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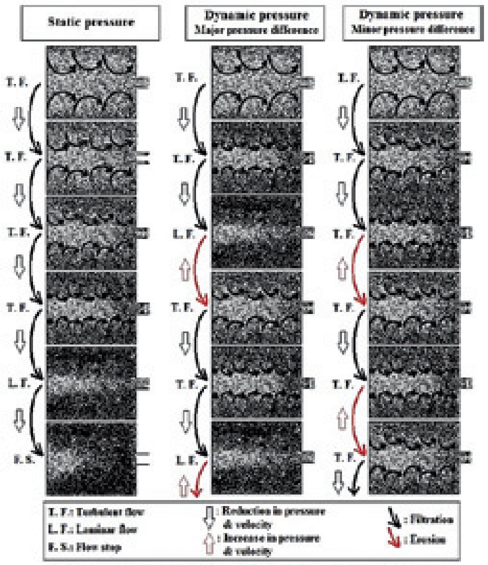

Hypothetical mechanism of action of dynamic pressure

AN EXPERIMENTAL STUDY OF THE INFLUENCE OF DYNAMIC PRESSURE ON IMPROVING GROUT PENETRABILITY

Ali Nejad Ghafar
Almir Draganovic
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BeFo Report 149

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AN EXPERIMENTAL STUDY OF THE INFLUENCE OF DYNAMIC PRESSURE ON IMPROVING GROUT PENETRABILITY

Effekten av varierande tryck på inträngningsförmågan hos injekteringsbruk. En experimentell studie

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PREFACE

Rock mass grouting is of importance in Scandinavian tunnelling to be able to control surrounding groundwater levels and leakage into the tunnel. Demands for water sealing, especially in urban areas, increase successively and even more narrow fractures needs to be sealed to reduce the risk for settlement in existing buildings and other structures. To allow grouting of the finest water bearing fractures to result in very low permeability for the rock mass, specific grouting measures needs to be applied regarding material and methodology. A problem that restricts the grout material to penetrate fine fractures is clogging of particles, so called filtration. The grout process during construction works is time consuming and result in high costs, thus an incentive and interest for improvements.

This research project has studied improved penetration of cement based grout material by varied pressure, i.e. dynamic pressure, to reduce filtration. This methodology was studied before, but in this project the frequency is lower in order to give time to break down the filtration during the low pressure phase. The project is a limited study based on laboratory tests. The results are positive and if further developed to full scale grouting in construction projects, this may have a large impact on sealing efficiency and the time consumption to grout.

The research was primarily carried out by Ali Nejad Ghafar, supervised by Professor Stefan Larsson and Amir Draganović (assistant supervisor), all at KTH in Stockholm, Sweden. A M.Sc. thesis work by Anastasios Mentesidis contributed greatly to the project laboratory work and reporting.

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Stockholm in December 2015
Per Tengborg

FÖRORD

Injektering av bergmassan är centralt i Skandinaviskt tunnelbyggande för att kontrollera omgivande grundvattennivåer och inläckage till tunneln. Täthetskraven på tunnlar, speciellt i urban miljö, ökar successivt och man vill kunna täta allt finare sprickor för att minska risken för sättningar i byggnader och andra anläggningar. För att lyckas injektera de finaste vattenförande sprickorna som krävs för att nå krav på mycket låg permeabilitet i bergmassan så behövs speciella åtgärder vid val av såväl material som -metodik. Ett problem som begränsar spridning i de finare sprickorna i berget är att injekteringsmedlets partiklar sätter igen sprickorna, så kallad filtration. Injekteringsprocessen är också ett tidskrävande moment i tunnelbyggande och innebär höga kostnader så det finns ett stort intresse för effektiviseringsåtgärder.
Detta forskningsprojekt har studerat ökad inträngning av cementbaserat injekteringsmedel genom varierat tryck för att minska filtration. Det är en metodik som studerats tidigare men i detta projekt används lägre frekvens med syfte att under en längre lågtrycksfas bryta ner filtrationen. Projektet är en begränsad studie och genomfördes med hjälp av laboratorieförsök. Resultaten har varit positiva och om de kan utvecklas vidare till att omfatta fullskalig injektering i undermarksprojekt så kan det få stor betydelse för både möjligheten att täta finare sprickor och effektiviteten i utförandet, d v s tidsåtgången.
Forskningen har i första hand utförts av doktorand Ali Nejad Ghafar med handledare Professor Stefan Larsson och assisterande handledare Dr Almir Draganović, samtliga vid KTH, Stockholm. Genomförande av ett examensarbete av mastersstudent Anastasios Mentesidis har inneburit att projektet fått hjälp med laboratoriearbete och rapportering.
En referensgrupp bestående av Håkan Stille (KTH), Robert Sturk (Skanska), Thomas Janson (Tyréns), Emmeli Johansson (SKB), Kent Lundin (TeliaSonera), Niclas Bockgård (Golder Ass.), Tommy Ellison (Besab), Hans Hargelius (Trafikverket), Daniel Eklund (SKB) och Per Tengborg (BeFo) har bidragit med granskning och kommentarer till projektet.
Projektet finansierades av Stiftelsen Bergteknisk Forskning (BeFo), SBUF och Trafikverket.

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Per Tengborg

SUMMARY

In order to increase the sealing efficiency in rock grouting, the fractures should be entirely grouted while the filtration of cement particles is an obstacle. By reducing the filtration, penetrability of grout will be increased resulting in a more reliable grouting. Some of the advantages of controlling filtration are decreas in time, costs and the environmental impacts of the projects. Increase in the safety margins of the projects during both the construction and the operation are also among the benefits of regulating the filtration.

Use of variable pressure for improving grout penetrability has been studied in both the lab and the field over the years. The focus of the previous investigations was mainly on application of high frequency oscillating pressure using artificial parallel plates without constrictions with openning sizes larger than 100 μm. The mechanism of improvement of grout penetrability was interpreted as reduction in viscosity due to the oscillation in all those studies. The missing parts of the resulted knowledge are the influences of different shapes of the variable pressure and the effects of low frequencies i.e. longer cycle periods to penetrate through micro fractures smaller than 100 μm with constrictions. Moreover, other mechanisms of improvement of grout penetrability might also be more efficient than reduction in viscosity due to the oscillation.

The focus of this study is therefore to investigat the influence of low frequency instantaneous variable pressure with different peak and rest periods on regulating the filtration. A pneumatic pressure control system has been thus employed using parallel plates with constrictions of 43 and 30 μm. The proposed mechanism of action was change of flow pattern due to the change in pressure and the corresponding velocity. Comparison of results of the variable and the constant pressures revealed the great impact of the examined variable pressure on improving grout penetrability.

KEY WORDS

Penetrability, filtration, erosion, cement-based grout, variable/dynamic grouting

SAMMANFATTNING

För att öka tätningseffektivitet i berginjektering måste sprickorna injekteras helt men filtration av cementpartiklar är ett hinder till det. Med reducerad filtration, inträngningsförmåga av bruket vill öka vilket resulterar i en mer pålitlig injektering. Vissa fördelar av att kontrolera filtration är minskad injekteringstid, minskad projektkostnad och påverkan på miljö. Att kunna kontrollera filtration skulle öka säkerhetsmarginaler av projekt både under konstruktions- och drifttid.

Användning av varierande tryck för förbättring av inträngningsförmåga har studerats både i labboratoriet och i fält under många år. Fokus i dessa undersökningar var huvudsakligen användning av högfrekvensoscilleradetryck i konstgjorda parallella plattor utan viddminskningar och större än 100 μm. Mekanismen bakom förbättringen av injekteringsförmåga har interpreterats som minskning av viskositeten av bruket pga. oscillationer i bruket. I dessa studier har man inte studerat effekten av olika former av varierande tryck och effekten av låg frekvens dvs. längre cykel perioder på brukets inträngningsförmåga. Man har inte heller studerad det i sprickor mindre än 100 μm och med viddminskning. Dessutom andra mekanismer bakom förbättringen av brukets inträngningsförmåga kan bli mera effektiva än reducerad viskositet pga. oscillationer och borde studeras.

Fokus i denna studie har därför varit att undersöka påverkan av varierande tryck med låg frekvens med momentan tryckändring och med olika topp och botten perioder på filtrering. Ett pneumatiskt tryckkontrollsystem har tagits fram för injektering av spalter med spaltviddminskningar av 43 och 30 μm. Den studerade mekanismen var hur

ändringen av flödes regim pga. varierande tryck och flödeshastighet påverkar inträngningsförmåga. Jämförelse av resultat från varierande och konstant tryck visade att studerade varierande tryck har en stor påverkan på brukets inträngningsförmåga.

ACKNOWLEDGEMENTS

The survey was carried out within the frame of Trust3.3-GeoInfra (http://trust-geoinfra.se). The authors warmly acknowledge the funders of the project, viz. the Rock Engineering Research Foundation (BeFo), the Swedish Transport Administration (Trafikverket), and the Development Fund of the Swedish Construction Industry (SBUF) for their financial and technical supports. Success in this project would definitely not have been possible without the much appreciated generosity of BeFo in providing the extra budget required for the project equipment. Hard-working and extreme efforts of master student Anastasios Mentesidis during the laboratory works and his collaboration in the analysis of the results and technical discussions of the project are also appreciated.

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1. INTRODUCTION

Cement grouting is one of the common solutions to seal an area in rock due to its benefites from economic, environmental and durability points of view. It delivers the required sealing efficiency in tunnels, dam foundations, hydropower plants and nuclear waste repositories provided that sufficient penetration length can be achieved during the injection process. Filtration of cement particles, defined as separation of suspended solid and liquid phases of a multi-phase fluid e.g. grouting material, is however an obstacle restricting the grout spread in rock (Rushton et al. 2000; Draganovic and Stille 2011; Eriksson and Stille 2003). The filtration phenomenon reduces the grout penetration length which consequently limits the efficiency of the rock grouting in any underground facilities.

To increase the grout spread through the fractures, the grout mix should be more stable and the filtration of the cement particles should therefore be decreased effectively. The effects of various parameters on controlling the filtration and improving the grout penetrability have been investigated by several researchers over the years. The grouting pressure has been found one of the most governing parameters affecting the grout penetrability (Eriksson et al. 1999; Hjertström 2001; Draganovic and Stille 2011; Draganovic and Stille 2014). The influence of the static pressure increment, studied by Nobuto et al. (2008), and the effect of the dynamic/vibrating grouting, investigated by Wakita et al. (2003) among the others, have been found satisfactory on improving grout penetrability both in the lab and the field. However, all the investigations on dynamic grouting were similarly limited on specific regions. The studies were mainly focused on application of high frequency oscillating pressure using artificial parallel plates without constrictions with aperture sizes larger than 100 μm, while the mechanism of improvement of grout penetrability was principaly explained as reduction in viscosity due to the oscillation. The influences of other alternatives of the variable pressure and the effects of low frequencies i.e. longer cycle periods on grout penetrability through micro fractures with constrictions smaller than 100 μm have been yet remained unknown. Moreover, other mechanisms of improvement of grout penetrability, which have not been investigated yet, might also be more efficient than reduction in viscosity due to the oscillation.

The main goal of this study was therefore, to further investigate the influences of other alternatives of the variable pressure e.g. the instantaneous variable pressure for improving the grout penetrability. It was also to study other probable mechanisms of improvement of the grout penetrability. Application of low frequencies i.e. less than 1 *Hz* with adjustable periods in peak and rest depending on the fracture/slot geometries and the material properties of the grout might improve the effectiveness of the method, while determining the extent of their influence on improving the grout penetrability were among the objectives of this investigation. The method was tested through parallel plates with constrictions smaller than 70 μm, whereas the cyclic change in flow pattern due to the change in flow velocity was proposed as the mechanism of improvement of the grout penetrability.

1.1 Scope of work and objectives

Variable/dynamic grouting is among the methods through which, considerable improvement on grout penetrability has been achieved both in the lab and the field since

1985. However, due to the aforementioned weak points and limitations in the previous investigations, there are still some places for improvement of the method. The aim of this study was therefore towards investigating the influences of other alternatives of the dynamic pressure e.g. instantaneous and/or ramp-shape vaiable pressures in the first place (Figure 1). In the second place, the goal was to study the effects of low frequencies i.e. less than 1 Hz on improving the grout penetrability. Based on some preliminary tests, the influence of the ramp-shape variable pressure on improving grout penetrability was however found less effective than the instantaneous pressure. This is probably because in the instantaneous variable pressure, the pressure change and the corresponding velocity variation occur approximately instantly. Consequently, the change of flow pattern will probably be faster and the resulting eroding of any partially built plugs will possibly be more effective than in the case of ramp-shape pressure. Investigating the influences of the low frequency instantaneous variable pressure was therefore, selected as the main objective of this project in order to further study the filtration at constrictions through the artificial fractures with aperture sizes less than 100 μm. Moreover, to better interpret the mechanism of action of the method on reducing filtration and improving the grout penetrability, the change of flow pattern under application of dynamic pressure was considered and studied in the presented study.

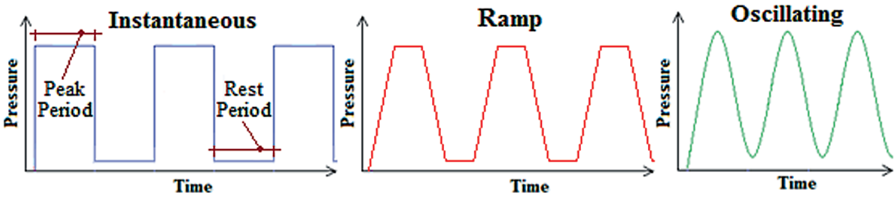


Figure 1 Various types of dynamic pressure

Figur 1 Olika typer av dinamik tryck

According to Draganovic and Stille (2011), short slot is a measuring instrument that provides the potential to investigate the influence of various parameters on grout penetrability. In this study the short slot was selected as the main instrument together with a programmable pneumatic pressure control system to examin the efficiency of the proposed method. The selected slots were the constriction sizes of 30 and 43 μm with the maximum applied pressure of 15 bars to make the test condition more similar to the real grouting condition in field. Moreover, two choices of the peak and rest periods of 4s/8s and 2s/2s were utilized in order to examine the influences of different peak and rest periods on improving the grout penetrability (Figure 2). After all, the results of dynamic pressure were compared with the results of the static pressure of 15 bars and the conclusions on the most efficient details of the grouting pressure together with the extent of their productivity were established.

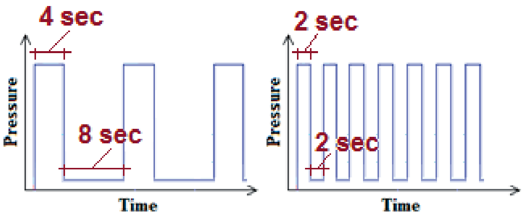


Figure 2 Instantaneous variable pressure with peak/rest periods of 4 s/8 s and 2 s/2 s

Figur 2 Momentan varierande tryck med topp/botten period av 4 s/8 s och 2 s/2 s

1.2 Limitations

Limitations of the current investigation comprised of following issues:

- *Number of the test repetitions* – Although the number of the test repetitions was judged to be enough to draw the conclusions, more data would be beneficial to raise the reliability of the findings.
- *Slot geometry* – The geometry of the short slots chosen in this investigation were supposed to simulate real fractures in rock. The slots' dimentions were predefined and just with one constriction compared with many irregularities in fracture's dimentions in rock. The smooth surface of the steel-made slots was also different with the rock surface of the fracture walls. However, these limitations facilitate examining of the penetration in lab under controlled and completely known conditions. Factors such as the limited longitudinal flow before and after the constrictions, the limited width of the slot and the lack of irregularities of the grout path should be taken into consideration specially in future steps of the project.
- *Lack of prior research* – Previous ivestigations in related area scarcely covered the influences of the dynamic pressure with similar pressure conditions on improving the grout penetrability. This made the design process of the required equipment and the evaluation methods as well as the interpretation of the results principally based on the judgement of the authors.
- *Equipment limitations* – Limitation in the capacity of the grout tank used in this investigation together with some limitations concerning the rate of the pressure variation might have some influences on the results which should be improved in further steps of the project.

- *Technological limitations* – To verify the proposed mechanism of improvement of grout penetrability under the suggested pressure conditions in this investigation, the flow pattern of the grout before the constriction inside the slot should be observed during the injection process. This was not possible, due to the limitation of the bending capacity of the transparent materials, such as Plexiglas, which led us to build the slot of steel. An indirect solution to this issue is using the Computational Fluid Dynamic technic (CFD) to simulate the flow pathern inside the slot under the influence of the dynamic pressure. This is going to be a part of the future steps of the project to verify the proposed mechanism of action.
- *Language of the existing resources* – The language of several existing resources in the related area was in Japanese. This unfortunately made them unusable for the authors.

1.3 Future prospect

Current technology of the grouting injection pumps, especially the piston pumps, is associated with a grouting pressure with uncontrolled fluctuations. This pressure is however considered as static pressure in the current design procedure which corresponds to our previous knowledge from the past decades. Nowadays the grouting process is principally done in field by applying the static pressure which is increased stepwise to improve the grout penetrability and obtain the required sealing efficiency.

A better understanding of dynamic pressure might provide a more effective alternative for the grouting pressure. The result would be adjusting the existing grouting design procedure based on application of dynamic pressure. The future outcome of this investigation could also be developing the new generation of grouting injection pumps with more efficient function in rock grouting. This might increase the potential to reduce the time and the costs of the projects and increase the safety margins during both construction and operation, resulting in a great influence on projects from economical point of view. Having a better grout penetrability, demands for use of chemical grouting could also be reduced which as a result might decrease their negative environmental impacts. Furthermore, reduction in time of the grouting process could result in less machinery works which could reduce the energy and fuel consumption. This might also decrease the environmental impacts of the construction works.

1.4 Organization of the report

This report is principally based on the M.Sc. thesis report of Anastasios Mentesidis and the scientific article submitted to the journal of Rock Mechanics and Rock Engineering by the authors. After presenting a short introduction to motivate the current investigation, the scope of work, objectives, limitations, and the future prospect of the project are discussed in the first chapter of the report. In chapter 2, a background on grouting is followed by presenting some details of various penetrability measuring instruments, the parameters and methods influencing the grout penetrability and finally the weak points and limitations of the previous investigation related to the dynamic grouting technic. Chapter 3 consists of the material in use in current investigation, the mixing process, the test procedure and the details of the test apparatus as well as some details about the selection of the peak and the rest periods, the evaluation methods and finally a hypothetical conceptual model for the mechanism of improvement of grout penetrability. In chapter 4, the test results are presented and discussed under four different evaluation methods. Conclusions are drawn in chapter 5 followed by the recommended future steps of the project. Following that. the references are presented in chapter 6. The report will be finished by appendices A and B, which presented the results of the pressure-time graphs, the software setting of the project.

2. RESEARCH BACKGROUND

Due to the significance of the grouting operations and the complexity involved, many researchers focused on the topic from different perspectives over the years. Literature review on related investigations revealed that several measuring methods and equipment have been developed to better understand and study the grout penetrability and the associated influencing factors. According to the previous researches, the following factors were found to be the governing ones regarding filtration and grout penetrability.

- Aperture size
- Water to cement ratio (w/c)
- Rheology (viscosity, shear resistance)
- Grain size and distribution
- Additives (e.g. dispersing agents)
- Constriction geometry (e.g. slot or mesh)
- Chemical reactions (hydration)
- Attractive – repulsive forces between grains (flocculation, agglomeration)
- Cement storage time
- Waiting time mixing and injection
- Mixing time and mixer type
- Magnitude and type of applied pressure

These parameters were examined using various measuring methods and equipment with different assumptions, limitations and test conditions. Due to these differences, the obtained results were sometimes in contradict. This led us in presented investigation to start with deeply examining of some of the aforementioned governing factors together with the differences between the equipment and methods.

2.1 Filtration and penetrability measuring instruments and methods

2.1.1 Sand column

Sand column is a very common used instrument for measuring grout penetrability designed by the French standard (NF 18-891, n.d.). A general depiction of the instrument is illustrated in figure 3 (Axelsson, et al., 2009).

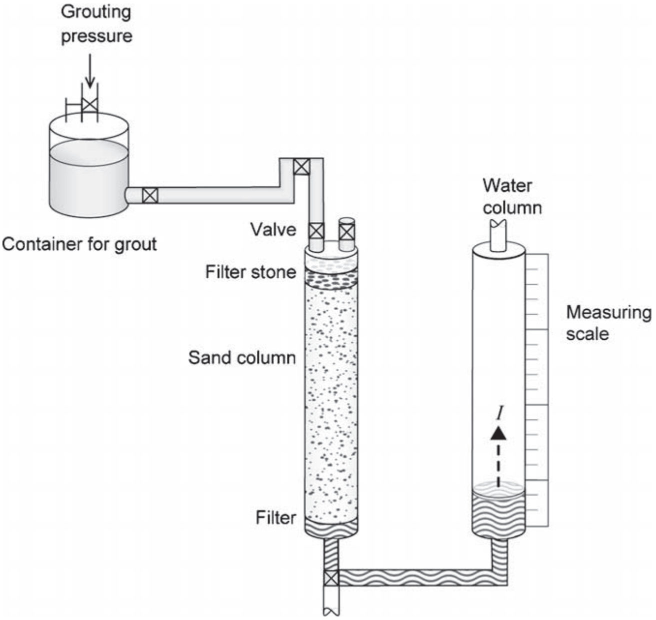


Figure 3 Sand column according to Axelsson et al. (2009)

Figur 3 Sandkolumn enligt Axelsson et al. (2009)

The sand column is comprised of three main parts: the grout container, the glassy sand column and the water column. The grout under pressure is pushed from the container towards the sand column which is filled with sand of known particle size distribution. The penetration length of the grout is measured in three different ways:

- By measuring the raised water in the water column in the case where the sand column is saturated
- By measuring the grout volume in unsaturated conditions
- By visual inspection of the sand column

Axelsson et al. (2009) stated that, parameters such as the porosity, hydraulic conductivity and theoretical aperture could be used to relate the sand column's medium to a real rock fraction.

They concluded with the following stop mechanisms:

- Clogging, where the grains are stuck before entering the aperture.
- Filtration, where the grains enter the aperture but gradually separate from the flow and eventually plug the pores
- Resistance, where the grouting pressure reaches the frictional resistance.

The apparent difference of the nature of flow patherns between a porous medium and a rock fracture urged many researchers to study the possible relation between the two. However, obtaining a clear relation between them was found difficult or rather impossible.

2.1.2 Pressure chamber or filter press

Another experimental instrument for measuring the filtration stability is the pressure chamber. The test procedure in pressure chamber is as follows:

The designated grout container of the instrument is filled with the prepared grout mix and then pressed out by compressed air. The grout suspension is forced to pass through a filtering surface with known penetrability made of varying materials such as paper, fine sand and other hardened materials such as soft rock etc. (Gandais & Delmas, 1987). Figure 4 shows the general depiction of the instrument according to Widmann (1996).

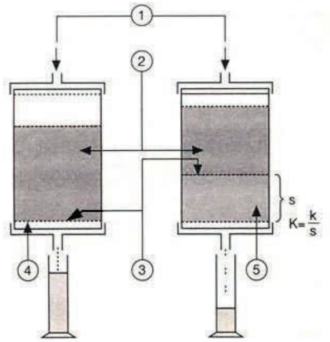


Figure 4 Pressure chamber as seen in Widmann (1996)

Figur 4 Tryckkammare från Widmann (1996)

According to Gandais and Delmas (1987) the density of the residue at the fllter surface is varying linearly with the depth which is directly proportional to the quantity of the filtered water. As stated by the same authors, the corresponding type of filtration mechanism is representative of the one occurring through a rock fracture. The grout is pressed against the fracture walls and filtered through the walls, due to the porosity of the rock matrix and existing micro-cracks. The result will be the flow stop due to the plug formation of the cement particles (Figure 5).

As Draganović (2009) commented, this type of stop mechanism might not be relevant in the study of very impermeable materials, specially in the test instruments, i.e. , the artificial fractures made of steel.

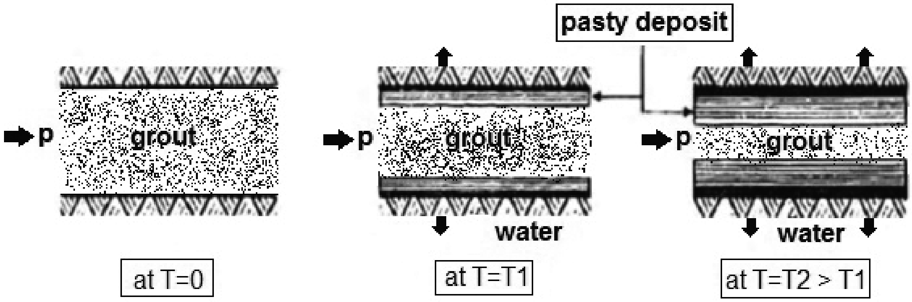


Figure 5 Plug formation as depicted in Gandais and Delmas (1987)

Figur 5 Pluggbildning illustrerad i Gandais and Delmas (1987)

2.1.3 Filter pump

Filter pump was another measuring instrument developed by Hansson (1995) for evaluation of filtration stability. The instrument was portable and easy to use, making it suitable to work both in the lab and the field as well. Figure 6 illustrates the general depiction of the instrument.

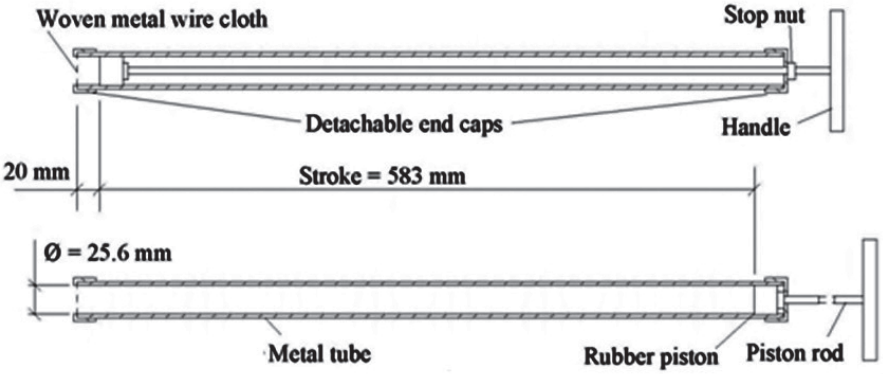


Figure 6 Filter pump as seen in Hansson (1995)
Figur 6 Filterpump från Hansson (1995)

To start the test, the grout is sucked by pulling the handle, while it is forced to pass through a woven metal wire cloth (Figure 7). The wire cloth consists of a mesh of predefined widths of 32, 45, 75, 100 or 125 μm (Hansson, 1995). At the end, based on the the amount of collected material a qualitative evaluation of the filtration stability is conducted.

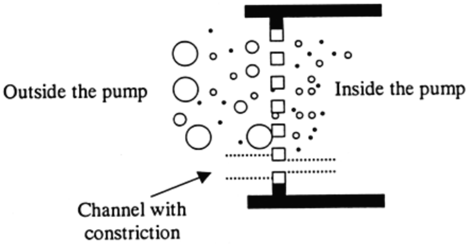


Figure 7 General depiction of constriction in mesh filter from Eriksson et al. (2000)
Figur 7 Illustration av kanaler med viddminskningar i nätet från Eriksson et al. (2000)

It seems that the mesh geometry of the filter pump is rather correlated to the porous medium of the sand column than to a fracture/concrete crack. An assumption for the above correlation is the behavior of the grouting material which should be closely

Newtonian (Hansson, 1995). The repeatability of the experiments done by this isntruments is however somewhat questionable. It will possibly be due to the variable applied pressure during the test procedure, since it is done manually.

By gradually increasing the filter width in each successive test, the amount of grout passing through the filter is increased (Eriksson et al. 2000). Based on this, they proposed two definitions of the b_{min} and b_{crit} for describing the penetrability of a given grout as illustrated in figure 8.

At the aperture sizes below the $b_{critical}$, the grout will be filtered while no grout can pass through a constriction with an aperture below the b_{min}. These properties will be utilized in presented research for evaluation of the grout penetrability.

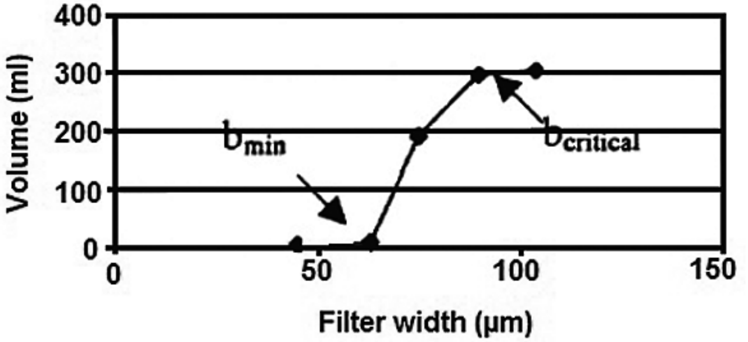


Figure 8 Depiction of bmin and bcrit according to Eriksson et al. (2000)

Figur 8 Illustration av bmin och bkritiskt enligt Eriksson et al. (2000)

2.1.4 Penetrability meter

Penetrability meter is another commonly used instrument, developed by Eriksson and Stille (2003), for measuring filtration and grout penetrability. The instrument consists of a grout container with an attached outlet ended by a cap holder for locating various sizes of mesh filters. The grout is pushed out under 1 bar of constant pressure while passes through a woven metal mesh filter. The same parameters of the b_{min} and $b_{critical}$ as used in the filter pump are utilized in penetrability meter for measuring the filtration tendency of the grout. Figure 9 illustrates the penetrability meter.

Figure 9 Penetrability meter developed by Eriksson and Stille (2003)
Figur 9 Filterpress utvecklad av Eriksson and Stille (2003)

Eklund and Stille (2008) used the penetrability meter both with the mesh and the slot geometries. They concluded that the probability of filtration in mesh geometry from 4 sides is more than that in the slot geometry from 2 sides, whereas the slot geometry is rather more similar to a real fracture geometry in field. This was explained and illustrated in figure 10.

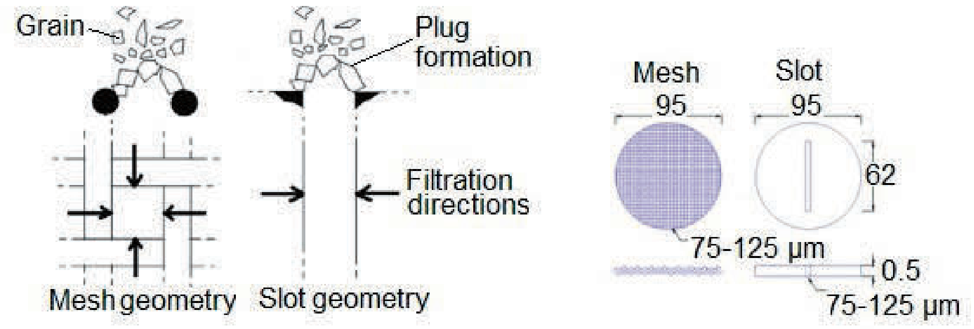


Figure 10 Mesh and slot geometry in penetrability meter (Eklund & Stille, 2008)

Figur 10 Nät och splatgeometry i filterpressen (Eklund och Stille, 2008)

2.1.5 NES method

The method, developed by Sandberg (1997), was a man-made artificial fracture in the form of two steel parallel plates. The instrument consisted of a slot attached to a grout tank suspended through a scale in a steel frame for measuring the weight of the passed grout in time. The grout mix was injected into the slot under different constant pressures provided by a high-pressure gas tank. The filtration mechanism in the instrument was similar to the filtration at connection between a borehole and a fracture. Figure 11 shows a general depiction of the NES method.

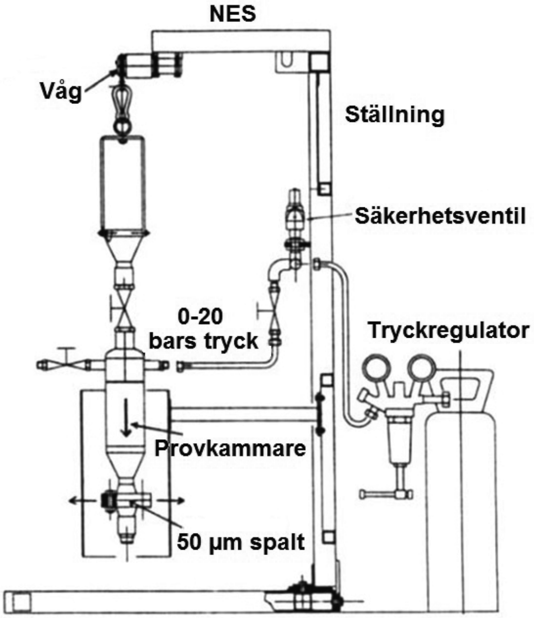
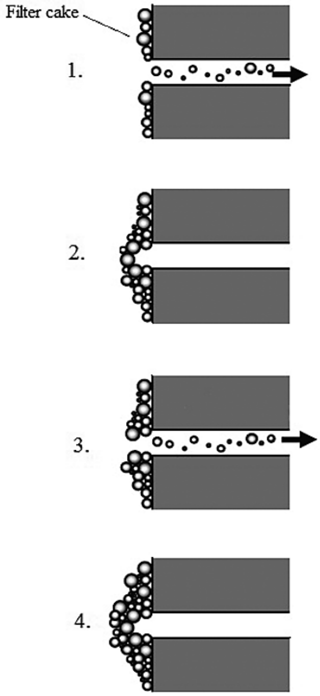


Figure 11 General depiction of the NES method (Sandberg, 1997)

Figur 11 Illustration av NES metoden (Sandberg, 1997)

The system was capable to support higher pressure of up to 20 bars. Using high-pressure during the test procedure, disregarding the many other differences with the previous measuring instruments, highly affected the obtained values of grout penetrability.

A slightly modified version of this instrument was used by Nobuto et al. (2008). The steel parallel plates in Nobuto system had four outflow paths using the field equipment of mixing, agitating and injecting. They tried to increase the grout penetrability using an stepwise pressure increament of 0 to 50 bars (Nobuto et al., 2008). The mechanism of filtration and clogging, proposed by Nobuto et al. (2008), is illustrated in figure 12.



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

Figur 12 Illustration av filtreringprocessen enligt Nobuto et al. (2008)

2.1.6 PenetraCone

PenetraCone, developed at Chalmers University of Technology, provided another alternative for field penetrability measurement. The measuring instrument is comprised of two conical cylinders, the outer and the inner. By rotating the inner one, the aperture size between the two cones can be adjusted during the test procedure. A typical test begins with a fairly large aperture size. According to Axelsson & Gustafson (2009), the out flow of grouting material is changed to drip by gradually decreasing the aperture size of the instrument. The chanell is then re-opened again making the grout flow continuous. The test is finalized by gradual decreasing the aperture size ended by the flow stop.

According to Axelsson & Gustafson (2009), the gauge reading at the time, when the continuous flow turns to dripping is called the b_{filter}, while the reading at the flow stop gives the b_{stop}. Figure 13 is an illustration of the PenetraCone.

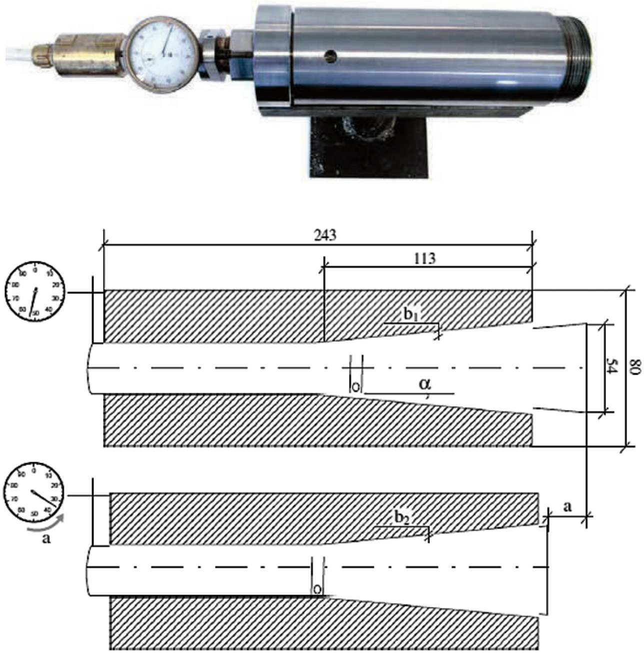


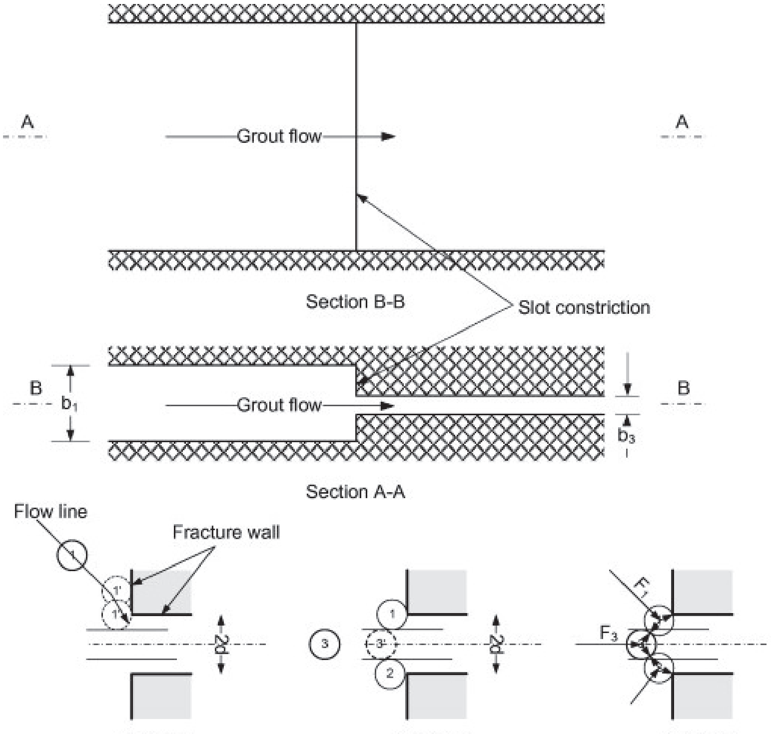
Figure 13 Illustration of PenetraCone (upper) and cross-section (lower) from Axelsson et al. (2009)

Figur 13 Illustration av Penetrakon från Axelsson et al. (2009)

2.1.7 Short Slot

Based on the configuration of the instrument in NES method, Draganović and Stille (2011) developed a new instrument for measuring grout penetrability. it was a manufactured artificial fracture made of two steel parallel plates. The major difference of the new instrument with the NES method was that the two channels of the short slot led to two constrictions before the outlet point. This made the principal filtration location of the new instrument at constrictions instead of at connection between the borehole and the fracture (NES method). The rest of the experimental set-up included a high-pressure gas tank as a source of pressure, a grout tank which was attached to the slot and a weighting system for registering the weight of the passed grout in time. The instrument was capable to withstand agains high pressures up to 20 bars with different constriction geometries. It also provided the potential of visual examination of the filter cakes after the tests.

According to Draganovic and Stille (2011), the linear relation in weight – time measurement was an indication of no filtration, while a non-linear relation implied the filtration. Figure 14 shows the cross- sections of the slot's constriction as well as arching of the cement particles during the penetration.



(a) $t = t_0$ (b) $t = t_1$ (c) $t = t_2$

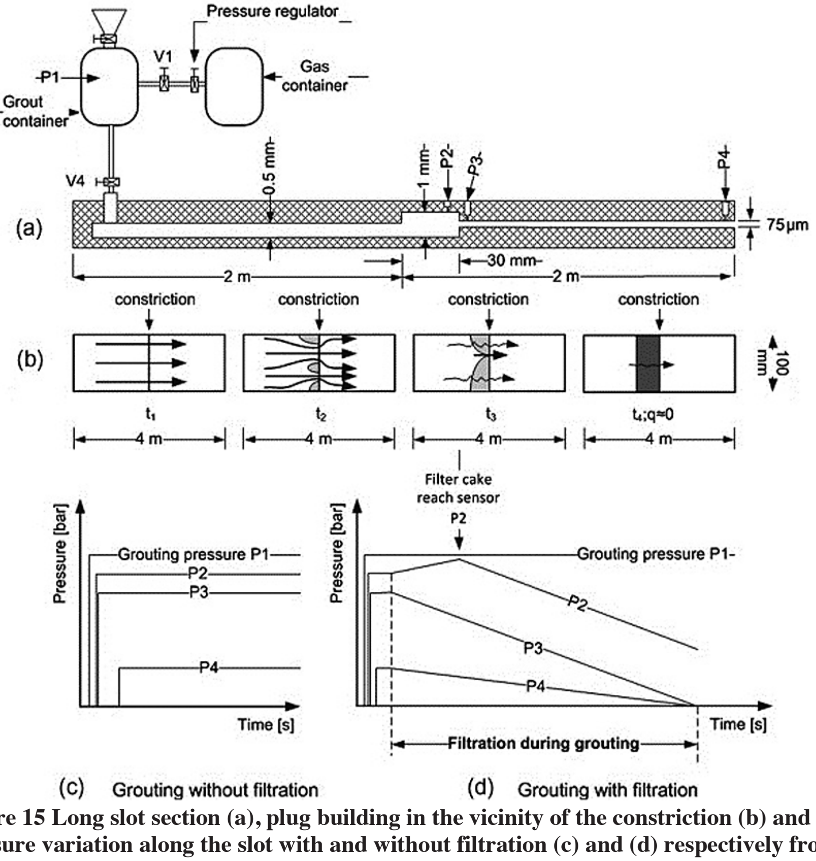
Figure 14 Slot constriction's sections (upper) and arching of the cement particles at the constriction (lower) (Draganović and Stille, 2011)

Figur 14 Spalt med spaltviddminskning (övre bild) och valvbildning med cementpartiklar vid spaltviddminskning (lägre bild) (Draganović och Stille, 2011)

2.1.8 Long Slot

Long slot is another instrument developed by Draganovic and Stille (2014) to measure grout penetrability and study the pressure condition along an artificial fracture. It was a four meter slot with a constriction of 75 μm in the middle. The pressure was provided by a high-pressure gas tank adjusted using a pressure regulator. The long slot was more similar to a real fracture in rock due to the considerable length of the slot before and after the constriction, compared to the short slot.

The main focus of their project was to identify the filtration process inside the slot using the pressure gradient as an indication of filtration (Draganović & Stille, 2014). To do this, four pressure sensors were placed in the longitudinal direction of the slot. Figure 15 shows a section of the long slot as well as the proposed grout flow pattern in the vicinity of the constriction and pressure variance with and without filtration. As seen in the figure, the pressure was monitored at the entrance of the slot, before and after the constriction, and right before the outlet.



(c) Grouting without filtration (d) Grouting with filtration

Figure 15 Long slot section (a), plug building in the vicinity of the constriction (b) and the pressure variation along the slot with and without filtration (c) and (d) respectively from Draganović & Stille (2014)

Figur 15 Långspalt sektion (a), pluggbildning vid spaltviddminskningen (b) och tryck ändring längst spalten med (a) och utan (b) filtration Draganović & Stille (2014)

2.2 Parameters and methods influencing the grout penetrability

Due to the significance of grouting both from economic and environmental point of views the affecting parameters on penetrability of grout have been the focus of several researches over the years. Based on the work done by Schwarz (1997) on cement particle sizes & distribution curves, the cement particles with the sizes of 0.4 - 4 μm are filtered sooner due to the flocculation. While the colloidal particles smaller than 0.4 μm remain dispersed in the suspension due the repulsive forces. The particles bigger than 4 μm do not flocculate so will penetrate longer. According to Hansson (1995) the filtration tendency is strongly dependent on w/c ratio. He also illustrated than the super plasticizer content has a great impact on grout penetrability in a smooth slot. Furthermore, he concluded than the best dispersion can be achieved after 100 sec of mixing and further mixing time does not influence the grout penetrability. Eriksson et al. (2004) stated that using a field mixer instead of a lab mixer will increase the penetrability, while Hjertström and Petersson (2006) recommended the use of colloidal mixers for micro fine cements. Eriksson et al. (2004) also showed that by increasing the cement storage time, the grout penetrability will be decreased. Moreover, Eriksson et al. (1999) and Hjertström (2001) illustrated that increasing the pressure will increase the grout penetrability, while according to Nobuto et al. (2008) clogging of cement particles can be prevented by applying the stepwise pressure increment.

The efficiency of dynamic/vibrating grouting on improving the grout penetrability due to the reduction in viscosity has been demonstrated in the Stripa mine by Pusch et al. (1985). Borgesson and Jansson (1990) illustrated that by superimposing a high frequency oscillating pressure with large amplitude on a high static pressure of 20 bar, even a low water content cement grout can penetrate well through 100 μm artificial fractures. The results were satisfactory in their full scale field tests as well. The mechanism of action of improving the grout penetrability in their investigation was explained as reduction in viscosity due to the oscillations. Wakita et al. (2003) performed several cases of laboratory and field tests through which, by adding an oscillating pressure to a static pressure the flow rate and the total grout take were increased. Like the Borgesson et al. (1990) they interpreted the improvement of grout penetrability based on the reduction in viscosity of grout suspension due to the oscillating pressure. Finally according to Mohammed et al. (2015), the influence of dynamic pressure on improving the penetrability of grout with the viscosity of 0.05-1.0 Pas into the fractures of 100-500 μm was significant, while the reason was again explained as reduction in viscosity.

The filtration phenomenon has also been the focus of several researchers who investigated it in various locations obstructing the grout spread in rock. These filtration locations are principally; 1) Filtration through the porous walls of a fracture (Gandais et al., 1987), 2) Filtration at connection between a borehole and a fracture (Sandberg, 1997) and finally 3) Filtration at a constriction through a fracture (Draganovic and Stille 2011). According to Draganovic and Stille (2011), filtration at a constriction through a fracture is the most governing filtration spot influencing the grout penetration. While by flocculating the cement particles, a stable arch is initiated and propagated over the constriction followed by a smooth decrease in penetration and finally the flow stop.

2.3 Weak points and limitations of the previous investigations related to the dynamic grouting technic

To sum up, the weak points and the limitations of the previous researches related to the dynamic grouting are among the following:

- The type of the applied pressure was a superimposed oscillating pressure on a static pressure. Other probable shapes of the applied pressure e.g. the instantaneous and/or the ramp variable pressures have not been investigated yet. While there might be different impacts on improving the grout penetrability, using various shapes of the applied pressure.
- The applied frequency has usually been high i.e. greater than 1 Hz. The influence of low frequencies i.e. less than 1 Hz, under application of oscillating pressure has not been sufficiently investigated yet. Furthermore, there might be a significant difference on improving the grout penetrability, under application of instantaneous and/or ramp pressures, using low frequencies i.e cycle periods more than 1 sec.
- The major mechanism of the achieved improvement on grout penetrability has always been stated as reduction in viscosity. The reason for that has been explained as disruption of the inter-connection of the cement particles and clusters and re-organizing the internal structure of the suspension under the influence of vibration. Other probable mechanism of action i.e. the cyclic change of flow patterns due to the change in pressure and consequently the flow velocity has not been examined yet. Moreover, in high frequency oscillating pressure i.e. greater than 1 Hz, the cycle time i.e. less than 1 sec, is probably not sufficient for effective change of

pressure and flow velocity. This means that the mechanism of action of change of flow pattern is probably not applicable in high frequency oscillating pressure.

- The laboratory tests were mainly performed on artificial fractures built as parallel plates without any constrictions. The influence of dynamic grouting on reduction of filtration at a constriction through a slot/fracture has not been investigated yet. While according to Draganovic and Stille (2011 and 2014) filtration at a constriction through a fracture is the most governing location with the highest probability of filtration.
- The aperture sizes of the used parallel plates were mainly bigger than 100 μm. The influence of the dynamic pressure on improving the grout penetrability in slot/fracture apertures less than 100 μm has not been sufficiently investigated so far. In fractured rock, the major portion of conductivity is through a few number of large fractures i.e. bigger than 100μm, while large number of small fractures i.e. less than 100 μm are responsible for the remaining small portion. In order to achieve the required sealing efficiency in rock grouting, especially in nuclear waste repositories with very high sealing requirements, successful grouting in small fractures i.e. less than 100 μm is crucial. This illustrates therefore, the significance of investigating the behavior of grout under influence of dynamic pressure in small fracture apertures i.e. less than 100 μm.

3. MATERIAL AND METHOD

3.1 Material

The selected recipe in presented study was one of the most common used recipes in grouting industry in Sweden. Cement of INJ30 with maximum particle size (d95) of 30 μm from Cementa AB with a water to cement ratio (w/c) of 0.8, together with iFlow-1 as the super-plasticizer from Sika AB with 0.5% of concentration were the used materials in this project.

Test plan

In order to study the efficiency and compare the influence of the dynamic pressure with the static pressure the following experimental program was organized to examine the prepared grout samples (Table 1). The designated test plan consists of six test groups. In the test groups C1 and C2, the samples were examined under application of a static pressure of 15 bar. In the test group V1 and V2, an instantaneous variable pressure with the maximum of 15 bar was applied to the material with the 4s/8s peak and rest periods. Finally, in the test groups V3 and V4, the same pressure was utilized just with the 2s/2s peak and rest periods.

Table 1 Test plan

Tabell 2 Testplan

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

3.2 Selection of peak and rest periods

In order to approach the real grouting condition in field, the static pressure of 15 *bars* was chosen as the applied pressure in test groups *C1* and *C2*. The aim was to achieve more realistic results as the bases of the comparison in this study. In the test groups *V1* and *V2*, instantaneous variable pressure with the peak and rest periods of 4 and 8 *sec* respectively was utilized for the injection (Figure 16). Based on the results of the static pressure in the first step, the filtration process was mainly started after 4 *sec* of injection. In order to increase the effectiveness of the dynamic pressure, the main idea was to either prevent or delay the filtration process effectively. This means that the duration of the peak period should be less than the required time for initiation of the filtration. By choosing a peak period more than 4 *sec* the filtration process has already been initiated in the slot during the first peak period and it would be much more difficult to erode it thereafter. That was the main reason for choosing the 4 *sec* as the

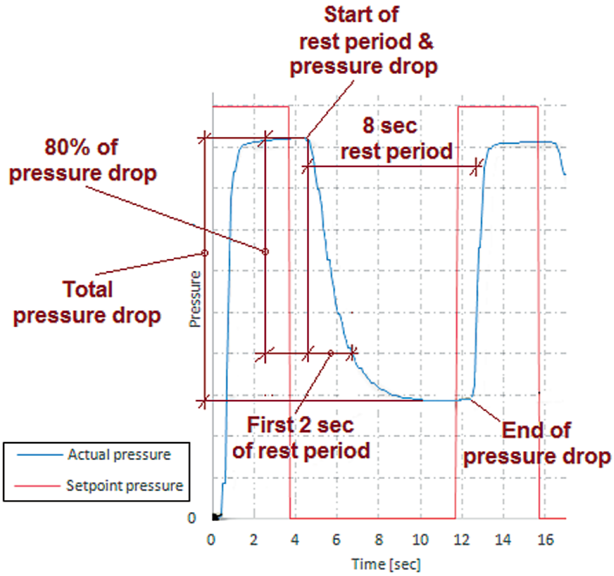


Figure 16 Instantaneous variable pressure, details of peak and rest periods

Figur 16 Momentan ändring av tryck med detaljer om topp och botten perioder

duration of peak period in step 2.

In each cycle after 4 *sec* of the peak period with 15 *bars* pressure the ball sector valve is instantaneously closed. This means that the applied pressure on grouting material tends to zero. However, sufficient time is needed for reduction of pressure after the valve. The choice of the rest period of 8 *sec* was therefore to provide this adequate time during each cycle (Figure 16).

Application of the peak period of 4 *sec* in *step 2* illustrated some gradual accumulation of the filtration in the test results during the peak periods (Figure 16). This observation led us to reduce the duration of the peak period to 2 *sec* in *step 3*. The test results of the *step 2*, also presented a pressure drop before the first 2 *sec* and a minor pressure reduction after 2 *sec* during the rest periods (Figure 16). The main portion of the pressure reduction therefore occurred during the first 2 *sec* of each rest period. This observation led us to decrease the duration of the rest period to 2 *sec* in *step 3*. The duration of peak and rest periods in *step 3* were thus both chosen as 2 *sec*.

3.3 Mixing process

A high speed rotor-stator lab mixer (*SR* Series) from *VMA* with 10,000 *rpm* was selected as the main mixer for the mix preparation. The duration of the mixing process was 4 minutes started by adding the prepared cements samples to the required water. A handy mixer was first utilized to pre-mix the materials before starting the main mixing process. After 1 minute of the main mixing process the prepared super plasticizer was added to the mixture. This was to maximize the dispersion influence of the super plasticizer. By finishing the mixing process, the grout container was then filled with the prepared grout to run the test immediately. The grout volume of each batch was about 2.8 liter.

3.4 Description of the test apparatus

The test apparatus was basically a steel grout tank attached to a short slot at the bottom (Figure 17). The grout tank with the capacity of 2.6 liters was suspended through a high accuracy S-shaped load cell in a steel frame designated for suppoting the weight of the whole system. The short slot was a disc-shape parallel plate made of steel with different constriction sizes of 30 and 43 μm. More detailes of the short slot can be found in Draganovic and Stille (2011). The load cell was the *RSCC C3/50kg* from *HBM* to register the weight of the injected grout in time. The grout tank was also connected to a high pressure gas tank of 200 *bars* to provide the grouting pressure during the test procedure. A pressure regulator was attached to the system to regulate the pressure to a static pressure of 15 *bars*. In order to control and register the provided pressure, a pressure transducer i.e. *P15RVA1/20BAR* from *HBM* was also connected to the beginning of the grout tank. This pressure was plotted in time using the *Catman easy* software. The grout tank from the bottom was then connected to a ball sector valve from *Ramén AB* through a high pressure hose. The valve was controlled by a *PID*-control unit from *Bronkhorst High-Tech*. It was a pneumatic pressure control system which was programmed through the *flow-plot* software from *Bronkhorst High-Tech*. After the ball sector valve a high accuracy pressure sensor i.e. *Vegabar 83* was located to measure the grouting pressure in time at the entrance of the short slot. This pressure sensor was also connected to the *PID*-control unit. The function was to compare the measured pressure with the pre-defined pressure i.e. the set point in time to control the opening situation of the ball sector valve.

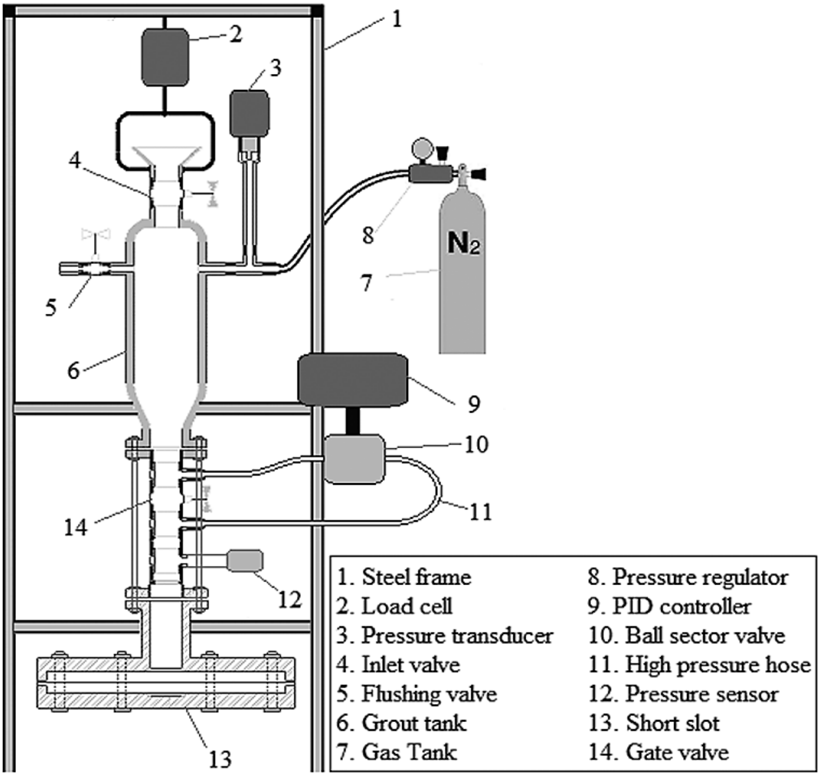


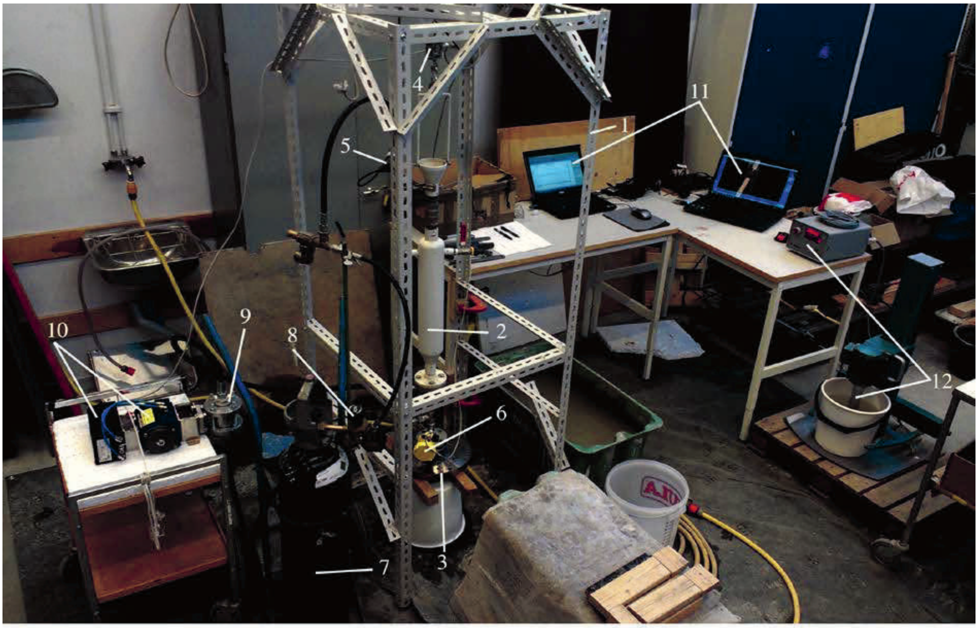
Figure 17 Schematic depiction of the test device configuration
Figur 17 Schematisk illustration av testutrustning

3.5 Test procedure

For each test a control script was written to define the pressure set points using the *flow-plot* software. In this script the magnitude and the duration of the applied pressure i.e. the peak and the rest periods were defined for the control system.

The test is regularly started by attaching the selected slot of 30 or 43 μm to the grout tank (Figure 18). After filling the grout tank with the prepared grout mix the inlet valve is closed. A static pressure of 15 *bars* is then applied, while valves 10 and 14 are fully closed. By running the control script, the ball sectore valve 10 is positioned at fully open situation. The grout flow is then initiated through the slot under the maximum pressure of 15 *bars* during the peak period. At the end of the peak period valve 10 is positioned at fully closed situation. The result is a sharp pressure drop followed by a gradual pressure reduction during the rest period. This process is repeated until either the entire grout volume has passed through the slot or flow stop occurs due to the complete filtration of cement particles at the constriction through the slot.

During the whole test procedure the measures of weight and pressure are registered and plotted in time. The repeatability of the test apparatus and the methods are also examined by re-performing the test randomly.



1. Steel frame
2. Grout tank
3. Short slot
4. Load cell
5. Pressure sensor-A
6. Pressure sensor-B
7. Gas tank
8. Pressure regulator
9. Ball sector valve
10. Actuator & I/P converter
11. Flow plot & Catman easy Softw.
12. Lab mixer

Figure 18 General overview of the test setup
Figur 18 Bild av testutrustning

3.6 Conceptual model

In order to better understand and interpret the mechanism of improvement of grout penetrability under application of dynamic pressure, a hypothetical overview of the flow patterns of the grout before the constriction through the slot during the static and dynamic pressures are depicted in the conceptual model in Figure 19.

When a high static pressure of 15 bars applies, a high flow velocity occurs before the constriction through the slot which makes the flow state rather fluctuated and turbulent with some vortexes. The static condition of the flow pressure makes the path of the streamlines and size of the vortexes rather stable. Due to shear stress and friction between the walls of the fracture/slot and the grout, the flow velocity decreases at the vicinity of the fracture walls before the constriction. This increases the interaction between the suspended cement particles and clusters before the constriction. The probability of clogging and filtration of the suspended cement particles is therefore increased. This results in an increase in the grout density in time before the constriction with an outward trend. The closer to the walls of the fracture/slot, the greater the grout density. The result will possibly be the necking phenomenon which occurs at the constriction reducing the opening size in time. Finally, the flow stop occurs after sufficient accumulation of the cement particles at the constriction.

When the dynamic pressure applies, the start of the process is the same. However, because of the pressure variation, the flow velocity varies periodically. Having a minor pressure variation, results in a slight cyclic change in velocity. This provides a continuous variation in position of the streamlines and size of the vortexes of the fluid.

Having a major pressure variation leads to a dominant velocity change. This varies the flow type from turbulent to laminar continuously. The flow pattern will therefore be thoroughly transversed cyclically. In both cases, the result will probably be removing the unstable accumulated cement particles and clusters and eroding the filter-cakes with high instability, which in the case of major pressure difference would be higher. The final result will be increasing the total amount of grout take, which is an indication of improving the grout penetrability.

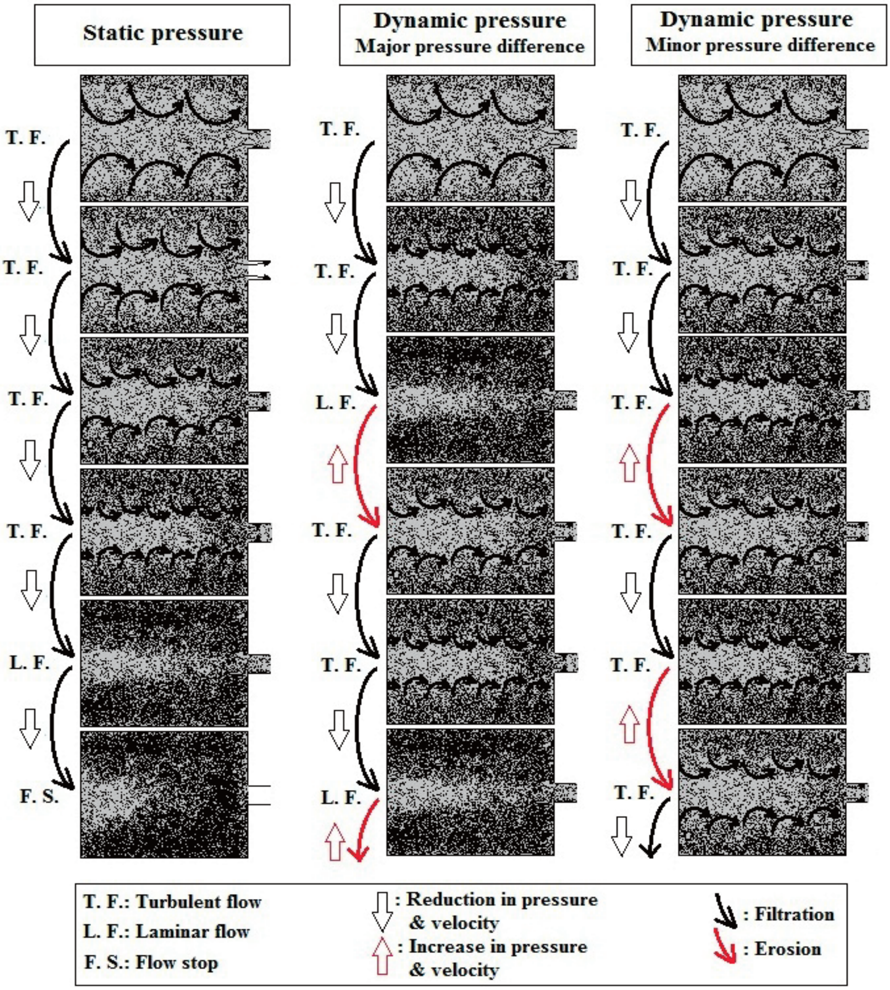


Figure 19 Conceptual model of grout flow under application of static and dynamic pressure
Figur 19 Konceptuellmodell av brukets flöde under injekteringen med statiskt och dynamiskt tryck

3.7 Evaluation methods

In order to evaluate and illustrate the influence of dynamic pressure on improving the grout penetrability various methods were employed in this study.

- The total weight of the passed grout
- The weight-time measurement
- The pressure-time measurement and the min-pressure envelope
- The cycle mean flow rate (CMFR)

Measure of the total weight of passed grout is a simple way to compare the influence of the dynamic and the static pressures. However, the method is unable to show the process of filtration and erosion in time. In the weight-time measurement, developed by Draganovic and Stille (2011), the method simply monitors the filtration process. However, the distinction between the filtration and erosion processes is unclear in the method. A linear relation in the weight-time measurement is an indication of no filtration versus a nonlinear relation which is an illustration of filtration.

The pressure-time measurement is another method which is capable to monitor the filtration and erosion processes during the injection. A polyline called the min-pressure envelope is utilized in the method to distinguish between the filtration and erosion processes (Figure 20). It is formed by connecting the consecutive vertices of the minimum pressure levels of the rest period in all cycles. A positive change or upward trend along this polyline is an indication of filtration while a negative change or downward trend is an illustration of erosion. At the end of the peak period by closing the valve the grouting pressure inside the slot tends to zero along the rest period. The magnitude of the pressure reduction is highly dependent on the size of the slot opening. The greater the opening size, the higher the magnitude of the pressure drop and consequently the lower the minimum pressure at the end of the rest period. Accumulation of the cement particles during the filtration process and the resulting necking phenomenon decreases the opening size of the slot in each cycle. This decreases the grout flow and consequently the magnitude of the pressure drop in subsequent cycles. Therefore, the associated minimum pressure level is increased in succeeding cycles. The result is an upward trend of the min-pressure envelope during the filtration process. By eroding the unstable filter-cakes of the accumulated cement particles and clusters, the size of the slot's opening is however increased. This results in a higher grout flow and consequently a higher magnitude of the pressure drop during the rest period. The associated minimum pressure level is therefore decreased resulting in a downward trend in the min-pressure envelope during the erosion process.

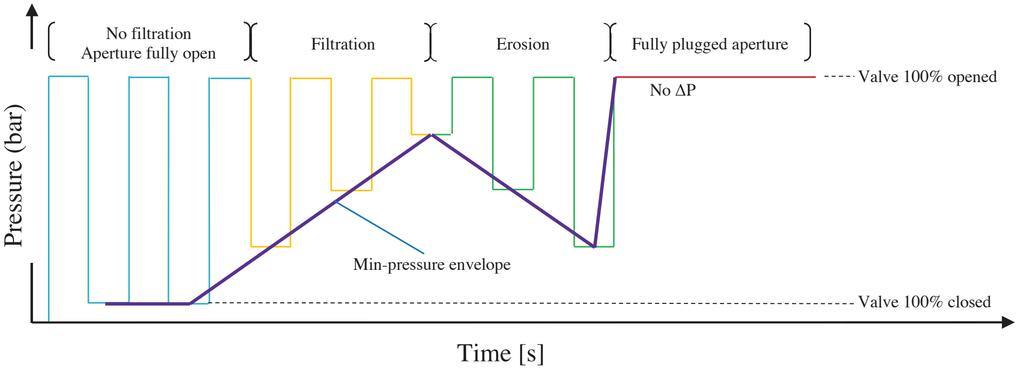


Figure 20 Illustration of the min-pressure envelope and the filtration and erosion
Figur 20 Illustration av tryck-envelopp och filtration/erosion process

The min-pressure envelope is a graphical method to monitor the filtration and erosion processes during the test procedure. However, to quantify them and to better distinguish between the influences of different peak and rest periods, a new parameter called the cycle mean flow rate (*CMFR*) is introduced. The *CMFR* is defined as the mean value of the volumetric flow rate of the passed grout during each cycle. It is obtained using the registered weight of the passed grout in time. The grout density is first measured using a *Mud balance*. The volume of the passed grout during each cycle is then calculated. Finally the *CMFR* value can be determined as follows.

$$CMFR = \frac{V}{T}$$

Where:

V is the volume of passed grout during each cycle.

T is the duration of one cycle.

4. RESULTS AND DISCUSSION

4.1 Evaluation of results using the total weight of passed grout

4.1.1 Test results using the slot with 43 μm constriction size

In first step of the study a short slot with 43 μm constriction size was employed to illustrate the influence of static and dynamic pressures on grout penetrability. Results of the test groups C1, V1 and V3 using the total weight of passed grout as the evaluation method are presented in table 2.

Table 3 – Comparison of total weight of passed grout for test groups C1, V1 and V3, using the 43 μm slot

Tabell 4 - Total vikt av paserade bruk i försöksgupper C1, V1 och V3 genom 43 μm spalten

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 condition
C1 (static)	1	-	1.339	Not empty	1.932	-
	2	-	2.055	Not empty		
	3	-	2.402	Not empty		
V1 (dynamic)	1	4s/8s	4.189	Empty	4.271	2.2
	2	4s/8s	4.302	Empty		
	3	4s/8s	4.321	Empty		
V3 (dynamic)	1	2s/2s	4.093	Empty	4.072	2.1
	2	2s/2s	4.177	Empty		
	3	2s/2s	3.947	Empty		

Under application of static pressure i.e. in the test group C1, the grout tank was not fully evacuated at the end of the tests. The average weight of passed grout through the slot in three performances was less than half the capacity of the grout tank. Under application of dynamic pressure i.e. in the test groups V1 and V3 with 4s/8s and 2s/2s peak/rest periods respectively, the final tank condition was however empty in all performances.

The average weight of passed grout in both groups of V1 and V3 illustrated an increase of more than 2 times compared to the test group C1 under the static pressure condition.

The method was unable to visualize any significant difference between the results of the 4s/8s and 2s/2s peak/rest periods. Meanwhile, it was not possible to monitor the filtration and erosion processes in time and during each cycle.

4.1.2 Test results using the slot with 30 μm constriction size

In the next step a short slot with 30 μm constriction size was employed to better visualize the difference between the influences of the static and the dynamic pressures on grout penetrability. Results of the test groups C2, V2 and V4 using the total weight of passed grout as the evaluation method are presented in table 3.

Table 5 - Comparison of total weight of passed grout for test groups C2, V2 and V4, using the 30 μm slot

Tabell 6 - Total vikt av paserade bruk i försöksgupper C1, V1 och V3 genom 30 μm spalten

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		

All the test groups resulted in flow stop and the grout tank was not empty at the end of the experiments. Application of dynamic pressure in test group V2 and V4 however, showed a significant improvement in the average weight of passed grout compared to the static pressure condition. The test group V2 with the 4s/8s peak/rest period, illustrated an improvement of about 2.6 times compared to the case of the static pressure, whereas the test group V4 with the 2s/2s peak/rest period, showed an increase of nearly 11 times compared to the case of the static pressure. This is an indication of better control of filtration using the 2s/2s peak/rest period compared to the 4s/8s peak/rest period in the 30 μm slot.

4.2 Evaluation of results using the weight-time method

4.2.1 Test results using the slot with 43 μm constriction size

Measurement of weight in time was the second method utilized in presented study to visualize the difference between the influences of the static and the dynamic pressures. Under the static pressure condition the results of the test group C1 performed on the 43 μm slot, clearly illustrated the process of filtration by showing a non-linear relation and a consistent variation in the slope (Figure 21). However, under the dynamic pressure condition, the results of the test groups V1 and V3 with both the 4s/8s and the 2s/2s peak/rest periods approximately illustrated a linear relation in the weight-time measurement with a minor slope variation showing a slight filtration (Figure 21).

The method provides a simple way to follow the filtration process in time during the whole experiment. However, it is still not possible to distinguish between the filtration and erosion processes within each cycle of the dynamic pressure and determine the most critical cycle of filtration. Furthermore, the method is unable to quanify them as well.

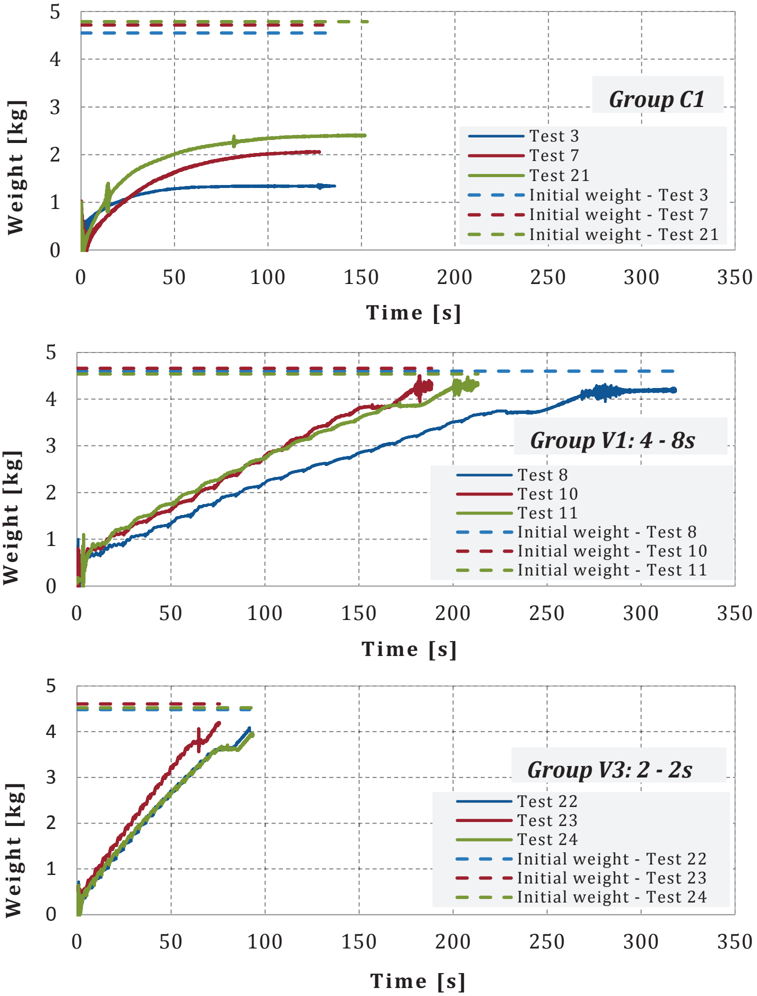


Figure 21 Weight - time measurement for test groups C1, V1 and V3 using the 43 µm slot and the peak - rest periods of 4 s/8 s and 2 s/2 s
Figur 21 Vikt-tid mätningar av försöken C1, V1 och V3 med 43 μm spalt och topp och botten perioder av 4s/8s och 2s/2s

4.2.2 Test results using the slot with 30 μm constriction size

Under the static pressure condition the results of the test group C2 performed on the 30 μm slot, illustrated an early flow stop with a minor weight of passed grout (Figure 22). Quick variation in the slope of the weight-time measurement was an indication of quick filtration of the cement particles.

Under the dynamic pressure condition, the results of the test group V2 with the 4s/8s peak/rest period showed some improvement (Figure 22). However, the results of the test group V4 with the 2s/2s peak/rest period showed a considerable improvement keeping the slot open for longer time during the injection process, resulting a huge difference in the total weight of passed grout.

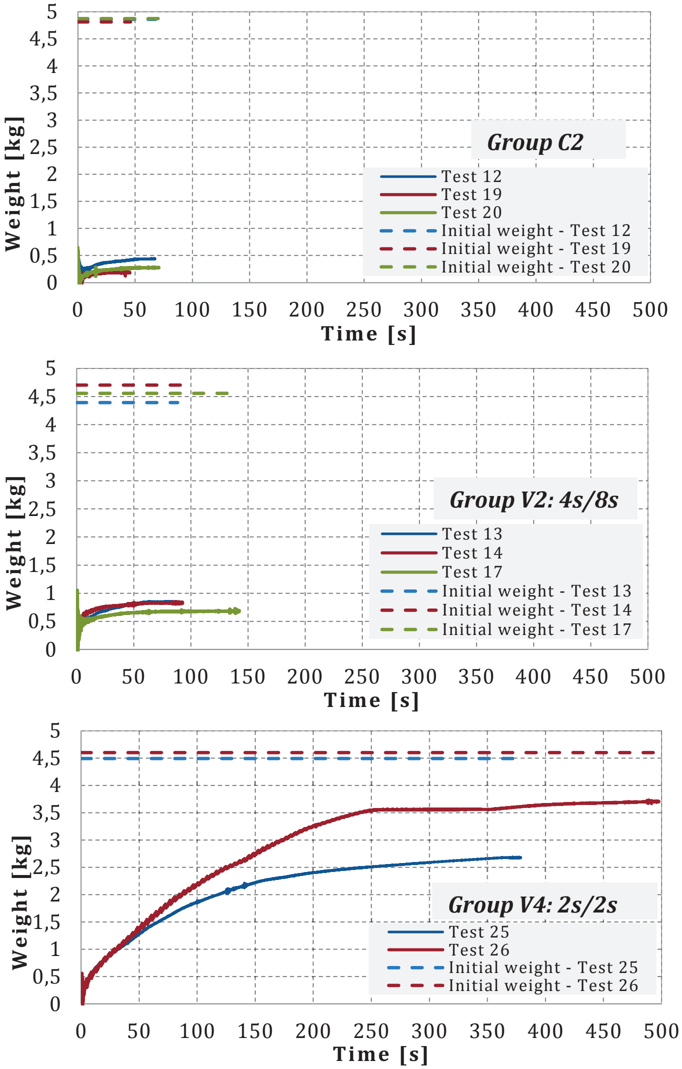


Figure 22 Weight - time measurement for test groups C2, V2 and V4 using the 30 µm slot and the peak/rest periods of 4 s/8 s and 2 s/2 s

Figur 22 Vikt-tid mätningar av försöken C1, V1 och V3 med 30 μm spalt och topp och botten perioder av 4s/8s och 2s/2s

4.3 Evaluation of results using the pressure-time method and the min-pressure envelope

4.3.1 Test results using the slot with 43 μm constriction size

The pressure-time measurement was the third method employed in presented study to monitor the filtration and erosion processes in each cycle and visualize the difference between the influences of different peak and rest periods on improving grout penetrability. The min-pressure envelopes resulted from the pressure-time measurements in the test groups V1 and V3 with 4s/8s and 2s/2s peak/rest periods respectively are illustrated in Figure 23. In both cases a short slot with 43 μm constriction size was used in the experiments.

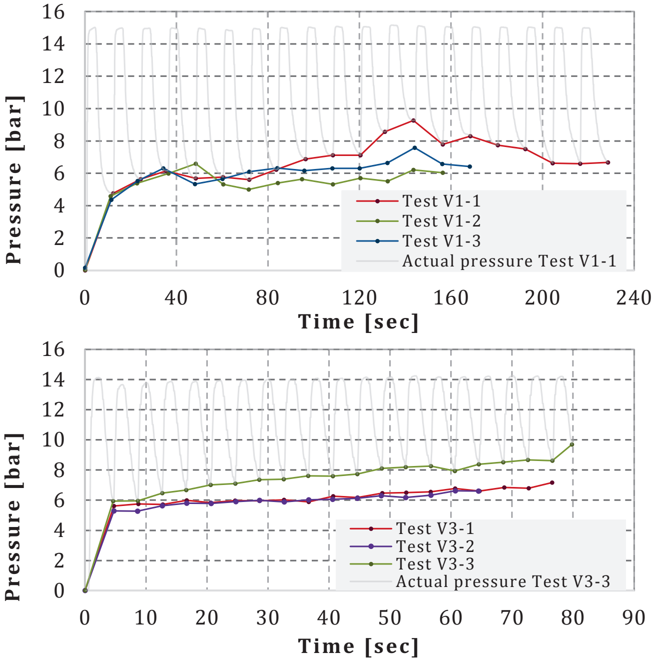


Figure 23 Filtration envelopes for test groups V1 and V3 with peak/rest periods of 4 s/8 s and 2 s/2 s respectively using the 43µm slot

Figur 23 Filtreringsenveloppen från försöken V1 och V3 med respektive topp/botten perioder av 4s/8s och 2s/2s med 43 μm spalt

In results of the test group V1, there were cycles with upward trend showing dominant filtration versus cycles with downward trend illustrating dominant erosion. However, randomness was visible in the test results. Results of the test group V3 with 2s/2s peak/rest period presented a more stabilized filtration distribution instead. They showed a gradual upward trend illustrating an approximately consistent compensation between the filtration and erosion phenomena with a minor accumulation of cement particles during each cycle. Time duration for evacuating the whole capacity of the grout tank was the other significant difference between the results of the test group V1 and V3 with 4s/8s and 2s/2s peak/rest periods. In the case of 4s/8s peak/rest period the time duration was about double, illustrating more effectiveness of the 2s/2s peak/rest period. The method was however unable to quantify the values of the filtration and erosion processes in each cycle.

4.3.2 Test results using the slot with 30 μm constriction size

The min-pressure envelopes resulted from the pressure-time measurements in the test groups V2 and V4 with 4s/8s and 2s/2s peak/rest periods respectively are illustrated in Figure 24. In both cases a short slot with 30 μm constriction size was used in the experiments. Results of the test group V2 showed a sharp upward trend during just a few cycles illustrating a quick and dominant filtration probably with some minor erosion (Figure 24).

Results of the test group V4 with 2s/2s peak/rest period, showed a sharp jump of the pressure envelope, during the first 25 sec of the tests. This indicated that the most part of the filtration occurred at the very beginning of the injection. However the results revealed that dynamic pressure with the 2s/2s peak/rest period was good enough to keep the slot with 30 μm constriction open for a longer time during the injection process. The reason, as can be seen in the figure, was random erosion and re-opening of the partially plugged constriction.

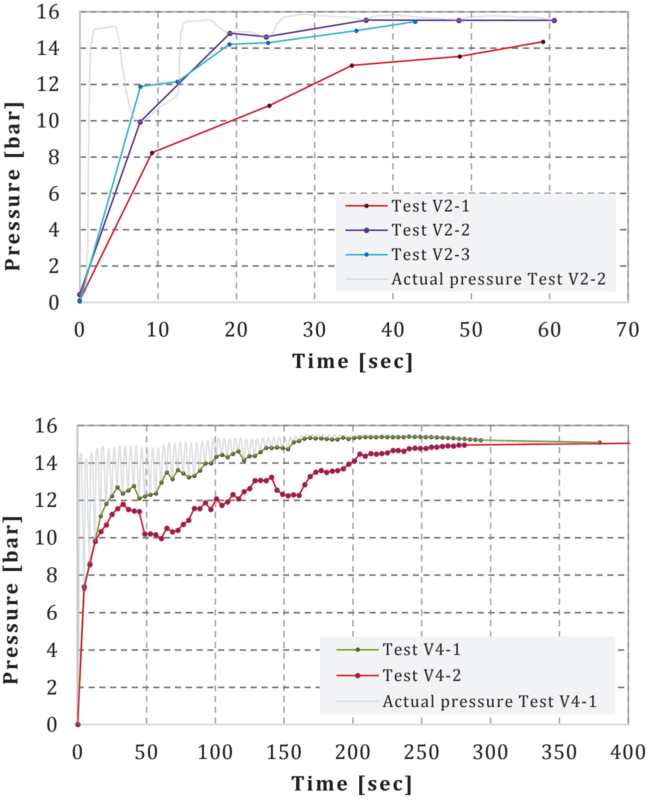


Figure 24 Filtration envelopes for test groups V2 and V4 with peak/rest periods of 4 s/8 s and 2 s/2 s respectively using the 30 µm slot

Figur 24 Filtreringsenveloppen från försöken V2 och V4 med respektive topp/botten perioder av 4s/8s och 2s/2s med 30 μm spalt

4.4 Evaluation of results using the Cycle Mean Flow Rate (CMFR)

4.4.1 Test results using the slot with 43 μm constriction size

To quantify the filtration and erosion processes during each cycle, a new parameter called the Cycle Mean Flow Rate (CMFR) was defined as the fourth evaluation method in presented study. The results of the CMFR, together with the average CMFR of all cycles using the short slot with 43 μm constriction size are illustrated in figure 25.

The values of the average CMFRs for the tests with peak/rest period of 4s/8s were principaly lower than that for the case of 2s/2s peak/rest peroid. The mean value of the average CMFRs for the three performances with 4s/8s peak/rest period was 0.72 *lit/min*, compared to 1.76 *lit/min* for the 2s/2s peak/rest period, showing an almost 2.5 times higher average for the latter.

By closely examining the resulting flow rate values, one can clearly see that the first cycle in each case, has the highest flow rate compared to the following ones. This is then more stabilized to lower values. The difference between cycle one and cycle two is rather huge which indicates that the most part of filtration occurs through the first cycle. This has a serious impact on the further development of the flow rates.

The test results of the 2 – 2 sec period almost always show higher flow rates in cycle one compared to the 4 – 8 sec tests. This means that in the case of the 2 – 2 sec period, the filtration is lower in cycle one compared to 4 – 8 sec, resulting in a better grout penetrability.

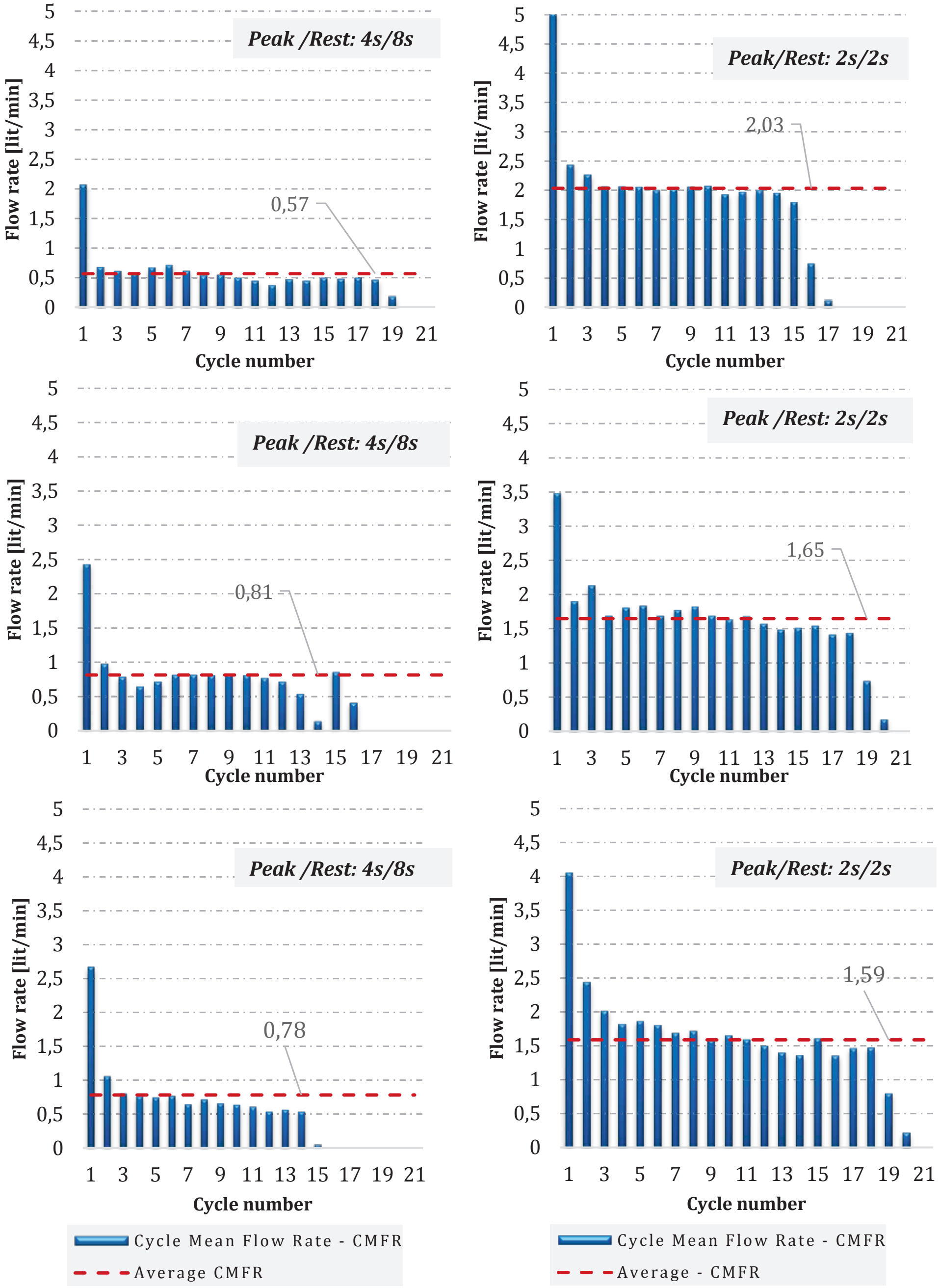


Figure 25 Cycle mean flow rates (CMFRs) and average CMFRs for the test results of 43 μm with 4 s/8 s and 2 s/2 s peak/rest periods

Figur 25 Cyklisk medelflödesgrad (CMFRs) och medel CMFRs från försök med 43 μm spalt med respektive topp/botten perioder av 4s/8s och 2s/2s

4.4.2 Test results using the slot with 30 μm constriction size

The CMFR, together with the average CMFR of all cycles for the peak/rest periods of 4s/8s and 2s/2s with 30 μm slot size are illustrated in figure 26. Similar to the test results with 43 μm slot, the considerable differences between the CMFRs of the first and second cycles of each test with 30 μm slot indicate that the main part of the filtration occurs during the first cycle. Moreover, the lower values of the CMFRs in 4s/8s compared to the 2s/2s peak/rest period is an illustration of lower filtration during the first cycle in the tests with 2s/2s peak/rest period.

All the test results with 4s/8s peak/rest period had less than 5 cycles completed with very low CMFRs, compared to the test results of 2s/2s peak/rest period. The results of 2s/2s peak/rest period showed a significantly larger number of cycles between 38 to 60 cycles with a gradual trend of CMFRs down to zero after the second cycle. The values of the average CMFRs, here, were not a clear indication of the significant difference between the influence of 4s/8s and 2s/2s periods on grout penetrability, probably due to the fact that the mean value is highly dependent on the number of cycles.

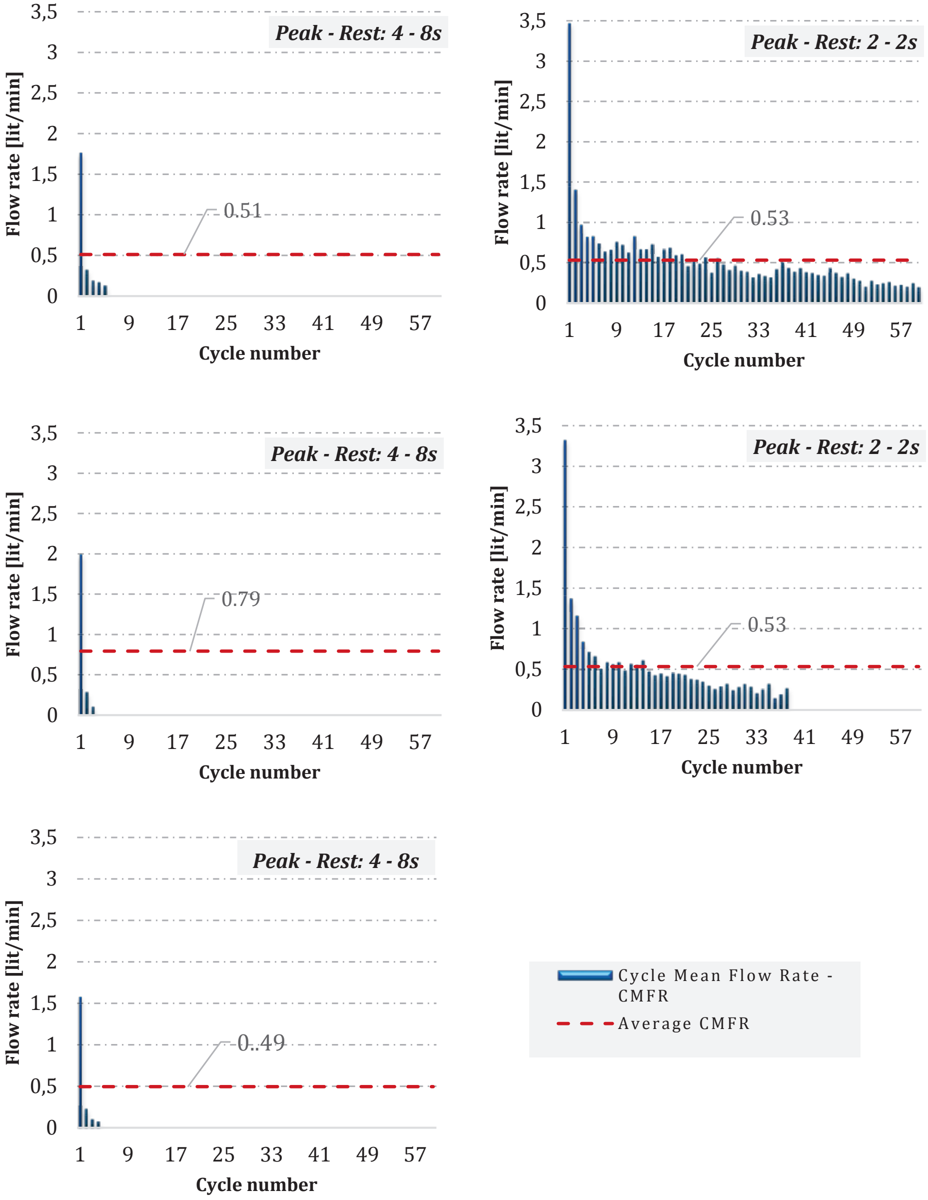


Figure 26 Cycle mean flow rates (CMFRs) and average CMFRs for the test results of 30 μm with 4 s/8 s and 2 s/2 s peak/rest periods

Figur 26 Cyklisk medelflödesgrad (CMFRs) och medel CMFRs från försök med 30 μm spalt med respektive topp/botten perioder av 4s/8s och 2s/2s

5. CONCLUSIONS AND FUTURE STEPS OF THE PROJECT

5.1 Conclusions

The general conclusions of the presented study are as follows:

- In general, application of instantaneous variable pressure had a great impact on improving grout penetrability compared to the application of constant pressure at constrictions through the artificial fractures.
- The results of both selections of the peak and rest periods, i.e. the 4s/8s and 2s/2s, revealed that cycle periods higher than 1 sec regulated the filtration and improved the grout penetrability effectively.
- The results also showed that application of the 2s/2s peak/rest period is much more efficient than the 4s/8s period. In the 30 μm slot, the 4s/8s and 2s/2s peak/rest periods showed about 2.6 and 11 times improvement respectively compared to the static pressure.
- In the 43 μm slot, the average *CMFR* was higher (about 2.5 times) for the 2s/2s peak/rest period, which emptied the grout tank in just half of the time required for the 4s/8s period. This means that choosing the correct peak/rest period depending on the grout recipe and the conductivity of the area, i.e. the fracture sizes, will significantly reduce construction time in the field.
- The results of the first step of the current project revealed the potential of success of the proposed method in grouting through micro-fractures down to 30 μm in field which definitely needs further investigation. This would be of greater interest in projects with very high sealing demands like the nuclear waste repositories, accompanied with the latest achievements of Mohammed et al. (2013; 2014 and

2015) concerning the materials and mix designs to fulfil the severe requirements of such areas.

- Accumulation of cement particles, i.e. filtration, mostly occurs during the first cycle. The key to a successful dynamic grouting is thus to prevent or reduce the filtration in first cycle.
- The mechanism of improvement of grout penetrability under application of instantaneous variable pressure is hypothetically variation in flow pattern before the constriction due to the change in pressure and flow velocity. This is under further investigation within experimental and numerical approaches and the results will be revealed in later stages of the project.

5.2 Future steps of the project

In the next phase of the project, the proposd method is recommended to be employed using a Varying Aperture Long Slot (VALS) recently developed by the authors at KTH with 4 m length and varying aperture sizes between 250-20 μm. The aim will be to determine the influence of the suggested method along a fracture, before and after each constriction, under different dynamic pressure setups and find the proper set up concerning the maximum penetration length using different grout recipes.

According to Stille et al. (2012), evaluating the hydraulic conductivity of the rock mass expressed as the Lugeon value is a common way and the first step for characterizing the rock fractures condition. Due to the flexible design of VALS, various conductivities can be obtained in different sections of the instrument which can be set similar to the obtained values from the field. Finding the proper peak and rest periods associated with the evaluated hydraulic conductivity of the rock mass in field is therefore the next step of the project using VALS. The obtained results will be thereafter verified in field in the final stage of the project using the new design of the varying pressure system, which will be added to a Unigrout to make the applied pressure programmable.

The proposed mechanism of improvement of the grout penetrability in this study is also under further investigation through a theoretical approach. The results will be presented in the next step of the project.

To verify the proposed mechanism of improvement use of computational fluid dynamic technic (CFD) is also recommended. Regarding to the results of some preliminary efforts in collaboration with the experts in department of fluid and climate technology at KTH, this investigation is feasible.

6. REFERENCES

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7. APPENDIX A – PRESSURE-TIME DATA

Measurements of the grout pressure in time at the beginning of the slot and the grout tank are presented as follows:

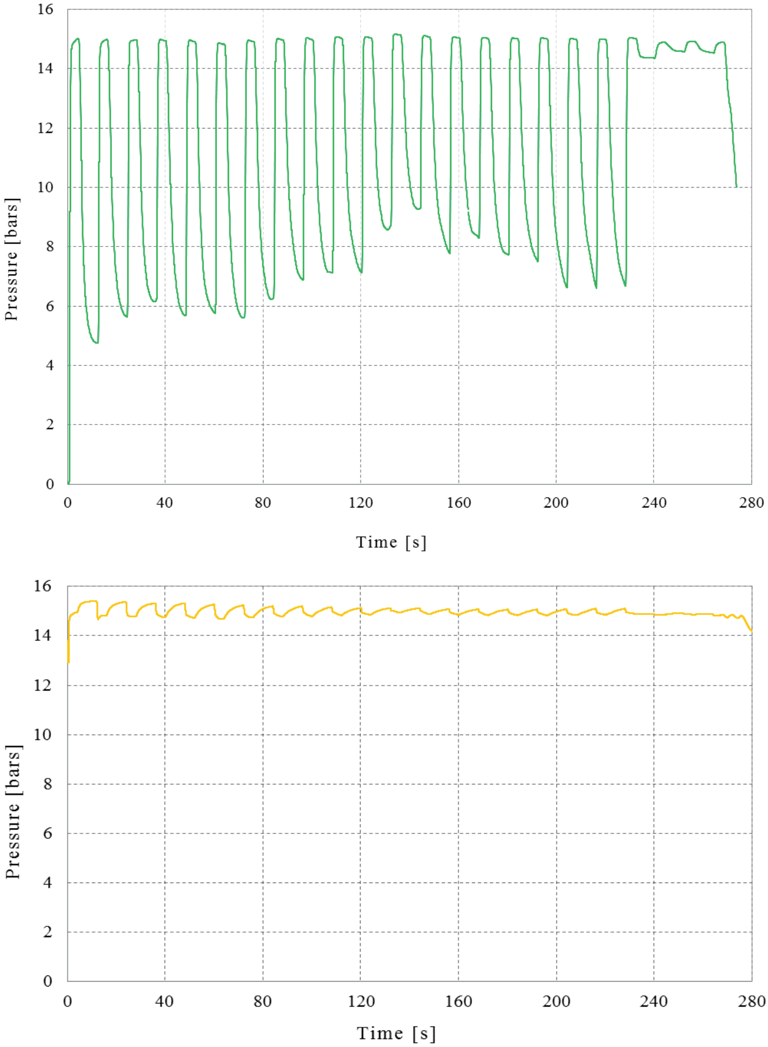
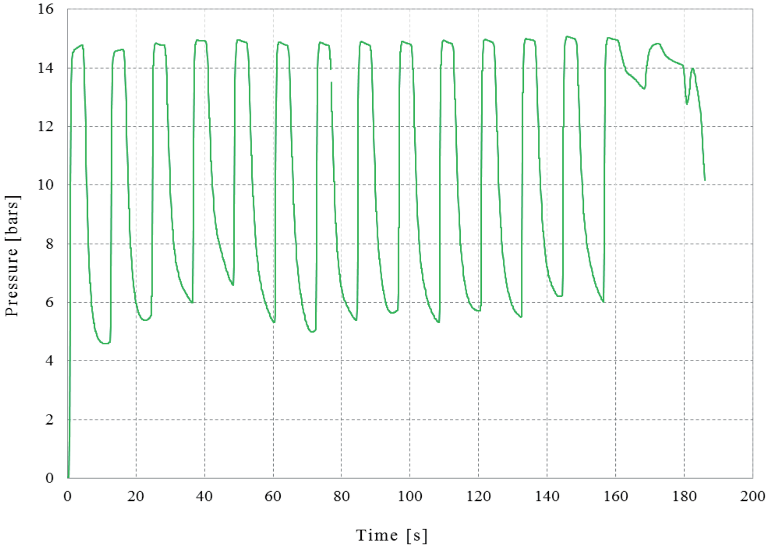


Figure 27 Pressure - time plots of test V1-1 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 27 Tryck – tid grafs av försök V1-1 i början av slottet (övre bild) och I injekteringstanken (nedre bild)



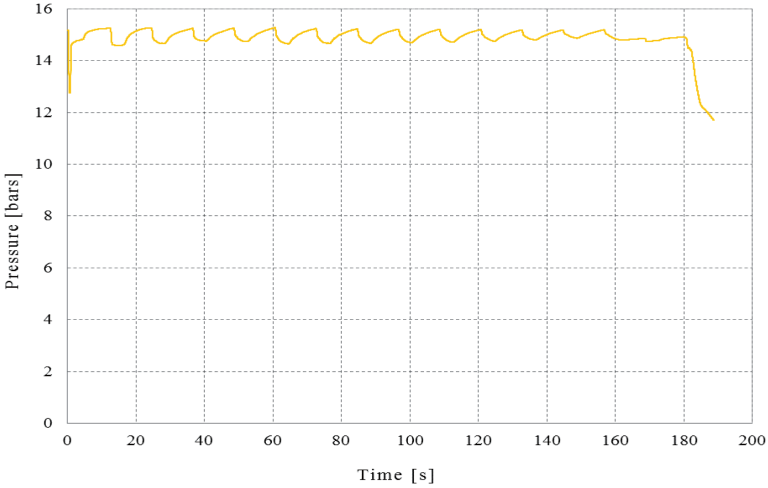
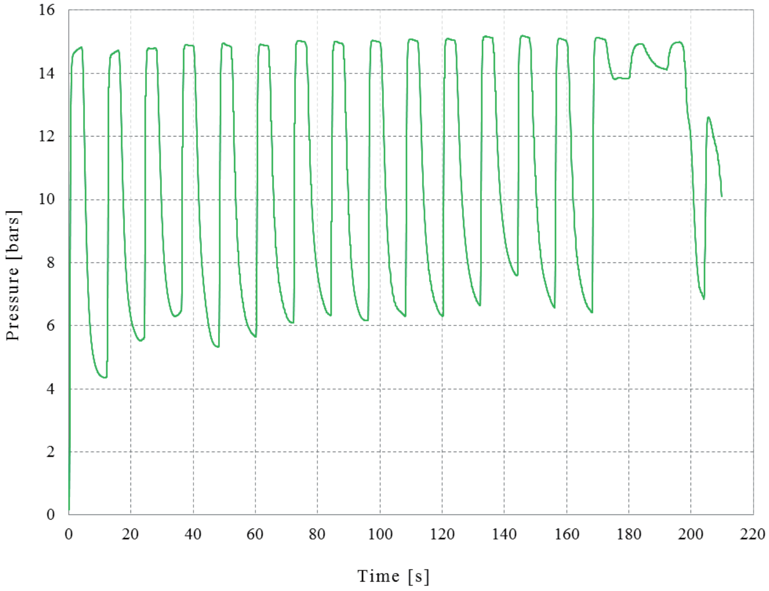


Figure 28 Pressure - time plots of test V1-2 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 28 Tryck – tid grafer av försök V1-2 i början av slottet (övre bild) och I injekteringstanken (nedre bild)



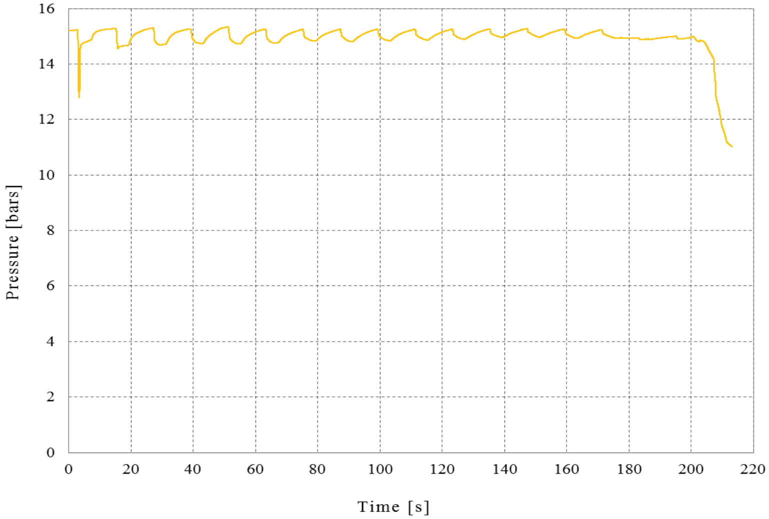
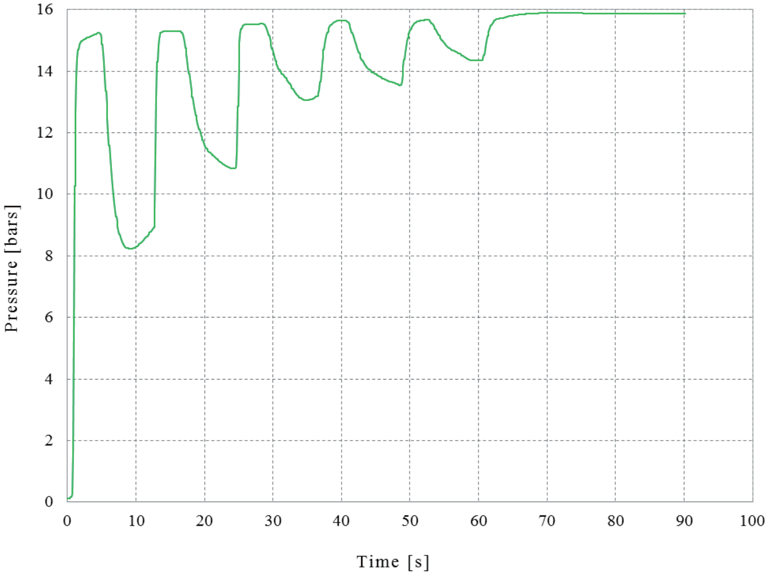


Figure 29 Pressure - time plots of test V1-3 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 29 Tryck – tid grafer av försök V1-3 i början av slottet (övre bild) och I injekteringstanken (nedre bild)



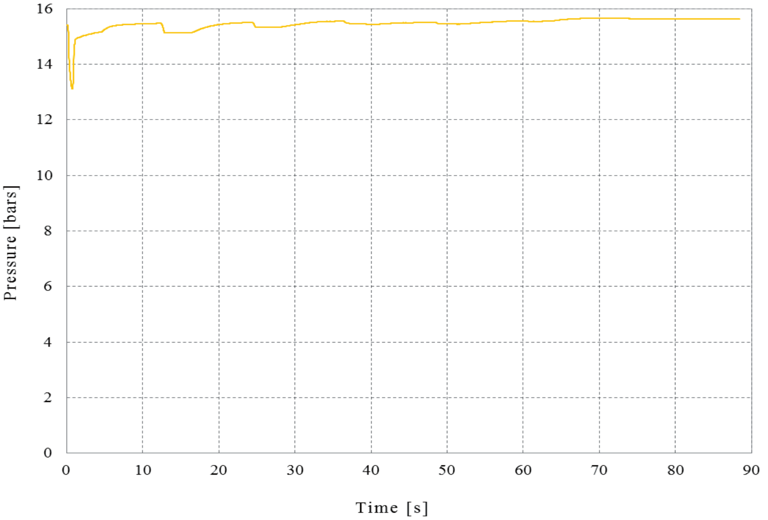
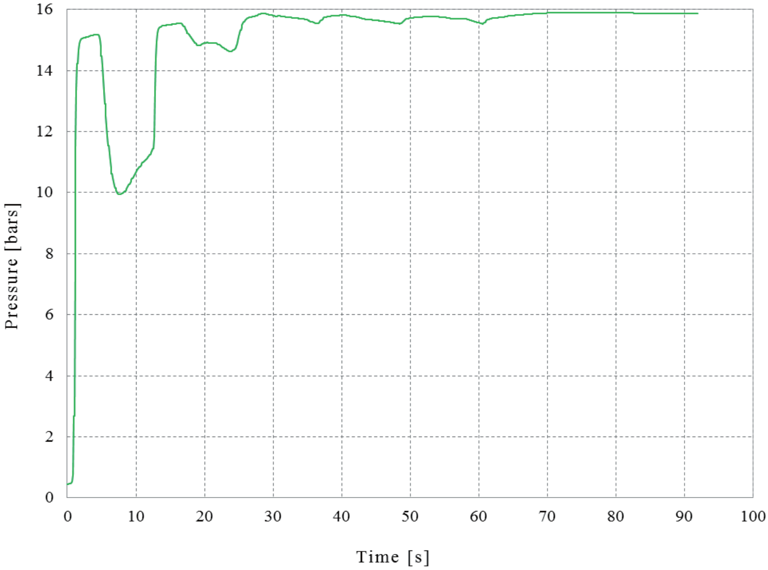


Figure 30 Pressure - time plots of test V2-1 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 30 Tryck – tid grafer av försök V2-1 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



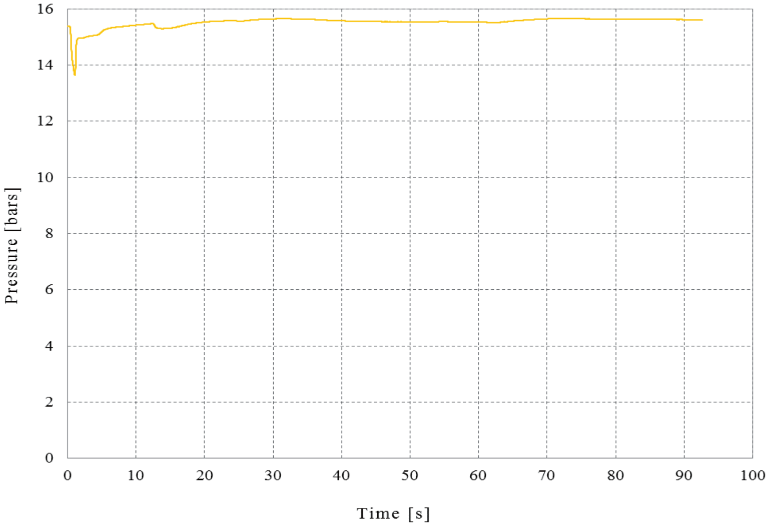
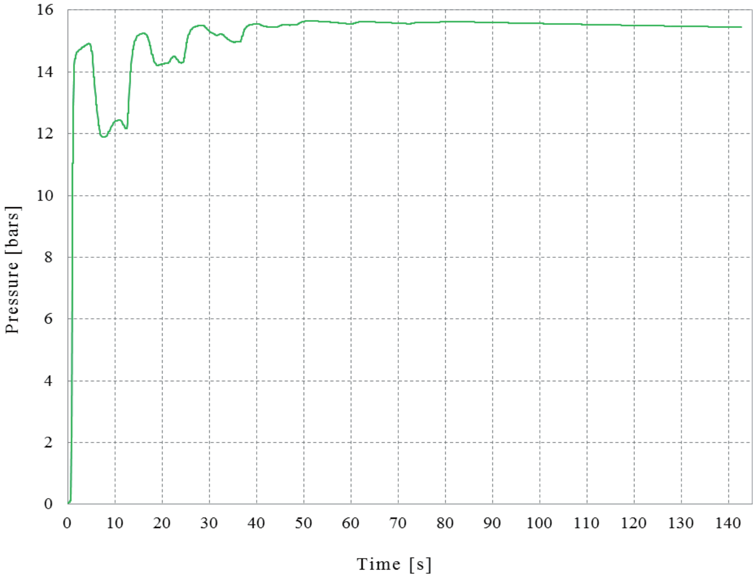


Figure 31 Pressure - time plots of test V2-2 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 31 Tryck – tid grafer av försök V2-2 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



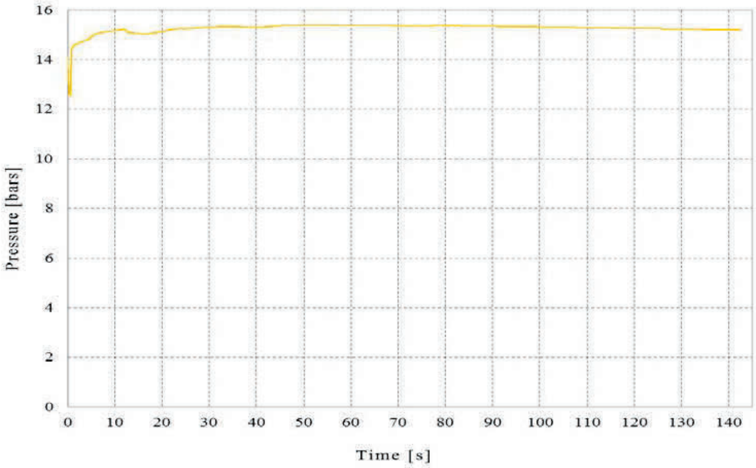
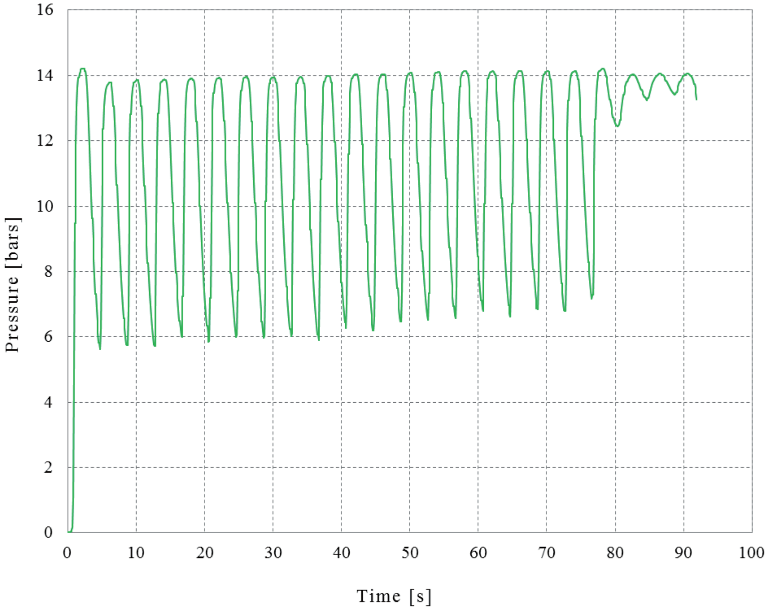


Figure 32 Pressure - time plots of test V2-3 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 32 Tryck – tid grafer av försök V2-3 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



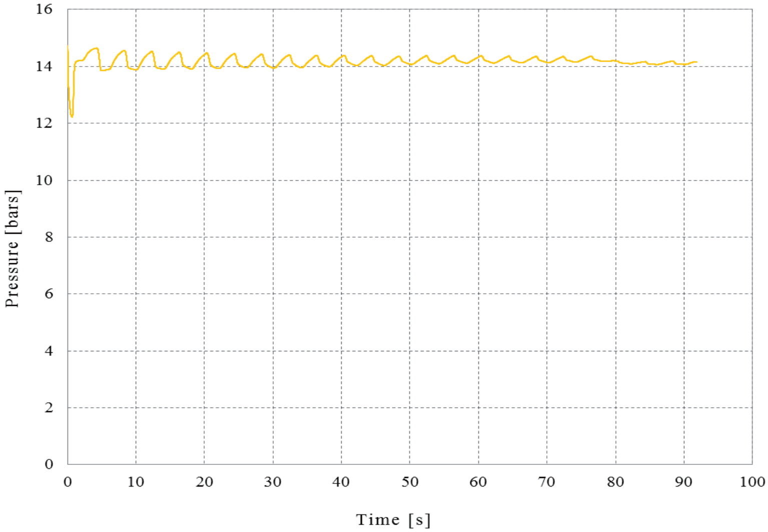
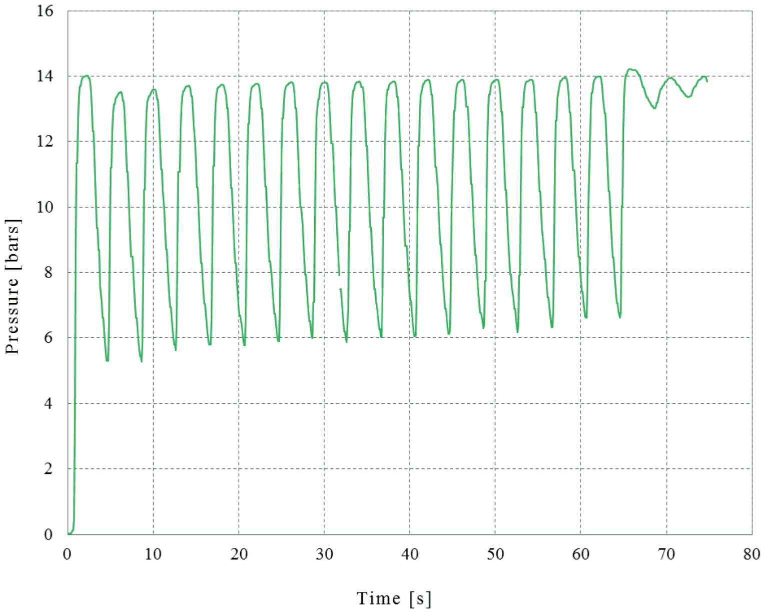


Figure 33 Pressure - time plots of test V3-1 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 33 Tryck – tid grafer av försök V3-1 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



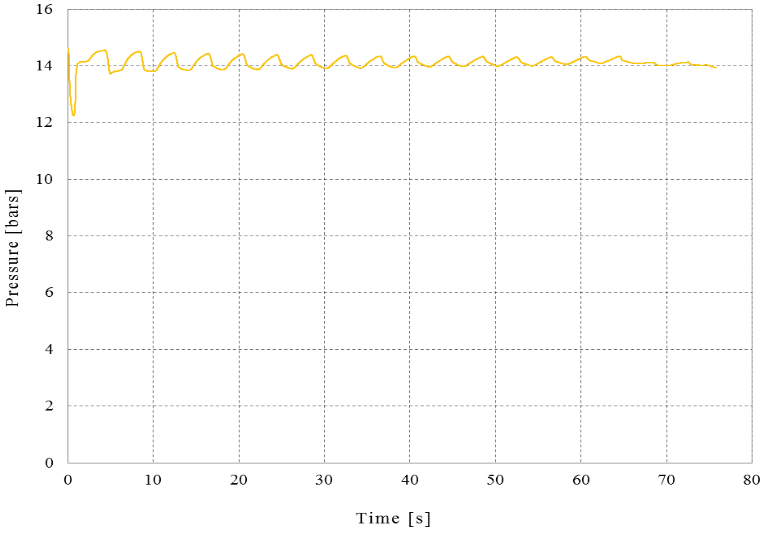
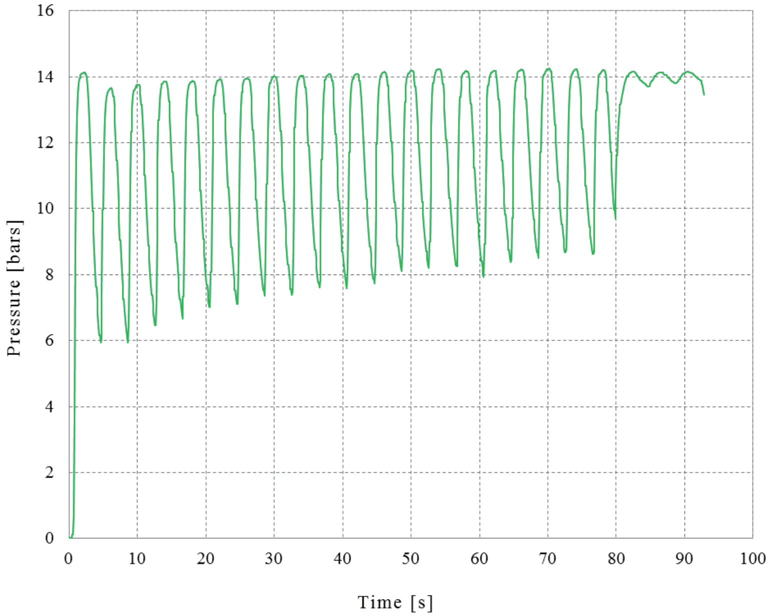


Figure 34 Pressure - time plots of test V3-2 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 34 Tryck – tid grafer av försök V3-2 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



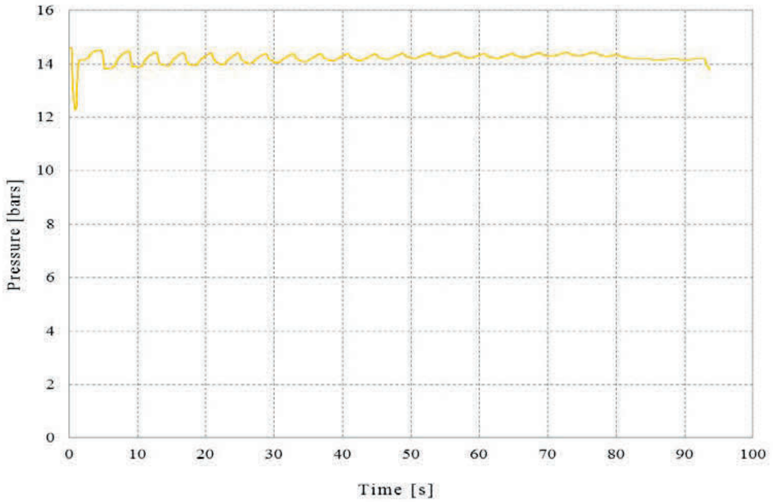
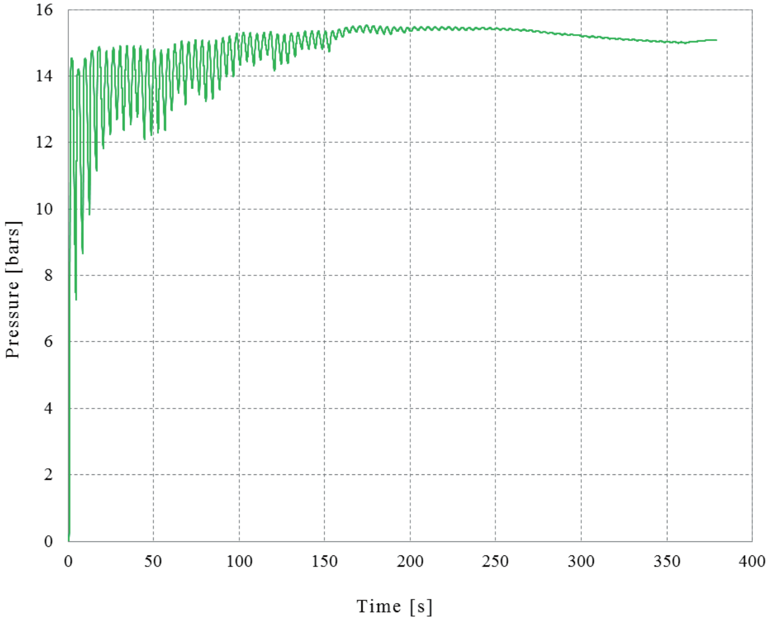


Figure 35 Pressure - time plots of test V3-3 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 35 Tryck – tid grafer av försök V3-3 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



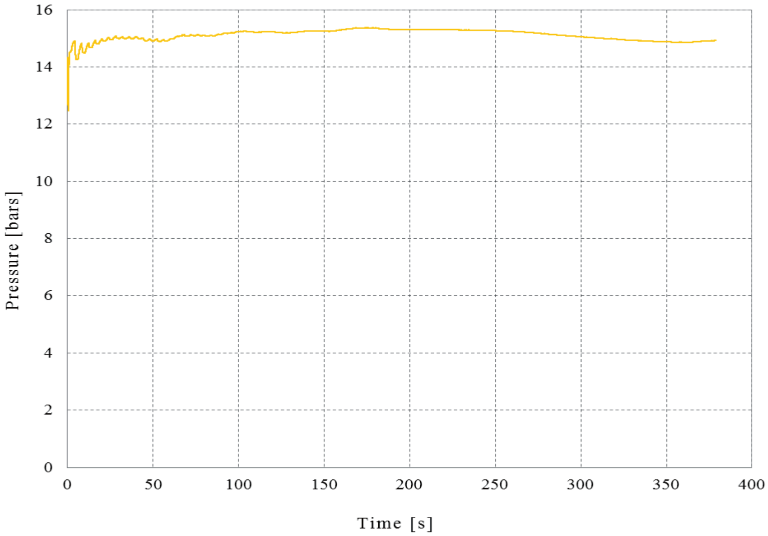
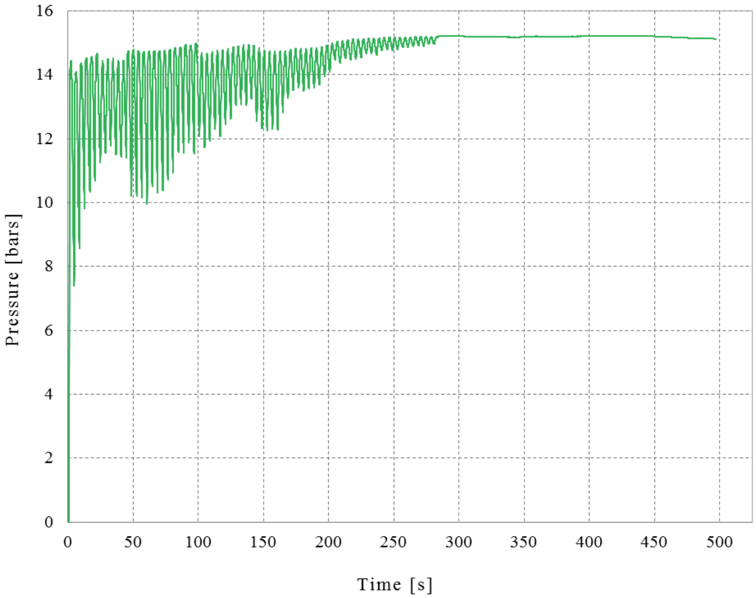


Figure 36 Pressure - time plots of test V4-1 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 36 Tryck – tid grafer av försök V4-1 i början av slottet (övre bild) och i injekteringstanken (nedre bild)



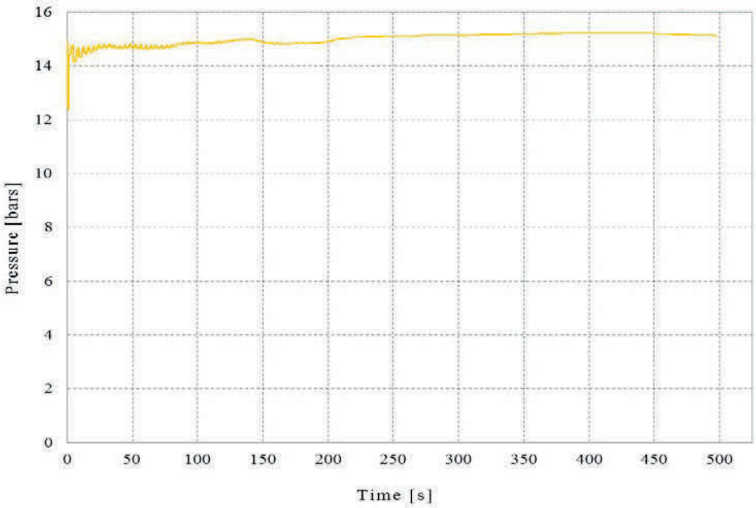
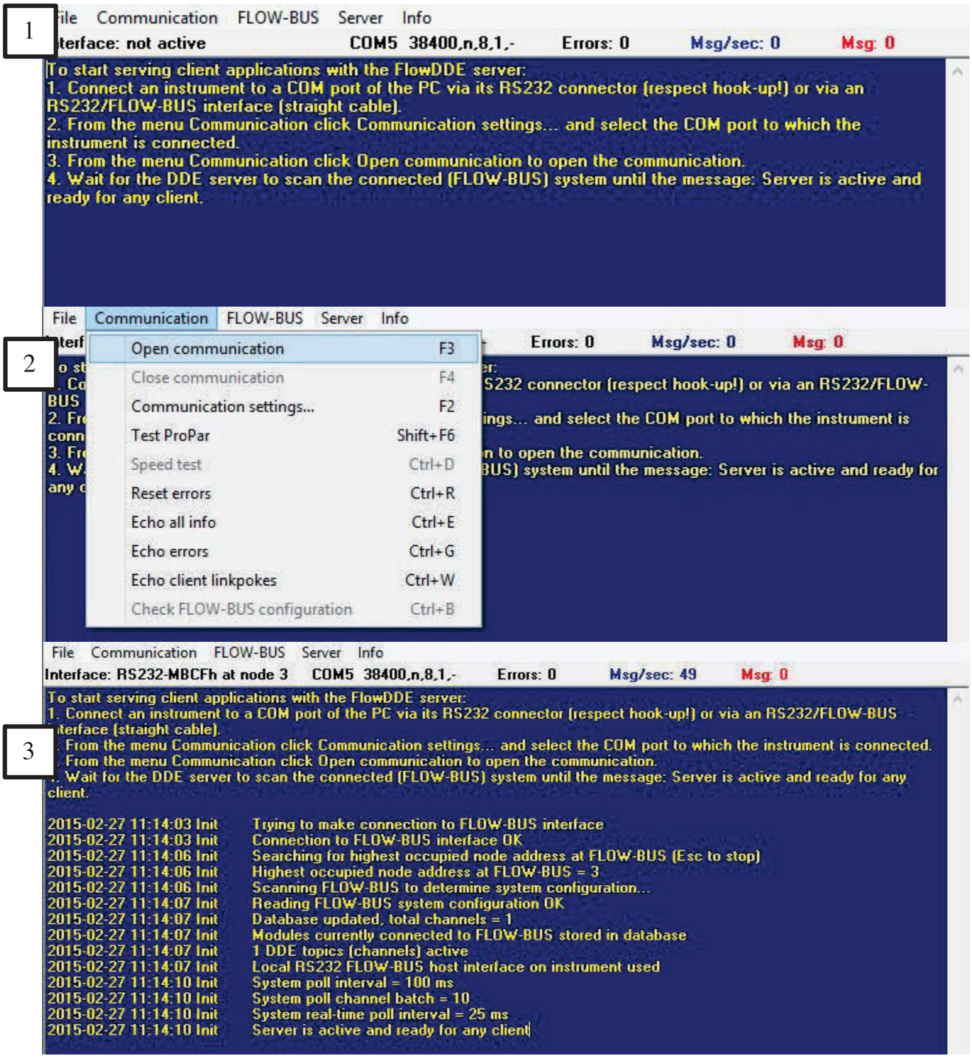


Figure 37 Pressure - time plots of test V4-2 at the beginning of the slot (upper) and at the grout tank (lower)

Figur 37 Tryck – tid grafer av försök V4-2 i början av slottet (övre bild) och i injekteringstanken (nedre bild)

8. APPENDIX B – SOFTWARE SETTINGS

The FlowDDE and the FlowPlot settings and interfaces are presented as follows:



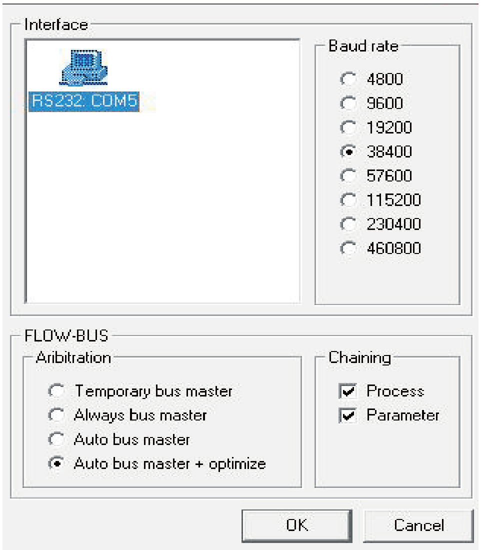
```
terface: not active          COM5  38400,n,8,1,-     Errors: 0     Msg/sec: 0     Msg: 0
To start serving client applications with the FlowDDE server:
1. Connect an instrument to a COM port of the PC via its RS232 connector (respect hook-up!) or via an
RS232/FLOW-BUS interface (straight cable).
2. From the menu Communication click Communication settings... and select the COM port to which the
instrument is connected.
3. From the menu Communication click Open communication to open the communication.
4. Wait for the DDE server to scan the connected (FLOW-BUS) system until the message: Server is active and
ready for any client.
```

```
Interface: RS232-MBCFh at node 3   COM5  38400,n,8,1,-   Errors: 0   Msg/sec: 49   Msg: 0
To start serving client applications with the FlowDDE server:
1. Connect an instrument to a COM port of the PC via its RS232 connector (respect hook-up!) or via an RS232/FLOW-BUS
terface (straight cable).
. From the menu Communication click Communication settings... and select the COM port to which the instrument is connected.
. From the menu Communication click Open communication to open the communication.
. Wait for the DDE server to scan the connected (FLOW-BUS) system until the message: Server is active and ready for any
client.

2015-02-27 11:14:03 Init     Trying to make connection to FLOW-BUS interface
2015-02-27 11:14:03 Init     Connection to FLOW-BUS interface OK
2015-02-27 11:14:06 Init     Searching for highest occupied node address at FLOW-BUS (Esc to stop)
2015-02-27 11:14:06 Init     Highest occupied node address at FLOW-BUS = 3
2015-02-27 11:14:06 Init     Scanning FLOW-BUS to determine system configuration...
2015-02-27 11:14:07 Init     Reading FLOW-BUS system configuration OK
2015-02-27 11:14:07 Init     Database updated, total channels = 1
2015-02-27 11:14:07 Init     Modules currently connected to FLOW-BUS stored in database
2015-02-27 11:14:07 Init     1 DDE topics (channels) active
2015-02-27 11:14:07 Init     Local RS232 FLOW-BUS host interface on instrument used
2015-02-27 11:14:10 Init     System poll interval = 100 ms
2015-02-27 11:14:10 Init     System poll channel batch = 10
2015-02-27 11:14:10 Init     System real-time poll interval = 25 ms
2015-02-27 11:14:10 Init     Server is active and ready for any client
```

Figure 38 FlowDDE communication commencement steps. Request (1), attempt (2) and establishment (3) of communication

Figur 38 Olika steg i FlowDDE vid etableringen av kommunikation. Förfråga (1), försök (2) och ettablering (3) av kommunikation



Interface

RS232: COM5

Baud rate

○ 4800
○ 9600
○ 19200
● 38400
○ 57600
○ 115200
○ 230400
○ 460800

FLOW-BUS

Aribitration

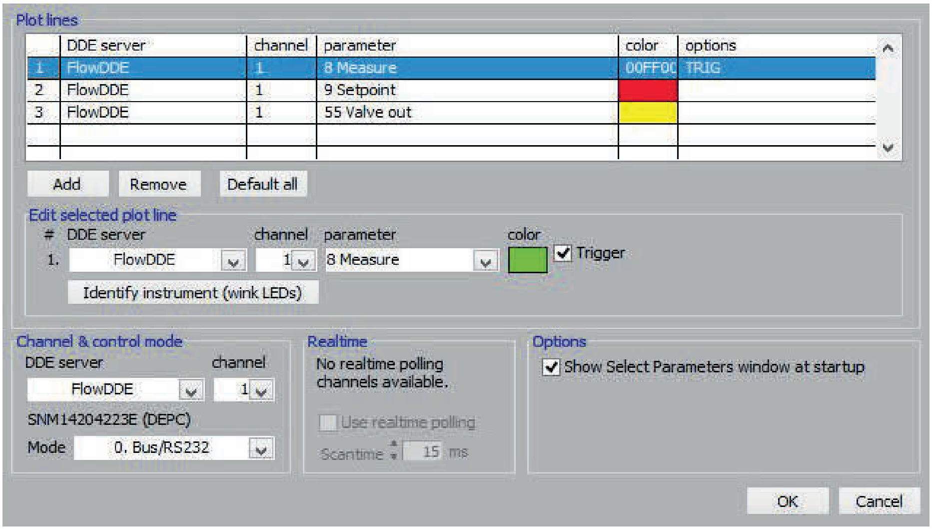
○ Temporary bus master
○ Always bus master
○ Auto bus master
● Auto bus master + optimize

Chaining

☑ Process
☑ Parameter

Figure 39 FlowDDE communication settings

Figur 39 FlowDDE kommunikations inställningar



Plot lines

	DDE server	channel	parameter	color	options
1	FlowDDE	1	8 Measure	00FF0C	TRIG
2	FlowDDE	1	9 Setpoint	🟥	
3	FlowDDE	1	55 Valve out	🟨	

Edit selected plot line

#	DDE server	channel	parameter	color	
1.	FlowDDE	1	8 Measure	🟩	☑ Trigger

Channel & control mode

DDE server: FlowDDE
channel: 1
SNM14204223E (DEPC)
Mode: 0. Bus/RS232

Realtime

No realtime polling channels available.

☐ Use realtime polling
Scantime 15 ms

Options

☑ Show Select Parameters window at startup

Figure 40 Parameter selection window. The selected parameters for were measure (1), setpoint (2) and valve output (3)

Figur 40 Fönster för parameter inställningar. De valada parametrarna för mätplats (1), start punkt (1) och utgångventil (3)

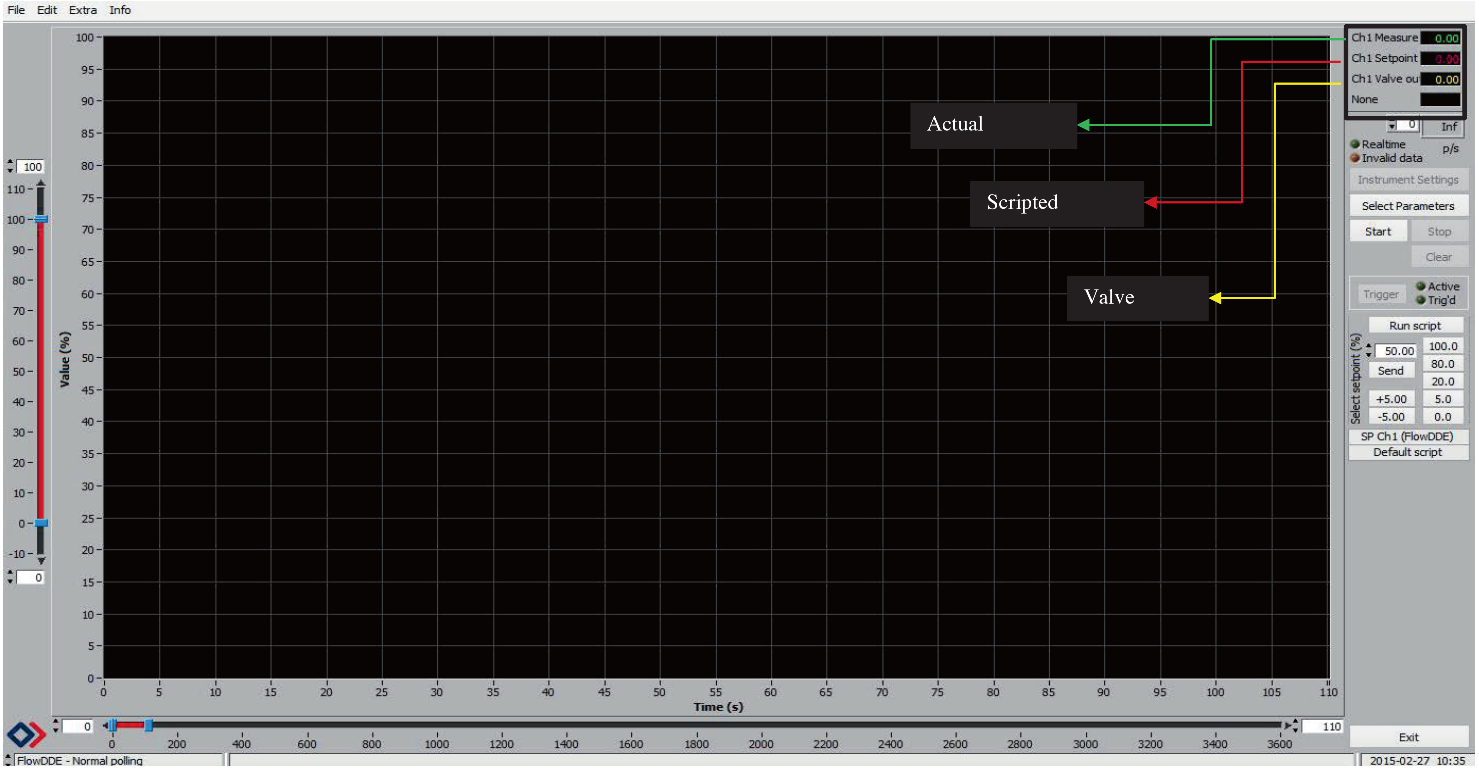
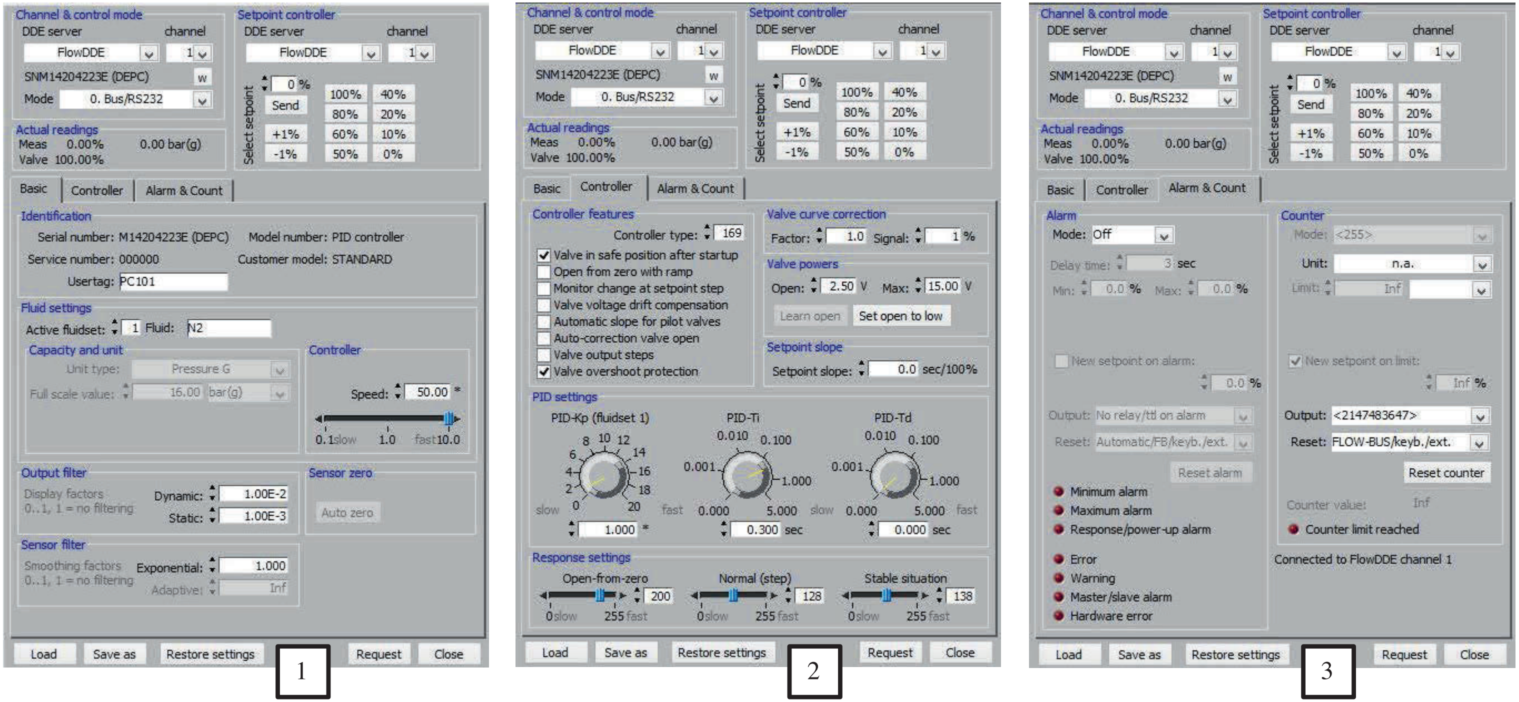


Figure 41 FlowPlot main user interface

Figur 41 FlowPlot huvud fönster



Channel & control mode
DDE server: FlowDDE
channel: 1
SNM14204223E (DEPC) w
Mode: 0. Bus/RS232

Setpoint controller
DDE server: FlowDDE
channel: 1
0 %

Actual readings
Meas 0.00% 0.00 bar(g)
Valve 100.00%

Identification
Serial number: M14204223E (DEPC)
Model number: PID controller
Service number: 000000
Customer model: STANDARD
Usertag: PC101

Fluid settings
Active fluidset: 1 Fluid: N2

Capacity and unit
Unit type: Pressure G
Full scale value: 16.00 bar(g)

Controller
Speed: 50.00 *
0.1 slow 1.0 fast 10.0

Output filter
Display factors 0..1, 1 = no filtering
Dynamic: 1.00E-2
Static: 1.00E-3

Sensor zero

Sensor filter
Smoothing factors 0..1, 1 = no filtering
Exponential: 1.000
Adaptive: Inf

Controller features
Controller type: 169
☑ Valve in safe position after startup
☐ Open from zero with ramp
☐ Monitor change at setpoint step
☐ Valve voltage drift compensation
☐ Automatic slope for pilot valves
☐ Auto-correction valve open
☐ Valve output steps
☑ Valve overshoot protection

Valve curve correction
Factor: 1.0 Signal: 1 %

Valve powers
Open: 2.50 V Max: 15.00 V

Setpoint slope
Setpoint slope: 0.0 sec/100%

PID settings
PID-Kp (fluidset 1): 1.000 * (slow 0 2 4 6 8 10 12 14 16 18 20 fast)
PID-Ti: 0.300 sec (0.000 0.001 0.010 0.100 1.000 5.000)
PID-Td: 0.000 sec (slow 0.000 0.001 0.010 0.100 1.000 5.000 fast)

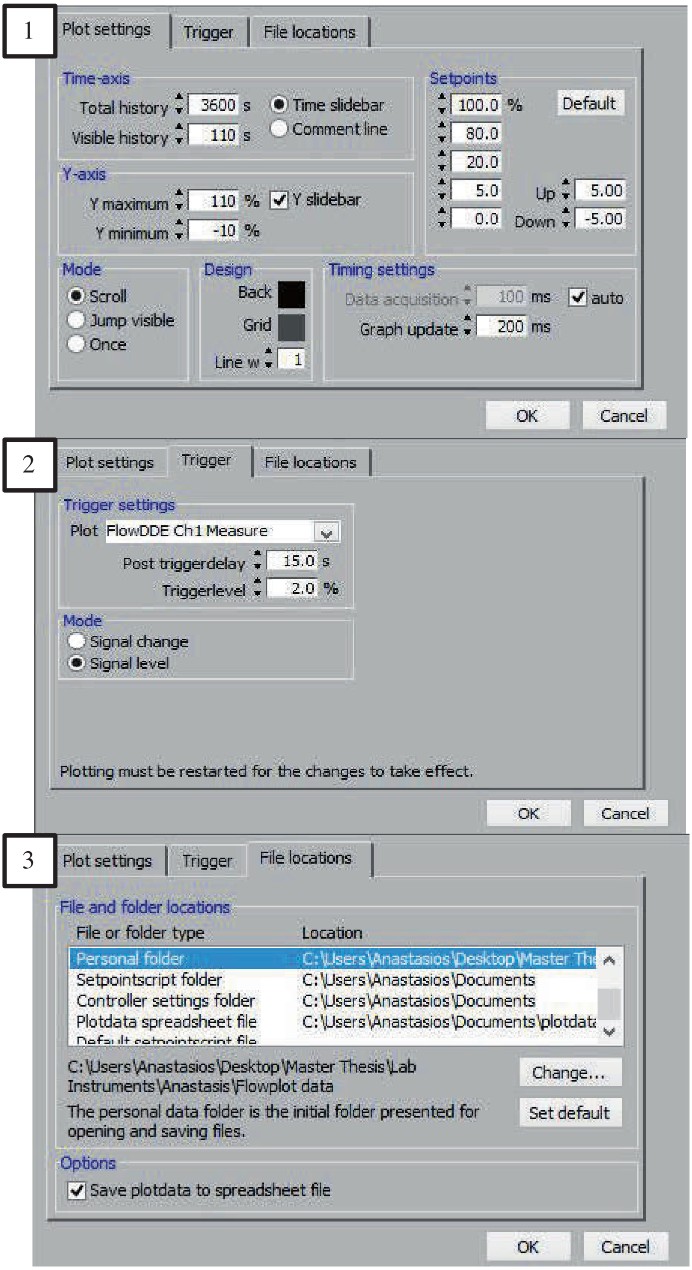
Response settings
Open-from-zero: 200 (0 slow 255 fast)
Normal (step): 128 (0 slow 255 fast)
Stable situation: 138 (0 slow 255 fast)

Alarm
Mode: Off
Delay time: 3 sec
Min: 0.0 % Max: 0.0 %
☐ New setpoint on alarm: 0.0 %
Output: No relay/ttl on alarm
Reset: Automatic/FB/keyb./ext.
● Minimum alarm
● Maximum alarm
● Response/power-up alarm
● Error
● Warning
● Master/slave alarm
● Hardware error

Counter
Mode: <255>
Unit: n.a.
Limit: Inf
☑ New setpoint on limit: Inf %
Output: <2147483647>
Reset: FLOW-BUS/keyb./ext.
Counter value: Inf
● Counter limit reached

Connected to FlowDDE channel 1

Figure 42 FlowPlot settings tabs. Basic (1), controller (2) and alarm & count (3)
Figur 42 FlowPlot inställningar. Bas (1), kontroller (2) och larm & räknare (3)



Time-axis

Total history 3600 s

Visible history 110 s

● Time slidebar

○ Comment line

Y-axis

Y maximum 110 %

☑ Y slidebar

Y minimum -10 %

Setpoints

100.0 % Default

80.0

20.0

5.0 Up 5.00

0.0 Down -5.00

Mode

● Scroll

○ Jump visible

○ Once

Design

Back ■

Grid ■

Line w 1

Timing settings

Data acquisition 100 ms ☑ auto

Graph update 200 ms

Trigger settings

Plot FlowDDE Ch1 Measure

Post triggerdelay 15.0 s

Triggerlevel 2.0 %

Mode

○ Signal change

● Signal level

Plotting must be restarted for the changes to take effect.

File and folder locations

File or folder type	Location
Personal folder	C:\Users\Anastasios\Desktop\Master Th
Setpointscript folder	C:\Users\Anastasios\Documents
Controller settings folder	C:\Users\Anastasios\Documents
Plotdata spreadsheet file	C:\Users\Anastasios\Documents\plotdat

C:\Users\Anastasios\Desktop\Master Thesis\Lab Instruments\Anastasis\Flowplot data

The personal data folder is the initial folder presented for opening and saving files.

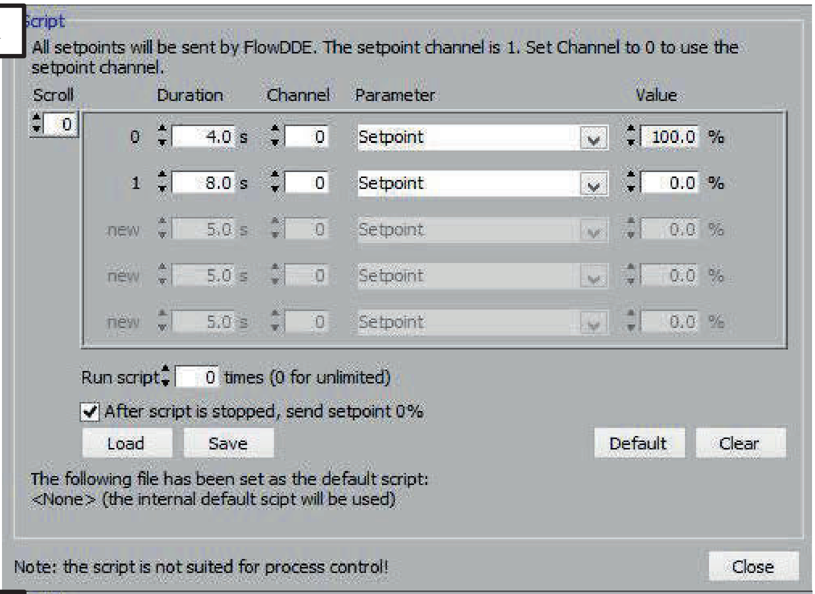
Options

☑ Save plotdata to spreadsheet file

Figure 43 FlowPlot options menu. Plot settings (1), trigger (2) and file locations (3)

Figur 43 FlowPlot valmeny. Graf inställningar (1), trigger 82) och filplacering (3)

1



Script

All setpoints will be sent by FlowDDE. The setpoint channel is 1. Set Channel to 0 to use the setpoint channel.

Scroll		Duration	Channel	Parameter	Value
0	0	4.0 s	0	Setpoint	100.0 %
	1	8.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %

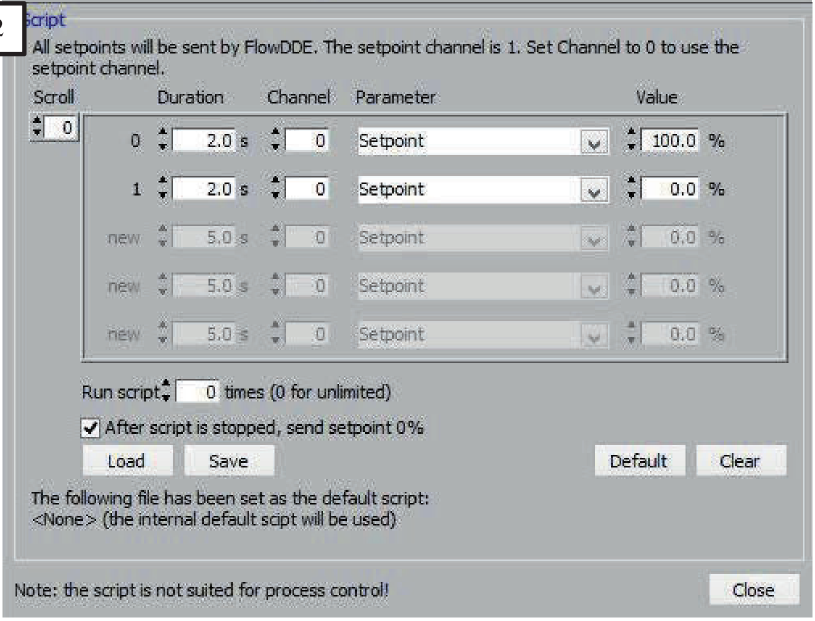
Run script 0 times (0 for unlimited)

☑ After script is stopped, send setpoint 0%

The following file has been set as the default script:
<None> (the internal default scipt will be used)

Note: the script is not suited for process control!

2



Script

All setpoints will be sent by FlowDDE. The setpoint channel is 1. Set Channel to 0 to use the setpoint channel.

Scroll		Duration	Channel	Parameter	Value
0	0	2.0 s	0	Setpoint	100.0 %
	1	2.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %
	new	5.0 s	0	Setpoint	0.0 %

Run script 0 times (0 for unlimited)

☑ After script is stopped, send setpoint 0%

The following file has been set as the default script:
<None> (the internal default scipt will be used)

Note: the script is not suited for process control!

Figure 44 FlowPlot script editing window. Script 4 s/8 s (1) and 2 s/2 s (2) of peak/rest durations

Figur 44 FlowPlot skript redigering fönster. Skript 4s/8s (1) och 2s/2s av top/bottom period

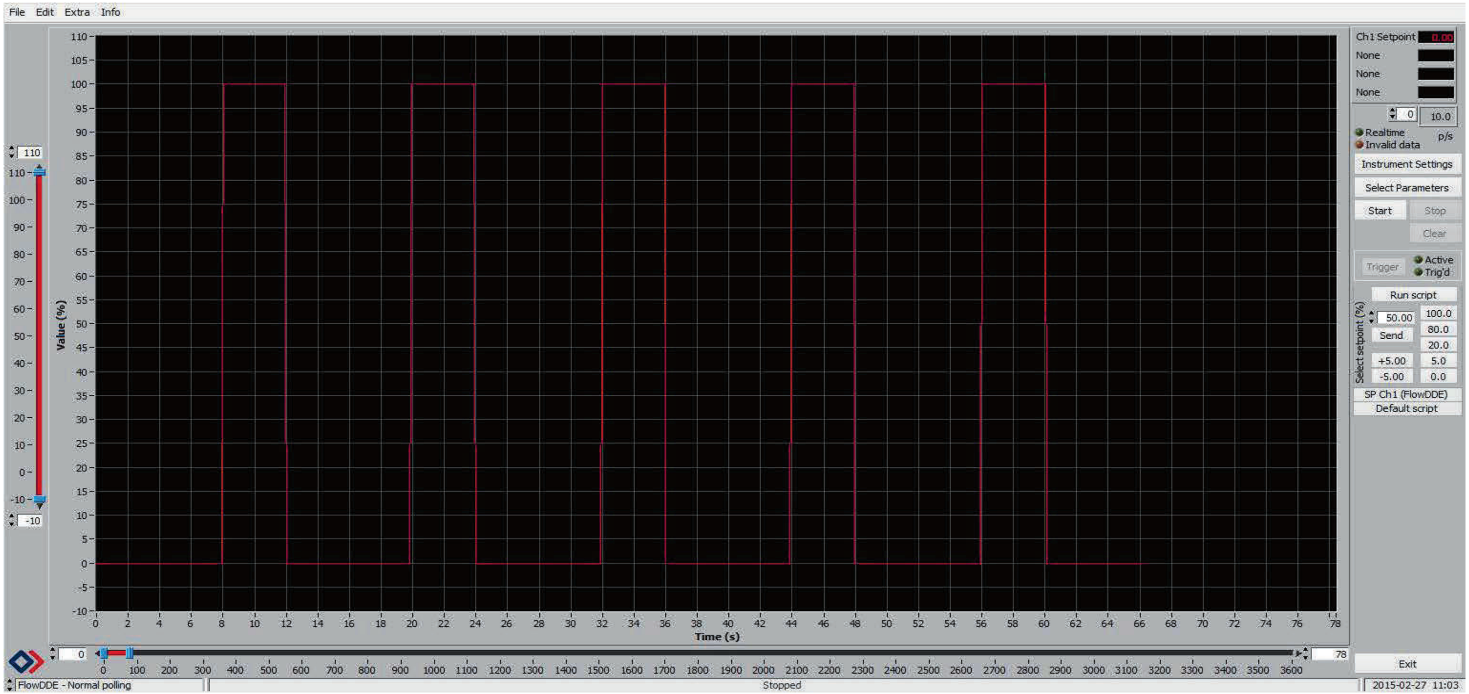


Figure 45 Illustration of FlowPlot's setpoint pressure. The script was 4 s/8 s of peak/rest durations.

Figur 45 Illustration av FlowPlot förvalt tryck. Skripten är för 4s/8s av topp/bottom tidperiod

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