same mesh size in the filter pump tests. During the tests, the resonance frequency of the artificial fracture system (38.5 Hz) was employed, and the constant pressure of 1.5 MPa was provided by a nitrogen gas tank (marked as 1).

The materials used in this study include a kind of cement with d95 of 30 µm, superplasticizer, and tap water with a w/c ratio of 0.8. After mixing cement and water for 4 min under a rotor-stator system with 10000rpm, the superplasticizer was added and mixed for 2 min again. Then the grout was immediately filled in the grout tank.

The first step to initiate the test is to open valve 1 before 40 µm constriction and the valve of a gas tank. Afterward, the grout was pressured from a 2.6 l grout tank and into the slot. Two pressure transducers (marked as 5) were installed at the inlets of the grout tank and slot respectively so that the grouting pressure can be recorded during the experiment. In addition, to measure the weight change of grout, the grout tank was suspended from a load cell (marked as 3). Accordingly, a diagram of the injected weight of grout against time can be plotted, and the gradient of this diagram represents the flow rate. If gradient alters with time, it means an evolution of filtration (Ghafar et al., 2016).

When outflow from V1 stopped, the valve (V2) before 50 µm constriction was opened until the finish of injection. Meanwhile, the amount of outflow from each valve was measured.

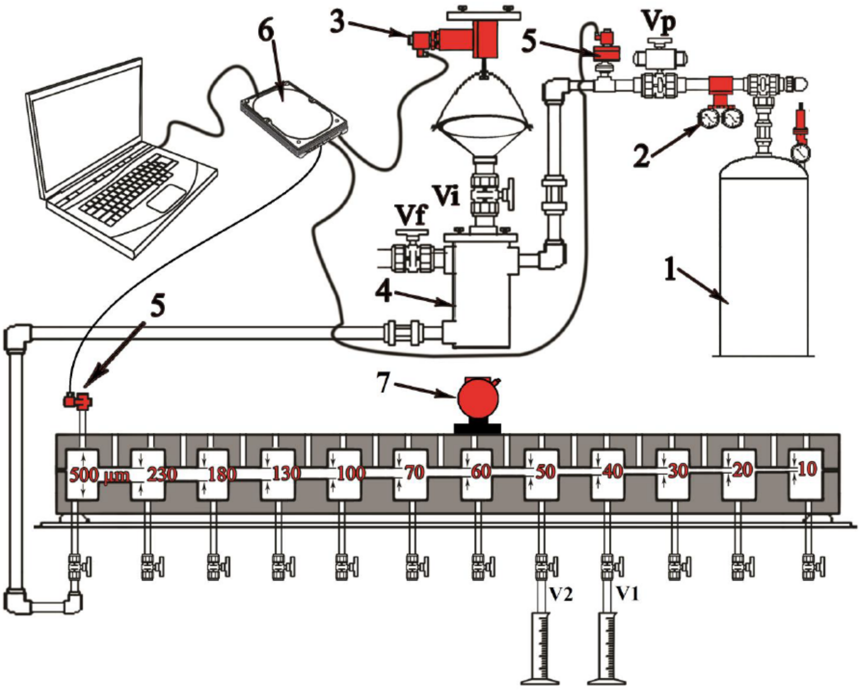


Figure 66. Experimental setup from Ghafar et al. (2019b).

Tests were performed with and without the application of oscillating pressure. The comparison of all testing results was shown in Table 13.

Table 13. Summary of injection results from Ghafar et al. (2019b).

Test condition	Grout injection when valve V1 (40 µm) was open					Grout injection when valve V2 (50 µm) was open		
	Weight (*g*)			Time (*sec*)	Average mass flow rate (*g/sec*)	Weight (*g*)	Time (*sec*)	Average mass flow rate (*g/sec*)
	A	B	C					
Without application of high-frequency oscillation	465	50	415	500	0.93	3400	2357	1.44
With application of high-frequency oscillation	665	94	571	500	1.33	3202	1829	1.75
Improvement	-	88%	37.6%	-	43%	-	-	21.5%

A: Weight of injected grout (penetrated + discharged)
B: Weight of grout discharge from valve V1
C: Weight of penetrated grout through the slot

A = B + C

Tests were divided into two parts, where the first part showed the results when valve V1 was open, and the second part gave the weight of grout during the opening of valve

V2. Moreover, there are three ways to evaluate grouting penetration. For example, the weight of grout discharged from valve V1 showed 88% improvement under oscillation compared with the case of applying static pressure. This suggested that high-frequency oscillation imposed on fracture can lead to better penetration in smaller apertures in the combination of constant injection pressure.

On top of that, around 38% improvement on the weight of penetrated grout through the slot was observed with the application of oscillation, which might result from better infilling of voids within the grouted slot. Lastly, the average mass flow rate was calculated based on the total weight of injected grout and grouting time. The bigger the average mass flow rate, the faster the grout penetration. In the first and second parts of the tests, using high-frequency oscillation improved the average mass flow rate by 43% and 21.5% respectively (Ghafar et al., 2019b).

Besides, another method for monitoring the evaluation of filer cake used in this study was the weight-time diagram (Shown in Fig.67). It was seen from the diagram that the gradients of the blue and green lines became smaller after 625 s of injection, which means the start of filtration.

In conclusion, compared with the static grouting method, performed tests in this study showed a distinct improvement of penetration caused by high-frequency oscillation on the slot. The reason for that was interpreted as a transition of loose cement particles and clusters in produced filter cake into higher density materials. However, possible improvement of penetration from changes in the rheology of the grout was not verified by the experiment in this study.

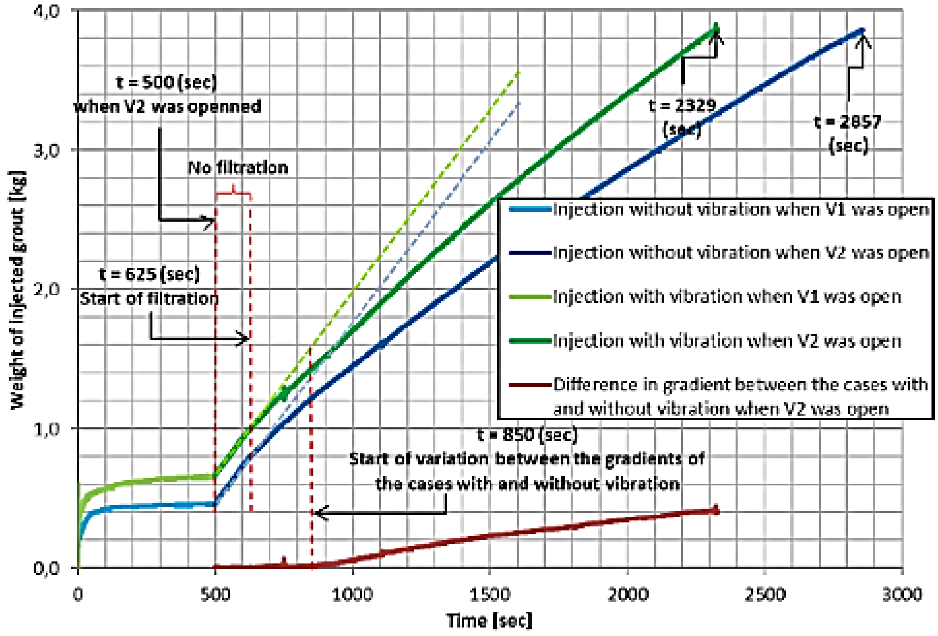


Figure 67. Variation of the weight of injected grout against time (Ghafar et al., 2019b).

3.4. M4-Ultrasound dispersing of cement-based grout

An interesting exploration made by Draganovic et al. (2020) is the application of ultrasound to disperse microfine cement grout instead of conventional laboratory dissolvers and thus achieve better penetration in microfractures. As mentioned in the previous section, grain size highly influences the filtration stability of cement-based grout and penetration. It is reasonable to use a smaller size of cement particles to penetrate micro apertures. The following problem is that once microfine cement is mixed with water and additives, flocculation of fine particles will easily occur if the same method of dispersion were used. According to Draganovic et al. (2020), the effect of the existing superplasticizer on improving the dispersion of these grouts is limited. Therefore, new methods of dispersing microfine cement grouts are critical.

Toumbakari et al. (1999) used ultrasound in combination with a mechanical mixer to investigate the effect of mixing produce on injectability of coarse cement where the d_{95} is around 60 µm. Two different rotation speeds of a mechanical mixer (2400 rpm and 300 rpm) were compared in the tests. The sand column was used to estimate the penetrability of the grout. It was found that rheology and penetration of grout under lower rotation speed were effectively improved by superposing an ultrasound frequency of 28 kHz. However, the amplitude and mixing time were not reported in the research.

By taking the study of Toumbakari et al. (1999) as a reference, Draganovic et al. (2020) continued to investigate the effect of ultrasound on the dispersion of micro cement grout. In this study, another two conventional dispersing methods, including rotational dissolver with disk and rotor-stator system, were compared with ultrasound.

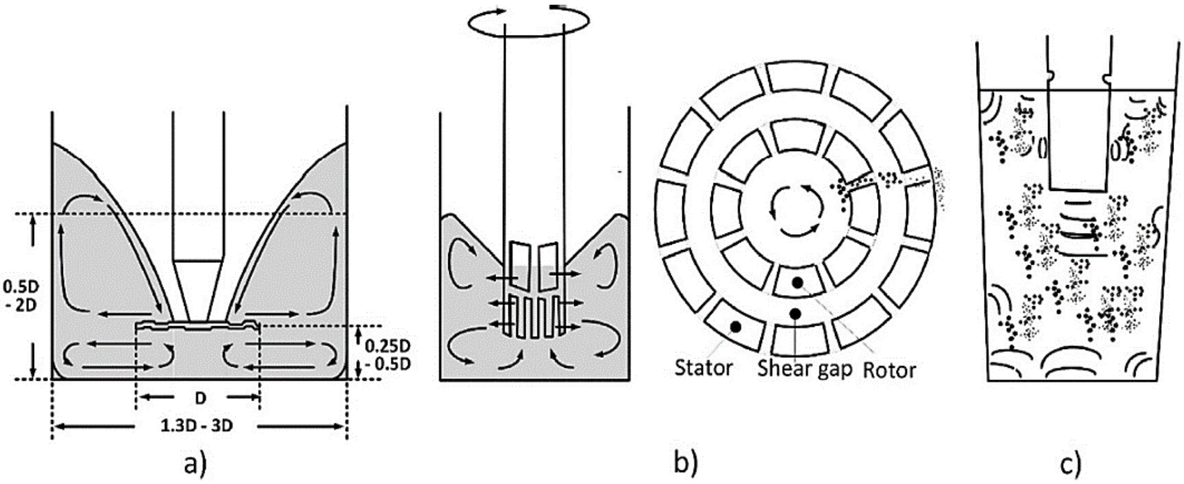
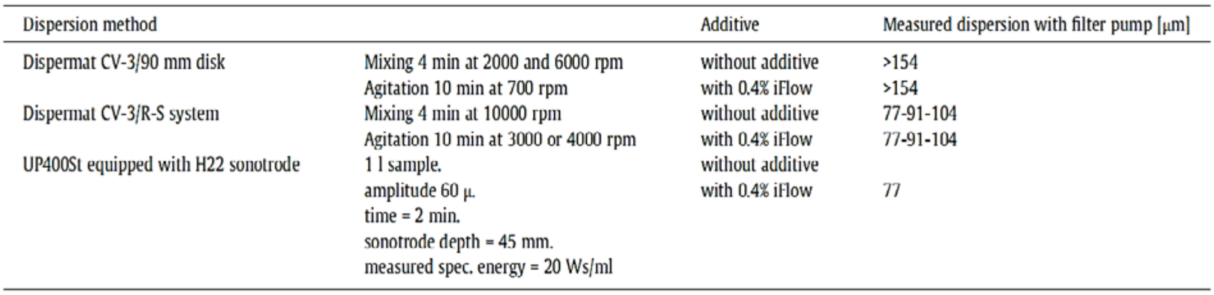


Figure 68. Mechanism of different dispersion systems. (Draganovic et al., 2020)

The possible mechanisms of each method are summarized below. For rotational dissolver with a disk (Fig. 68a), different flow speeds in each layer of liquid mainly provide shear force and disperse particles in the suspension. On the other hand, the dissolver with a rotor-stator system (Fig. 68b) breaks up the agglomerates by shear force resulted from the rotor, stator, and shear gap when the grout flows through them. In terms of ultrasound shown in Fig. 68c, the cavitation effect from the water helps with the dispersion of cement grout. Cavitation can be simply explained as a phenomenon in liquids where water vapor becomes gas bubbles and quickly collapse. The energy and shock waves created by collapsed bubbles are merits for dispersion.

To measure and quantify the effect of ultrasound on the dispersion of micro cement grout, filter pump tests were performed after cement with d_{95} of 30 µm were mixed with water by three dispersion methods. The results are summarized in Table 14 and the conclusions were clear. The mechanical dissolver with the disk is not suitable for micro cement grout since solid particles can only flow through apertures larger than 154 µm. However, the same dissolver with a rotor-stator system is more effective than disk since a smaller mesh size of filter can be penetrated, though the results showed a large variation. Compared that with ultrasound dispersion equipment, a more stable result of measured mesh size of the filter pump implied a better dispersion of materials.

Table 14. Comparison of penetrability among different dispersing methods. (Draganovic et al., 2020)



Dispersion method		Additive	Measured dispersion with filter pump [µm]
Dispermat CV-3/90 mm disk	Mixing 4 min at 2000 and 6000 rpm	without additive	>154
	Agitation 10 min at 700 rpm	with 0.4% iFlow	>154
Dispermat CV-3/R-S system	Mixing 4 min at 10000 rpm	without additive	77-91-104
	Agitation 10 min at 3000 or 4000 rpm	with 0.4% iFlow	77-91-104
UP400St equipped with H22 sonotrode	1 l sample.	without additive	
	amplitude 60 µ.	with 0.4% iFlow	77
	time = 2 min.		
	sonotrode depth = 45 mm.		
	measured spec. energy = 20 Ws/ml		

3.5. M5-Dynamic grouting based on feedback resonance

One project aiming at using feedback resonance in dynamic grouting is carried out by Ulriksen (2021). The principle of this method is also based on oscillating pressure utilized during grouting, and thus better rheology and penetrability of grout are obtained compared with injection by static pressure. Besides, an outstanding problem-rapid attenuation of oscillation along the injection hose and fractures was investigated.

Ghafar et al. (2019) performed a series of pilot tests by applying oscillation of resonant frequency on the artificial fracture in order to make the slot oscillate at a high amplitude than when other frequencies of force are applied. Each system or object has its own natural resonance frequency while it can change with the mass or addition of other objects. Therefore, the resonance frequency of fractures and injection hoses is not constant especially when the grout is injected into cracks. Accordingly, Ulriksen (2021) suggested the oscillation should be created by feedback from measurement during grouting. In other words, the system itself could find the optimal frequency and make an adjustment based on that.

To verify that assumption, a grouting system has been built up with an electrically controllable hydraulic cylinder as shown in Fig. 69a, a grouting pump, grouting hose of various dimensions, a borehole simulator, and a hose tree. And tests have been made with an open system with water flow and with a closed system, both at supply water pressure. For each case, tests have been made with swept frequency 5-55 Hz and transients. Experimental results showed that there are resonance peaks in the response spectra of injection tubing and fracture systems, which means feedback resonance is possible to measure and use to improve the penetrability of cement grout.

(a) (b)

Figure 69. a) Hydraulic grouting pump, 20 m grouting tube coild under the blue wagon and an injection pipe; b) Bifurcating tree of tubes. (Ulriksen, 2021)

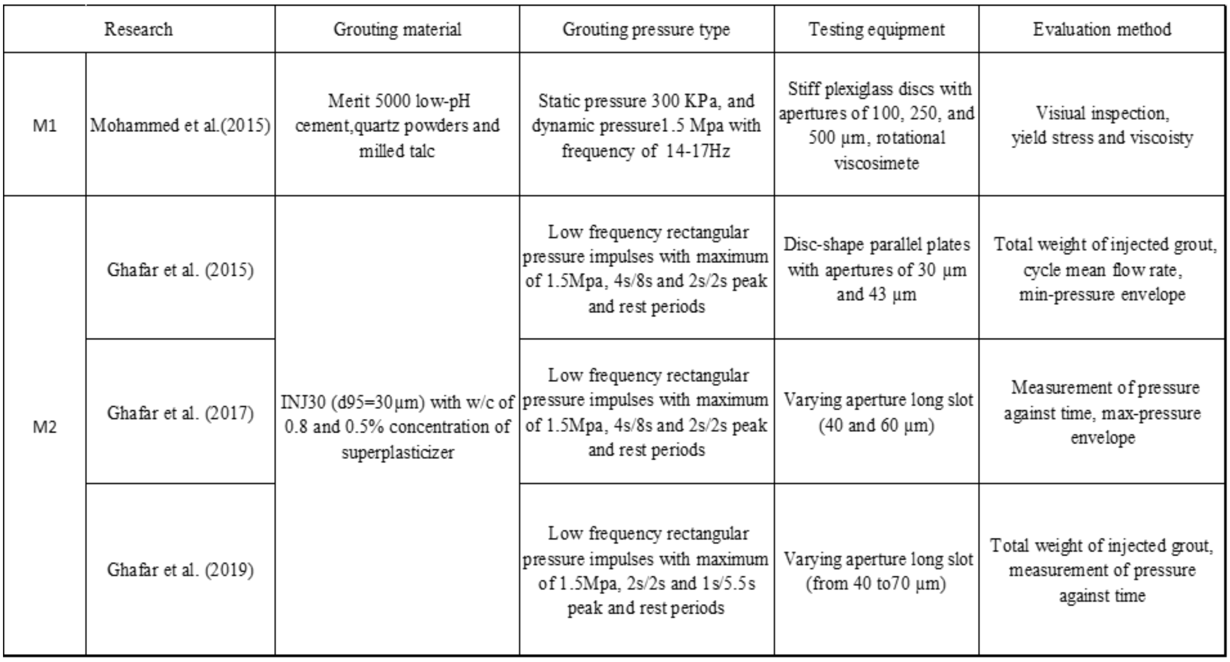
4. DISCUSSION

In this section, the above-mentioned grouting methods are compared from four aspects, including grouting materials, type of grouting pressure, testing equipment, and evaluation method. On one hand, in accordance with the effects of different factors on penetration, the variations in tests results are discussed with consideration of the discrepancies in equipment. Subsequently, a comparison of the efficiency of methods is tried to make to conclude the best one, which is found difficult. On the other hand, the limitations and advantages of each method are summarized and then the possible combinations are suggested.

4.1. Comparison of the dynamic grouting methods; M1 and M2

The comparison of dynamic grouting methods between M1 (chapter 3.1) and M2 (chapter 3.2) is shown in Table15. The grouting materials and evaluation methods in these two methods are different, and this makes a quantified comparison of the two methods difficult according to the results from each of them. Firstly, even though the amplitude of dynamic pressure in both methods is 1.5 MPa, the principles of these two methods differ in the improvement of grout penetrability. For example, a high-frequency oscillating pressure (shown in Fig. 70a) was superposed on a 300 kPa static pressure in the first method, and thus rheological properties of grouts, specifically field stress, and apparent viscosity were reduced. Therefore, the grout can flow further in the fractures so better grout spread is achieved.

Table 15. Comparison between Method 1 and Method 2.



Research		Grouting material	Grouting pressure type	Testing equipment	Evaluation method
M1	Mohammed et al.(2015)	Merit 5000 low-pH cement,quartz powders and milled talc	Static pressure 300 KPa, and dynamic pressure1.5 Mpa with frequency of 14-17Hz	Stiff plexiglass discs with apertures of 100, 250, and 500 μm, rotational viscosimete	Visiual inspection, yield stress and viscoisty
M2	Ghafar et al. (2015)	INJ30 (d95=30μm) with w/c of 0.8 and 0.5% concentration of superplasticizer	Low frequency rectangular pressure impulses with maximum of 1.5Mpa, 4s/8s and 2s/2s peak and rest periods	Disc-shape parallel plates with apertures of 30 μm and 43 μm	Total weight of injected grout, cycle mean flow rate, min-pressure envelope
	Ghafar et al. (2017)		Low frequency rectangular pressure impulses with maximum of 1.5Mpa, 4s/8s and 2s/2s peak and rest periods	Varying aperture long slot (40 and 60 μm)	Measurement of pressure against time, max-pressure envelope
	Ghafar et al. (2019)		Low frequency rectangular pressure impulses with maximum of 1.5Mpa, 2s/2s and 1s/5.5s peak and rest periods	Varying aperture long slot (from 40 to70 μm)	Total weight of injected grout, measurement of pressure against time

In the second method, with lower frequency rectangular pressures (Fig.70b), the flow patterns of grout quickly change in the fracture when different peak and rest periods of instantaneous pressure are applied. The reason behind this is the variations of the velocity of flow layers. As a result, the partially formed filter cake before constrictions can be eroded and thus more grouts penetrate smaller apertures.

As for testing equipment, the equipment used in the first method (M1) did not consider the various apertures in real rock fractures. Thus, the filtration caused by constrictions in the aperture is not able to be stimulated. The same issue existed in Ghafar et al. (2016) since a similar artificial aperture was used. While thanks to the application of VALS in the latter research, this issue has been addressed. However, the texture of rock surfaces with many micro voids is still difficult to stimulate by the current experimental setup.

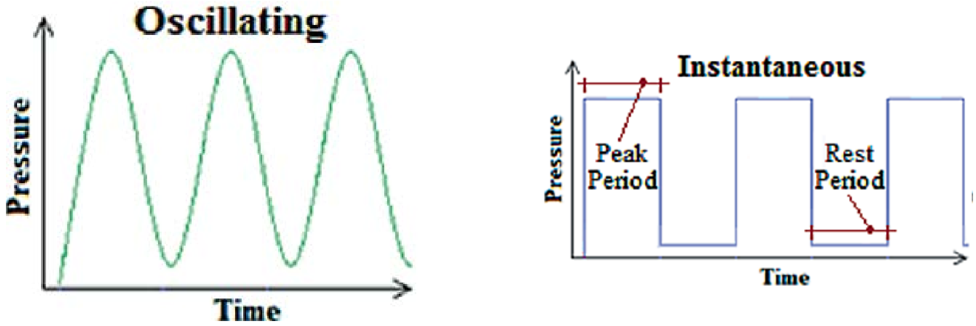


Figure 70. (a) high-frequency oscillating pressure (b) lower frequency rectangular pressures

In terms of the evaluation approaches used in the two methods, they are different due to the discrepancy in experiment equipment. Transparent plexiglass discs gave more convenience for visual inspection of the penetration process during grouting, which is an advantage compared with steel artificial fractures. In contrast, steel artificial fractures could take higher grouting pressures. To monitor the filtration development and penetration in the fractures, the total weight of injected grouts and the pressure-time diagram was proposed and proved to be effective in M2.

To sum up, the dynamic grouting results seem to be more efficient compared with results from static pressure in each method. In the experiment applying high-frequency oscillating pressure, improvement of penetration can only be observed if the aperture is 500 µm, but static pressure resulted in better grout spread than dynamic pressure in the apertures of 100 and 200 µm. This might be due to the rapid dissipation of energy along fine fractures. On the other hand, in experiments when low-frequency dynamic pressures were tested, a considerable improvement of penetration can always be observed.

4.2. Comparison of the dynamic grouting methods; M1 and M3

The comparison of dynamic grouting methods between M1 (chapter 3.1) and M3 (chapter 3.3) is shown in Table 16. These two methods share the same mechanism of improvement on the penetrability of grouts. However, in Method 1 oscillating pressure was imposed on grout suspensions, but rather the oscillations are applied on the slot in Method 3. By directly oscillating fracture, dissipation of oscillations could be decreased, and thus yield stress along with apparent viscosity is effectively reduced.

In Method 3 much smaller apertures, 50 and 40 µm, were injected compared with the minimum aperture of 100 µm in Method 1. Regardless of the effect of grouting pressure and method, the size of grouting material and size distribution seems to be more dominant factors in this case. Because the cement particle size used in M3(d95=30 µm) is much larger than 15 µm (one-third of aperture), which means the particles and clusters will more easily clog the slot.

Another difference in grouting pressure between the two methods is frequency. A relatively small frequency (between 14-17 Hz) was used in Method 1 when it is compared with a frequency of 38.5 Hz in Method 3. This is a crucial parameter for high-frequency oscillation pressure grouting. If the applied frequency is too big, the penetrability of grouts could be influenced. Because too much vibrational energy absorbed by each particle in suspension could cause turbulence inflow and more internal fiction among particles. Together with heat produced by fiction between slot walls, hydration could develop faster. As a result, the viscosity of grout increases, and penetration reduces. Whereas this needs to be further investigated by experiments.

Table 16. Comparison between Method 1 and Method 3.

Research		Grouting material	Grouting pressure type	Testing equipment	Evaluation method
M1	Mohammed et al.(2015)	Merit 5000 low-pH cement,quartz powders and milled talc	Static pressure 300 KPa, and dynamic pressure1.5 Mpa with frequency of 14-17Hz	Stiff plexiglass discs with apertures of 100, 250, and 500 µm, rotational viscosimete	Visiual inspection, yield stress and viscoisty
M3	Ghafar et al. (2019)	INJ30 (d95=30µm) with w/c of 0.8	Constant pressure of 1.5 Mpa, oscillation of fractures with 38.5Hz	Varying aperture long slot 50 and 40 µm	Total weight of injected grout, gradient of weight time diagram

It might be difficult to find a suitable frequency for each type of grouts to achieve the best viscosity. But it is worthwhile to notice that a large frequency of vibration transfers extra energy to the grouts and may result in acceleration of hydration. Subsequently, the penetrability of grout will be influenced.

4.3. Comparison of the dynamic grouting methods; M1 and M4

Using ultrasound to disperse cement grout as the fourth method (chapter 3.4) is compared with Method 1 (chapter 3.1) in this subsection. A detailed comparison between the two methods is listed in Table 17. In fact, these two methods were used in different phases of grouting, where Method 1 improved the rheological properties of grouts in the process of injection while Method 4 aims for the same during the preparation of grouts. In the research of Mohammed et al. (2015), a conventional mechanical dissolver was utilized as a mixing device which might not be suitable for the used materials, such as quartz powders with a grain size of 30 µm, according to the study of Draganovic et al. (2020). Because the intermolecular attraction of fine particles in suspensions is hard to destroy by conventional dissolvers and formation of clusters will have an adverse impact on filtration stability and penetration.

Table 17. Comparison between Method 1 and Method 4.

Research		Grouting material	Grouting pressure type	Testing equipment	Evaluation method
M1	Mohammed et al.(2015)	Merit 5000 low-pH cement,quartz powders and milled talc	Static pressure 300 KPa, and dynamic pressure1.5 Mpa with frequency of 14-17Hz	Stiff plexiglass discs with apertures of 100, 250, and 500 µm, rotational viscosimete	Visiual inspection, yield stress and viscoisty
M4	Draganovic et al. (2020)	Poland cement (d95=30µm) with w/c of 0.8, 0.4% superplasticizer	Suction from filter pump	Filter pumps,rotational viscosimeter	Mesh size of filter pumps ,yield stress and viscoisty

Nevertheless, the grouting pressure provided by the pump in Method 1 is more stable and larger than the test pressure of 0.3-0.6 MPa in the filter pump. Grouting pressure with 1.5 MPa amplitude is more similar to the pressure used on site. Moreover, the relatively small volume of grouts in the filter pump can hardly stimulate the situation when a considerable amount of grout is injected. On the other hand, according to Eklund (2005), the cement-based grout can penetrate deeper into the slot experiments compared to the mesh geometry. So, the results obtained in the research of Draganovic et al. (2020) might be different if the slot-geometry testing setup is used.

All in all, ultrasound is a good tool to disperse super fine cement in reality compared with a traditional dissolver. It improves the rheological properties of grouts before injection. Together with dynamic grouting methods, desired penetration in fractures (<70 µm) should be achievable.

4.4. Comparison of the dynamic grouting methods; M2 and M5

In general, Method 2 (chapter 3.2) aims at increasing erosion of partially formed filter cake by dynamic pressure in a more macroscopic way, yet Method 5 (chapter 3.5) focused on the improvement of rheology by using a system that can monitor the resonant frequency of grouting equipment so that imposed oscillations could be changed accordingly.

The constant movement of particles caused by oscillation can effectively reduce sediment as well as yield stress. However, the efficiency of the equipment used in Method 5 needs to be verified by comparing the penetration speed and depth with other methods. Meanwhile, tube systems can hardly replicate micro-fractures in the rock mass.

In contrast, even though there were defects from the valve system in Method 2, it is relatively simple and convenient to operate. Compared with equipment in Method 5, the configuration of equipment in Method 2 is simple, which is also of value for industrial applications.

The advantages of each method could have a large influence on the penetrability of grouts when the different materials are involved in the tests. Therefore, it is meaningless to conclude the best grouting method without consideration of the grain size of materials, the aperture of fractures, and the objects of grouting, since grouting methods suitable to fine fractures may not be efficient for rock mass with the low sealing requirement.

4.5. Possibility and benefits of combining different methods

To obtain better penetration of cement-based grout in fine fractures, the advantages from the different methods mentioned above are possible to be combined. Meanwhile, the mixing approach, evaluation equipment, and methods have the possibility of integration so that some drawbacks can be overcome. In this subsection, the possibility and benefits of combing different methods will be discussed.

Firstly, the combination of Method 1 and Method 2 seems promising. Since no matter which pressure was applied in the test, both high-frequency oscillating pressure and rectangular pressure impulse are mechanical waves, which means the wave interference will occur when one of them is superposed on the other or two waves encounter. There are three key parameters to describe mechanical waves, including crest, trough, and amplitude, as shown in Fig. 71. On top of that, wave interference can be simply explained as enhancement or attenuation of amplitude when the superposition of two mechanical waves occurs. On one hand, when the crest of two waves encounter, the amplitude will be enhanced, and it is the same for two troughs. On the other hand, attenuation of amplitude results from the overlay of one crest and one trough.

Therefore, it is theoretically possible to combine high-frequency oscillating pressure with low-frequency rectangular pressure impulse to achieve a more drastic movement of cement particles in grout suspensions. Whereas it will be difficult to simultaneously impose two dynamic pressures with the same frequency and phase of the crest to the grout suspension. The complexity of equipment and device will reduce the efficiency and stability of grouting.

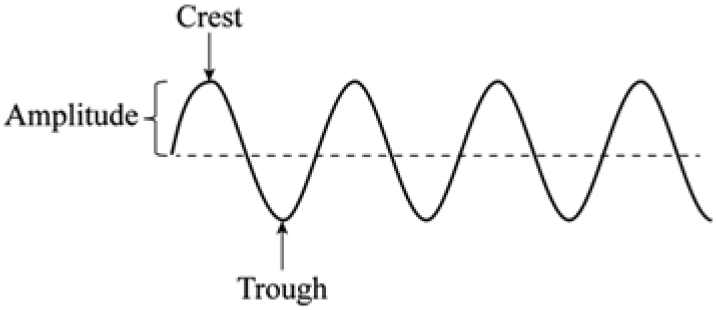


Figure 71. Three key parameters of a mechanical wave.

On the other side, the same possibility of combination can be seen between Method 2 and Method 3. By applying high-frequency oscillating pressure on the rock mass or artificial fractures will not only address the issue of dissipation of pressure along the slot but also make the oscillation generator independent from low-frequency pressure devices. As long as the matched frequency of each pressure can be found, the two proposed mechanisms for improving penetration are ought to be achieved at the same time.

While the application of oscillation on rock mass may require extra boreholes for the location of the generator, this raises one potential problem regarding the sealing of the boreholes after grouting. If the fractures are scattered in an area, more boreholes will be required in order to impose enough oscillation on the rock mass and fractures, and thus the cost will be increased.

Lastly, combing the ultrasound dispersing method with low-frequency rectangular grouting pressure would also be promising for better penetrability. As discussed in the previous chapter, the mixing time and mixing approach make an impact on the filtration tendency, rheology, and penetration. While the biggest advantage of this combination is the utilization of these two methods in different phases of grouting (preparation and injection). Thus, in the case of micro cement, an ultrasound dispersing device ensures the absence of clusters and flocculation which lowers the risk of filtration. Subsequently, low-frequency rectangular pressure impulse can erode the filter cakes during the grouting and forces the grout flow into fractures at the largest extent.

With discussion of these possibilities, some promising combinations, for example, the integration of high-frequency oscillating pressure and rectangular pressure impulse, are worthwhile to investigate. For fine fractures in the rock mass, the improvement of penetration is based on well-controlled phrases before and in grouting rather than grouting itself.

5. CONCLUSIONS

A review of the existing research on grouting provides answers to the five questions raised at the beginning of this study. In addition, several outcomes regarding the factors influencing the penetration of grout were also obtained by summarizing and comparing the test results in various investigations. They can be summarized as follows:

- Penetration of cement-based material mainly depends on rheology, filtration stability, and grouting pressure (Draganovic and Stille 2011, Nejad Ghafar, A., 2017). The factors are interdependent with changes in others. From existing experimental results, it was found that some factors such as w/c ratio, additives, grain size, and distribution have more significant impacts on flirtation stability than the others, including mixing equipment & time, cement age, etc. Meanwhile, most of these factors can influence the rheology of grout as well, which means rheology and filtration are largely coupled. Prioritizing the factors with the most significant effects will improve the penetration of grouting in an efficient way. Also, unexpected experiment results caused by coupled factors could be better interpreted with an enhanced understanding of the connection between them.
- Since the flow grouting method was first used for the reparation of a basement, there have been many effective methods such as static constant pressure and static pressure increments developed for sealing and other purposes. They have proved to be simple and efficient in a variety of construction projects. However, with the increased demands of underground construction and utilization of superfine grouting materials, conventional grouting methods have difficulties meeting the strict sealing requirements. These methods can hardly bring the grout into fine fractures due to filtration, especially for apertures < 70μm, in the rock mass. The main obstacles come from the preparatory

and grouting phase, where the viscosity and filtration stability of grouts are mostly influenced. Therefore, improvement of equipment and technique in both phases must be made to achieve better grout spread in fine fractures.

- To explore and validate the improvement of novel grouting equipment and techniques, understanding the limitations of existing ones and current evaluation methods is essential. Hence, a detailed look at the development of dynamic grouting methods from 1985 is presented in chronological order. Even though the roughness and texture in the real rock mass still cannot be simulated, there is a noticeable improvement in the evaluation equipment from the concrete slab (Pusch et al., 1985) to VALS (Nejad Ghafar, A., 2017). The filtration formation in the constrictions of fractures now can be simulated and monitored. On the other hand, quantitative comparisons of efficiency for each dynamic grouting technique are hard to carry out since there are wide discrepancies in materials and evaluation methods. Furthermore, researchers tended to compare the dynamic grouting technique they proposed to static pressure grouting rather than other dynamic grouting techniques. As a result, it is difficult to conclude the most efficient grouting method for micro fractures without experimental tests.
- A contradiction about the effect of high-frequency pressure on the viscosity of grouts was found in Mohammed et al. (2015). High-frequency oscillation caused an increase of viscosity of grouts compared with the static condition, which is contradictory to the conclusion of Pusch et al. (1985). Also, adverse impacts of dynamic grouting on penetration in fractures (250 and 100μm) were observed after 35s. One potential reason could be the faster hydration caused by the increased temperature in high-frequency oscillatory grouting. A similar effect can be observed when ultrasonic was used to disperse microfine cement in Draganovic et al (2020). Hence, high-frequency oscillatory pressure might not be suitable for long-time grouting.
- Lastly, the possible combinations of different grouting methods are discussed, with consideration of feasibility, rheology of grouts, and superimposed effect of mechanical waves. Although some combinations need sophisticated grouting equipment to generate desired dynamic pressures, the most achievable one is the combination of ultrasound dispersing method with low-frequency rectangular pressure impulse grouting. This technique is useful especially when micro cement-based materials are involved.

6. SUGGESTION FOR FUTURE WORKS

One conclusion that cannot be obtained in this thesis is the most efficient dynamic grouting technique is without the quantitative comparison of efficiency under the same evaluation system (equipment and method). Accordingly, it is worthwhile to conduct experimental tests with all other variables, such as grouting material, temperature, mixing type, and evaluation standard, controlled so that only different dynamic grouting pressures are compared.

Too high frequency or too long injection time of oscillatory grouting might have contrary impacts on penetration. Even though the mechanism can be interpreted with molecular dynamics, the increase of temperature and viscosity of grouts suspension depends on the heat conduction of the slot. High-frequency oscillation only brings energy to the molecules and increases the speed of molecular motion. As a result, the influence of high-frequency oscillation on grouts temperature needs to be investigated by either computational fluid dynamic (CFD)simulation with accurate boundary conditions and calculation of heat exchange or well-controlled experiments.

Meanwhile, another secondary problem about the filtration stability of grout at a temperature higher than 20 degrees isn’t studied well compared with low-temperature conditions. In some scenarios, with the operation of construction machines and other lighting equipment, the temperature and humidity in tunnels can be very high. Besides, the thermal effect from high-frequency oscillatory pressure can be more notable in high-temperature environment. It is valuable to give suggestions about the timing of dynamic grouting in the real project if more data are available.

In the end, CFD is also powerful to optimize the peak and rest periods for low-frequency rectangle impulse pressure with consideration of roughness and texture of the factures surface, which can hardly be simulated by steel slots.

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