CHALMERS

The Effect of Blast-Induced Vibrations on Grout

Master of Science Thesis in the Master's Programme
Infrastructure and Environmental Engineering

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Geology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Photography showing the drill rig and charging of the pilot by the contractor Veidekke during the initiation of the traffic tunnel project outside of Ulricehamn, Sweden.

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ABSTRACT

During a tunnel construction project in Sweden using the common method drill and blast, some of the construction time will be lost as waiting time. This master's thesis focuses on the waiting time between grouting and blasting. Although there are no specific standards for this, common practice requires the grout to harden and reach specific shear strength before the blasting process is allowed and initiated.

Blasting will create a release of energy in the form of vibration waves. For this project, a more simple calculation is performed to analyse the general behaviour of a propagation wave. In order to evaluate the effect of vibrations on the hardening process of grout, laboratory work was conducted. The laboratory work consisted of several tests, which were developed iteratively in order to find a suitable model. Firstly, the main hardening behaviour of grout was evaluated and its reaction to vibrations in general. Then, a weight-release equipment was designed to resemble the vibrations that a tunnel detonation induces and lastly, this equipment was applied to grout in a fracture replica.

The results of the laboratory tests indicate that vibrations slow down the hardening process, but the final shear strength is reached either way. In addition, the grout's permeability is affected but the extent of the effect needs to be further investigated.

Key words: *blasting, grouting, drill and blast method, vibrations, cement-based grout, hardening, waiting time, EDZ*

Contents

Preface

This Master's thesis has been carried out during the autumn of 2013 at the Department of Civil and Environmental Engineering, Division of GeoEngineering, research group Geology at Chalmers University of Technology in Gothenburg, Sweden. The work has been supervised by Assistant Professor Johan Funehag, examined by Lars O Ericsson and supported by the contractor Veidekke and the blasting consultant firm Nitro Consult AB. All laboratory work has been conducted in the GeoEngineering laboratory at Chalmers University of Technology and a field study has been made to a tunnel in the outskirts of Ulricehamn.

We would like to thank Aaro Pirhonen, Peter Hedborg and Johan Thörn for their standby assistance in the laboratory. Mathias Jern and Patrik Andersson have been valuable resources in the blasting part of the thesis. Johan Funehag has been invaluable due to his great knowledge in grouting and advice throughout this study. All professionals and experts who answered our emails helped us out and demonstrated a need for this research. In addition, we would like to thank Lars O Ericsson as well as the staff at Veidekke.

This has truly been a blast!

Göteborg December 2013

Mikaela Bäuml

Claes Sundqvist

List of Notations

Abbreviations

EDZ	[m]	Excavation damaged zone
INJ30	[-]	Injektering 30, commonly used grout product in Sweden
POI	[-]	Point of Interest
PPA	[m/s^2]	Peak particle acceleration
PPV	[m/s]	Peak particle velocity
W/C	[-]	Water-Cement Ratio

Commonly Used Expressions

Blasting process	Refers to the three steps drilling, charging and blasting.
Waiting time	Refers to the time between grouting and the blasting process.

Letters

α	[-]	Blast constant, site-specific
d_{95}	[µm]	Particle size distribution, where 95 percent of the grains are smaller than this value
f	[Hz]	Frequency
g	[m/s^2]	Gravity constant
H	[m]	Length of blasting charge
i	[mm]	Penetration length
K	[m/s]	Blast constant, site-specific
K_c	[-]	Cone tip angle parameter
m	[g]	Mass
q	[kg/m]	Linear charge density
r_o	[m]	Perpendicular distance from the linear charge to the POI
τ_g	[Pa]	Shear strength of grout
v	[m/s]	PPV
x_s	[m]	Distance from tunnel face to linear charge
x_o	[m]	Parallel distance from tunnel face to the POI

1 Introduction

When constructing a tunnel, factors such as tunnel length, shape of the tunnel and the time frame of construction will determine what method will be used. The drill and blast method has been successfully executed since the mid-1800s and it is still commonly used, especially for shorter tunnels (Norconsult AS, n.d.). This method consists of a cycle including seven main steps; pre-grouting, drilling, charging, blasting, mucking, scaling and rock stabilisation, as seen in Figure 1 (Trafikverket, 2013). Post-grouting is also possible and is sometimes added as an eighth step. When one cycle is finished, the process starts all over again until the tunnel is completed.

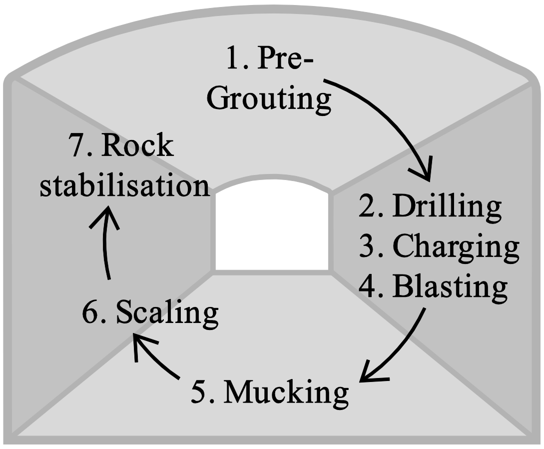

Figure 1 Schematic overview of one cycle in the construction of a tunnel using the drill and blast method.

The first step, pre-grouting, is made with the purpose of sealing the rock and ensure no or a very small water inflow into the finished tunnel (Trafikverket, 2013). When the grouting is finished the blasting process is initiated, which includes the three steps; drilling of blast holes, charging and detonation of the charges. The blasting produces a large volume of rock that has to be removed in order to proceed with the tunnel excavation. The unloading is called mucking and the material is often used as aggregates in other constructions. Also, some damaged rock may not be completely loosened and scaling is required. This step consists of knocking off loose rock in the tunnel contour; first using hydraulic hammers and then using manual force. If the rock is unstable stabilisation is needed, this is often accomplished by using rock bolts or shotcrete. As mentioned, these seven steps are repeated until the tunnel is finished.

During a tunnel construction project, some of the time will be lost due to waiting. This report will focus on the first four steps of the tunnel cycle and mainly the time between grouting and the blasting process, which will be referred to as waiting time. Common practice requires the grout to harden and reach specific shear strength before the blasting process is allowed to be initiated. According to a study based on six different tunnel projects, conducted by Dalmalm (2004), the waiting time for hardening amounts to 17 percent of the total sealing time on average. If blasting can be performed sooner after grouting, large economical savings can be achieved in every tunnel project due to time savings.

1.1 Background

In tunnelling projects the purpose of grouting is to fill holes, cavities and fractures in the rock to avoid transportation of water into a tunnel (Axelsson, 2013). A fluid, the so-called grout, is injected into these cracks through drilled boreholes in the rock and later solidifies. This can be done with different types of grout materials, either cement-based or chemical mixtures. In Sweden, a cement-based grout is usually used which consists of a mixture of cement, water, additives and sand, especially for larger fillings. The cement-based grout brand that is commonly used in Sweden is called Injektering 30 (INJ30). This cement has a particle size distribution (d95) of 30 µm, which means that 95 percent of all the grains are smaller than 30 µm. The proportions of the different substances in the cement mixture will be determined by the requirements of the grout and its application (Rosenqvist, 2011).

The grouting process starts with drilling of holes. These holes are designed as a fan around the tunnel. The geometry of the grouting fan depends on specific tunnel design criteria and foremost on the limits on inflow of water into the tunnel and some grout overlap from previous grout cycle is preferred, as seen in Figure 2 (Funehag, 2007). To achieve an appropriate seal, the holes have some inclination compared to the proposed tunnel stretch. According to Dalmalm (2004), a usual length of a hole is 20 to 25 meter which leads to an overlap of 5 to 10 meters between the previous and the current grout sequence.

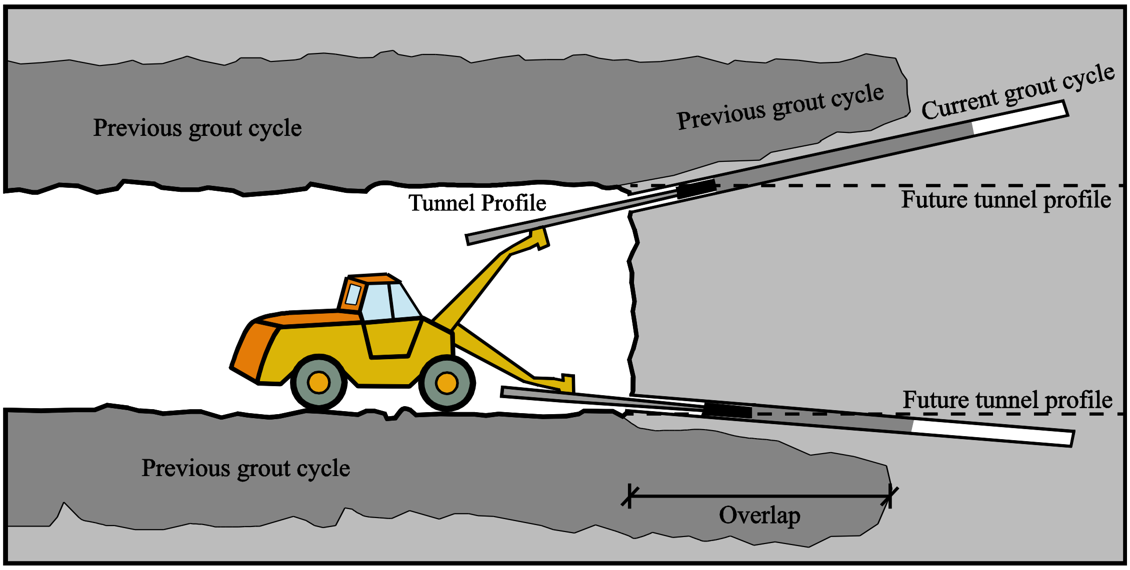

Figure 2 The process of grouting, where the previous and the current grouting cycles are shown. Also the overlap between these cycles is displayed.

When drilling is completed, the hole is flushed with water to remove drill cuttings (Dalmalm, 2004). In general, the bottom holes are grouted first and a simultaneous grouting of two holes is often carried out. To seal the grout holes and ensure that all grout is transferred into the holes, packers are installed in the grout holes. The grout material is then pumped at a high pressure. The grouting procedure is finished when a given pressure is reached, when a specified volume is used or when a certain time has elapsed. Packers are usually left in the hole until the grout has reached a specified strength after which they are removed, but there are also packers, called single-use packers, that are designed as permanent installations which will remain in the tunnel.

1.1.1 Description of the Hydration Process

The process in which cement and water are mixed together is called hydration. It can be described as a two-step process; dissolution and precipitation (Thomas & Jennings, 2009). During dissolution the cement is dissolved and releases ions, creating an aqueous solution called the pore solution. The concentration of ions will rapidly increase until it is energetically favourable for them to create bonds with each other rather than staying dissolved. This is called precipitation. When precipitation occurs, the saturation of the pore solution will be lowered and the remaining cement can continue to dissolve. Hence, the hydration process continues until all cement has hydrated.

The later part of the hydration process, when the grout develops from being a mixture of mainly cement and water to a solid matter, is often referred to as hardening. This is when the grout obtains an increase in shear strength. The precipitated solids have different properties from the original cement minerals. Early in the hardening process, when the grout is more like a liquid, it has a ductile behaviour, but when it has started to harden, it has more of a brittle behaviour.

Over time, hydration covers four phases (Thomas & Jennings, 2009), as seen in Figure 3, where the relationship between rate of hydration and time is displayed. Stage 1 describes the initial, fast reaction when cement and water are first in contact. A thin layer of C-S-H (hydrated calcium silicate) and C-H (calcium hydroxide) is formed around the cement particles (Preece, et al., 2001). This prevents further rapid dissolution, which is why this stage is so short. During stage 2, the so-called induction period, there is nearly no reaction that takes place.

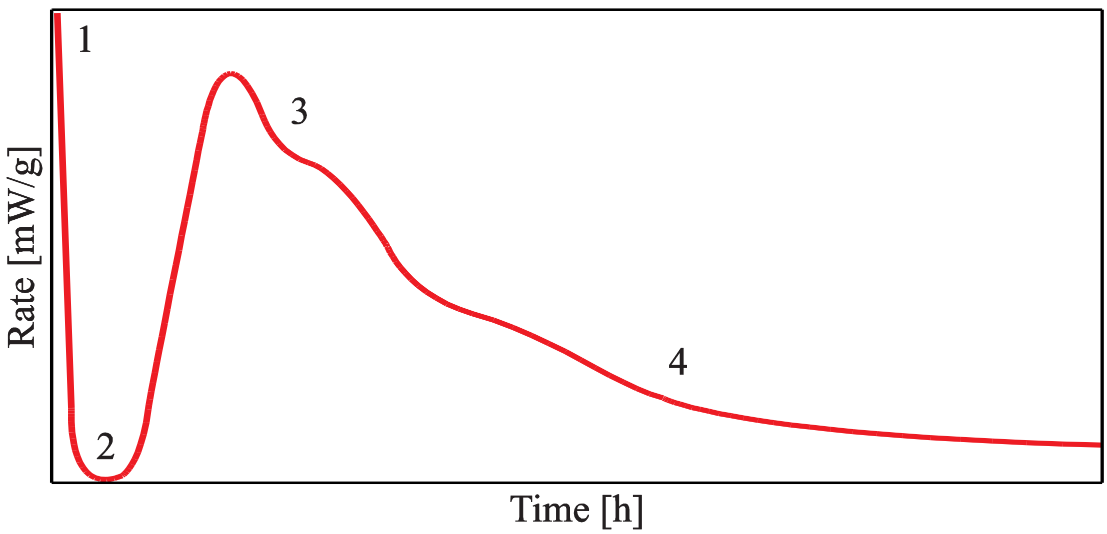

Figure 3 The four phases of hydration of concrete over time (Thomas & Jennings, 2009).

Stage 3 represents the rapid reaction period, when Tricalcium Silicate (C_3S) is hydrated and more C-S-H is developed (Thomas & Jennings, 2009). The rate of hydration reaches a maximum, usually within 24 hours of the initial contact between cement and water, followed by a rapid decrease. The rate of hydration is controlled by the rate at which the hydration products nucleate and grow. Temperature and average particle size are crucial for the maximum reaction rate as well as at what time it occurs. During this stage the total pore volume is decreased and strength is increased.

Stage 4 is the diffusion-limited reaction period, where water must diffuse into the unreacted cement particles, or dissolved cement ions must diffuse out into the capillary pores, for hydration to occur (Thomas & Jennings, 2009). The rate of hydration slows down due to the increasing thickness of the layer of hydration product around the cement particles.

For concrete, it takes 28 days on average to reach full potential strength (AB Byggmästarens förlag, 1968). Nevertheless, since stage 4 is slow, the majority of the strength of the material is accomplished within the first few days. Even though grout and concrete have some differences, their hardening behaviours are assumed to be similar enough, since they are both cement-based.

1.1.2 Description of the Blasting Process

The blasting process starts after the completion of grouting. The first step is to drill the blast holes, see Figure 4, which are done according to a pre-set blast design. Although there are no specific standards on how far in the hardening process or how high the shear strength of the grout needs to be before blasting, it is suggested by most contractors to wait a certain time, based on experience. When drilling is finished the holes are charged with an appropriate charge size and the detonation is timed using different sequences (Avén, et al., 1984).

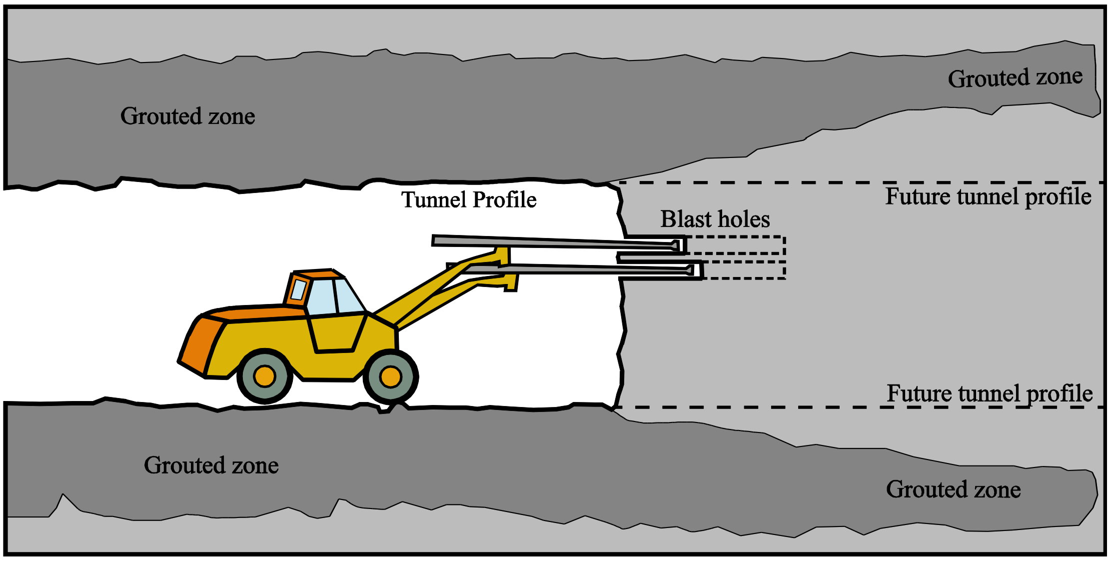

Figure 4 Sketch showing the drilling of blast holes after the completion of grouting.

When blasting, the tunnel face is often divided into five different parts; cut, stoping, floor, helpers and contour, as shown in Figure 5. Blasting is initiated in the cut and the detonations are sequentially timed outwards from the cut. The concentrations of the charges differ depending on where in the tunnel face the holes are located, for instance the contour holes often have the lowest charge. Outside the planned tunnel profile, blasting will damage the rock and fractures will appear. This is taken into account when designing the charges and this area is called the excavation damaged zone (EDZ). Generally, the EDZ surrounding the contour is approximately 0.3 metres, and the same distance is usually used between different blast holes (Svensk Byggtjänst AB, 2011). A larger EDZ is often allowed in the floor in Swedish tunnelling projects since a larger charge is required to lift the rock.

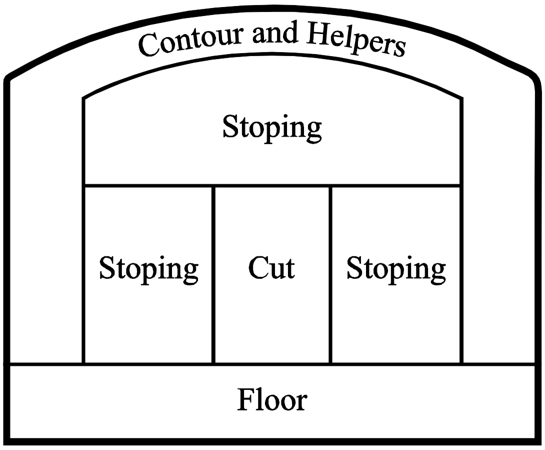

Figure 5 *The five parts of the tunnel face.*

1.1.3 Vibration waves

A detonation releases energy into the rock and creates different types of waves and vibrations. The energy consists of body waves (P-waves and S-waves) and surface waves (Rayleigh waves). Their behaviours are shown in Figure 6. P-waves, or Primary waves, are compressional waves that oscillate matter back and forth in the direction that they are travelling. This is the fastest type of wave and they travel through both liquids and solid materials, such as rock. Secondary or shear waves, called S-waves, directly follow the P-waves, but compress and expand matter at a perpendicular angle from the direction of travel, creating a shearing motion. S-waves have greater amplitude than P-waves, but move at a slower pace and cannot travel through liquids since liquids do not sustain shear strains. Rayleigh waves are surface waves meaning that they move near the surface of the matter. Hence, they will only disturb the ground above and are assumed in this thesis to not have any effect on the grouting in a tunnel project.

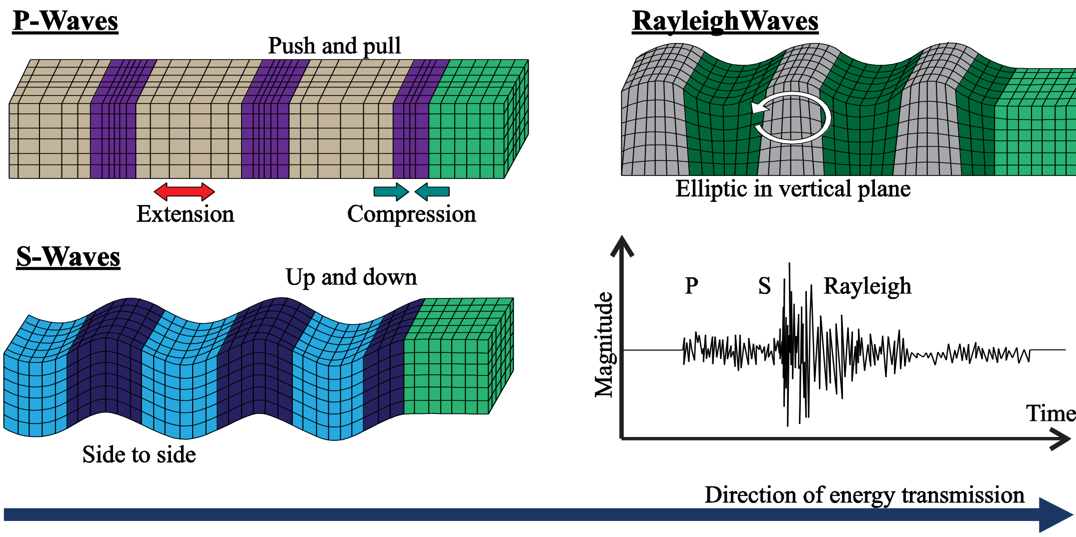

Figure 6 *The behaviour of P-waves, S-waves and Rayleigh waves (The Constructor, 2012).*

The propagation of the detonation wave has a velocity of 3 000 to 6 000 m/s, depending on the charge size and the diameter of the blast hole (Persson, et al., 1993). Closest to the detonation the force from the blast is high compared to the strength of the rock, leading to fracturing of the rock. Radial cracks occur as the wave propagates through the rock and when the waves reach an open rock surface, additional fractures are formed as long as the energy of the waves exceeds the strength of the rock (Ahmed, 2012). The energy of the wave is often denoted as the peak particle velocity (PPV). The effect of the PPV depends highly on the strength of the mass that the blast vibrations are transferred to. A standard value of the threshold in a granitic rock is a vibration level of 0.7 to 1 m/s (700 to 1 000 mm/s), which is when the rock starts to fracture ((Persson, et al., 1993); (Ahmed, 2012)).

1.2 Aim and Scope

This project aims at investigating the effects of vibrations on grout. The changes, if any, that occur will be explored in order to investigate if blasting is possible at an earlier stage than current experience-based recommendations suggest. This thesis can then form a basis for further development of ways of blasting at an earlier stage in the tunnelling process. The main objectives of this report are the following.

- Create and test a grout when it is ductile respectively brittle to assess possible differences.
- Test different types of vibrations on the grout to measure potential changes in the properties of the grout.
- Create a vibration equivalent to that of a tunnel blasting in order to conduct manageable laboratory experiments of a blast-induced vibration on grout.
- Discuss if blasting can be performed at an earlier stage without a possible decrease in performance of the grout.

1.3 Limitations

This thesis has been limited to pre-grouting using cement-based grout since this is the most commonly used method in Sweden. Furthermore, mainly the first hours of hardening are evaluated. The only cement used in the laboratory tests is INJ30 with a water-cement ratio (W/C) of 0.8, since this is a typical setup. In addition, the shear strength and permeability are the main properties observed; adhesion, viscosity and yield stress are only mentioned in this report.

There are several factors that may affect the grout and reduce the sealing of the tunnel, such as drilling, flushing of the boreholes, stress redistribution when removing rock, erosion and vibrations from different operations. In this thesis, the only studied effect of blasting is from the blast-induced vibrations on the grout when blasting is performed. Hence, vibrations from drilling, scaling and mucking are considered insignificant. In addition, the grouting is only considered to seal the rock to prevent water inflow into the tunnel and not work as a strengthening of the rock itself.

There are different aspects associated with the blast that may have an effect on the grout. The effects of the gas expansion as well as the grout in the floor of the tunnel will not be studied. Furthermore, specific details on the properties of the different vibration waves will not be identified or evaluated. Instead, the general effects on grout by vibration waves will be investigated.

2 Methodology

Initially, the standards and requirements for the waiting time had to be defined to enable an evaluation of the possibilities of a decreased waiting time. However, there is no general standard for this; it is set based on experience and the waiting time differs from project to project and between different companies. Together with several consultants working with rock engineering and tunnelling, a survey was conducted in which the waiting times applied in current tunnel projects were assessed.

After compiling the applied requirements on waiting time, a literature study was conducted in order to create a general understanding of the tunnelling process while gathering specific information about grouting and the blasting process. During the literature study a conceptualisation was made, concentrating on assessing important aspects such as boundary conditions, material properties and tools for evaluation. In addition, a number of different small-scale laboratory tests were made during this investigation in order to examine and illustrate how the grout behaves when exposed to vibrations similar to blasting in its proximity. To further deepen the knowledge and to receive feedback on the conceptual model, a field study to a tunnel construction site outside the city of Ulricehamn has been carried out.

2.1 Experiences in the Tunnelling Industry

A survey was conducted together with several different stakeholders in the tunnelling industry with the purpose of gathering information on regulations concerning the waiting time. The involved stakeholders are contractors, technical consultants and technical specialists. They have participated through email correspondence with two specific questions asked; *In your projects, how long waiting time between grouting and the blasting process is required?* and *Why is this specific time set?*. The general answers from some of those involved are summarised below. Depending on the received answers some more detailed follow-up questions were asked.

One contractor stated that the waiting time is related to the rock quality and the water flow conditions in the rock. Also, the grout is often required to have reached a certain shear strength before any adjacent work is started. For this contractor, a typical waiting time is about six hours, but if conditions are unfavourable, the waiting time could be up to twelve hours.

A technical consultant explained that a common limit value of the shear strength of a grout is 1 kPa in hydropower dam constructions. According to the consultant, this is somewhat similar to the construction of tunnels. It takes about four to six hours for a grout with a W/C of 1.0 to reach the strength of 1 kPa, but a lower W/C could decrease this time. The consultant is not certain from where this limitation comes from but refers to studies of the flushing resistance of grout.

Another technical consultant relates the waiting time to the strength development of the grout, which is relatively slow during the initial stage of the hardening process. Another important aspect that this consultant discusses is the overlap of previous grouting cycles which can reduce the waiting time since the rock is considered to be partly sealed when the drilling of the blast holes is initiated. In one of the consultant's projects, the waiting time was three to five hours between grouting and the initiation of the blasting process.

A technical specialist in tunnelling constructions has used the limitation of 0.5 kPa for the grout's shear strength in several projects. However, a specific time demand is sometimes stated together with the shear strength threshold. Often, the specified time is longer than the time it takes for the grout to reach 0.5 kPa in shear strength, and thus, it overrules the strength parameter. Historically, the waiting time has been up to six hours, but the technical specialist implies that an increasing number of contractors are decreasing their specified waiting time in recent tunnelling projects. With the requirement of 0.5 kPa in shear strength, the waiting time will almost solely consist of dismantling of the grouting equipment and establishment of the equipment for drilling of blast holes. In conclusion, the technical specialist adds that erosion of the grout and problems with resistance against flushing of the grout is regarded as insignificant.

In contrast to the technical specialist, a professor is of the opinion that the fresh grout could be disturbed by flushing from the drilling of blast holes and also that internal erosion may have a negative effect. However, if the grouting is conducted with a standard overlap (five to ten metres), the rock is considered to be sealed and thus, internal erosion is no longer a possible problem. This sealing would imply that no waiting requirements are necessary.

2.2 Literature Studies

In order to obtain a background and valid knowledge about grouting and the blasting process, a literature study was conducted. Several academic theses have been acquired in different topics related to the main subjects; blasting and grouting. Furthermore, a study in the specific topic of the effects from blast-induced vibrations on grout has been conducted in order to examine previous results and test methods. The literature study has led to introductory sections about grouting, hardening and the blasting process, as well as the following section about previous investigations.

2.3 Previous Investigations

The purpose of assessing previous studies has been to gather background information and critically evaluate other investigations made in the same field. However, published material on the effects of blast-induced vibrations on grout in a tunnel project has not been found. There are studies that focus on how other materials and other supporting structures respond to vibrations from a blast as well as how grout responds to different occurrences during the blasting process. Since these studies cover similar topics they have been considered important for this thesis and are summarised below.

Some conducted laboratory experiments in previous studies have examined different forces that the grout will be exposed to. Johansson (1997) focused on the effects of flushing during drilling and the risk of altering, or even destroying, the grout. Two mixes of cement-based grout were tested at several different stages in the hardening process in order to determine the breaking point at which the grout was not affected by the flushing. The conclusion was that the grout should attain a shear strength of 12 kPa.

However, in these tests, by Johansson (1997), the grout samples were exposed to a constant water pressure at one specific point unlike the real case where the drill will pass each fracture area with grout quickly and hence, have a much shorter time of impact. In addition, the modelled fracture had a width of 10 mm, far larger than regular cracks in massive rock. The results in this study are therefore somewhat unlikely and flushing should not have a significant impact on the applied grout. Since there is usually a grout overlap of five to ten metres, a little abrasion should not affect the overall performance of the grout. Furthermore, a required shear strength of 12 kPa is unreasonable since the experience-based recommendation is between 0.5 and 1 kPa which is applied in real tunnelling projects, see Section 2.1.

Dalmalm (2004) evaluates briefly if flushing has a significant effect on grouting, based on laboratory tests made by Johansson (1997). The reliability of these laboratory test results is questioned since the conditions in reality are different in many ways from how that laboratory model was designed. Therefore, Dalmalm (2004) suggests that drilling can be initiated straight after grouting, without any waiting time, as long as it is done at a specific distance, which needs further evaluation, from the completed grouting.

A Norwegian study by Stjern & Myrvang (1998) has examined the effect of blasting on grouted rock bolts. One of the scopes was to investigate how grout with different hardening time is affected by vibrations from blasting. The results from this study indicate that grouting is not affected by blasting despite a vibration level of 1 m/s and a hardening time of nine hours. Since this research is concentrated to grouting of the rock bolts and not for sealing fractures in the rock it is only considered as an *indication* of the grout response in this thesis.

Zhang, et al. (2005) have researched how a fresh concrete lining is affected by blasting. This study has shown that the compressive strength of the concrete is changed depending on when the blasting is carried out during the hardening process. There are three different time stages that affect the concrete. First, the strength increases due to the vibrations, then it enters a stage where the strength decreases if subjected to blasting and finally a stage where the strength is influenced insignificantly. However, this study is based on a vibration level of only 0.3 m/s and the extent of the first stage is reduced if the vibration velocity is increased according to this study.

An article by Ansell (2004) has tested the effect on young shotcrete that has been exposed to blasting. Field tests have been carried out with different charges, blast to grout distances and ages of the grout. The results indicate that the age of the shotcrete is not a governing parameter and that failure, in terms of lost adhesion, occurred at peak particle vibration levels of 0.5 to 1 m/s. This article is supported by a thesis by Ahmed (2012), where the response of the shotcrete is modelled using finite element analysis. This report concludes, amongst other things, that a younger shotcrete is not as highly affected as an older shotcrete. The lower effect is related to the lower propagation velocity and a lower impedance ratio. This means that the vibrations will have higher tendencies to reflect back into the rock mass than to continue through the unhardened shotcrete, thus the stresses will be lower.

The studies by Zhang, et al (2005), Ansell (2004) and Ahmed (2012) have been conducted with the scope of investigating how different concrete support structures in a tunnel are affected by blast-induced vibrations. Since these reports have studied concrete which, unlike the grout, consists of aggregates and also covers a non-injected structure they are only used as indications of possible outcomes of this thesis.

2.4 Conceptual Model

To be able to evaluate the effects on grout during the blasting process, the shear strength required of the grout needed to be determined. The hypothesis of this project was that blasting can be performed before the grout has entirely hardened, because the performance of grout should not be substantially affected. During the early stage of hardening, a disturbance like this may be beneficial since it will create a vibration of the grout and remove potential air bubbles. In addition, when the grout is still fluid, it is not affected by shear waves, since fluids cannot undergo shear. Hence, if blasting is performed at an earlier stage it may be more beneficial than at a later stage.

In order to create a conceptual model of the conditions for the waiting time, if any, different occurrences that may have an effect on the grout and its hardening process had to be defined to evaluate their importance. The drilling of blast hole creates a spread of vibrations in the rock, however since these are minor they have been assumed to have no substantial effect on the grout performance. The flushing of water during drilling should not cause any significant water inflow in the apertures, with the risk of dilution and erosion of the grout, since the drill will pass the fracture areas quickly and not wear the grout down. The rock characteristics are insignificant to the grout's behaviour when exposed to blast-induced vibrations, since the rock will be exposed to the same type of forces independently of *when* blasting is performed. The fracture apertures will also be insignificant to this investigation, since they will not change if the waiting time is changed.

Hence, the problem was narrowed down to the grout properties and mainly, the effects of a vibrating motion on the shear strength and how inflow is affected. Early in the hardening process the grout is a fluid and has a ductile behaviour, while once it starts to harden it has more of a brittle behaviour. Through tests of the effects on the grout's shear strength during different times of its hardening process, a distinction between ductile and brittle behaviour can be done in order to determine if one of them is more optimal for handling blast-induced vibrations.

From these assumptions and reasoning, a conceptual model was developed that explores the relationship between the hardening of grout, the distance to a linear charge and the size of the blast-induced vibrations, see Figure 7. Also an overlap of the previous grouting cycle is assumed since that would be an ideal situation.

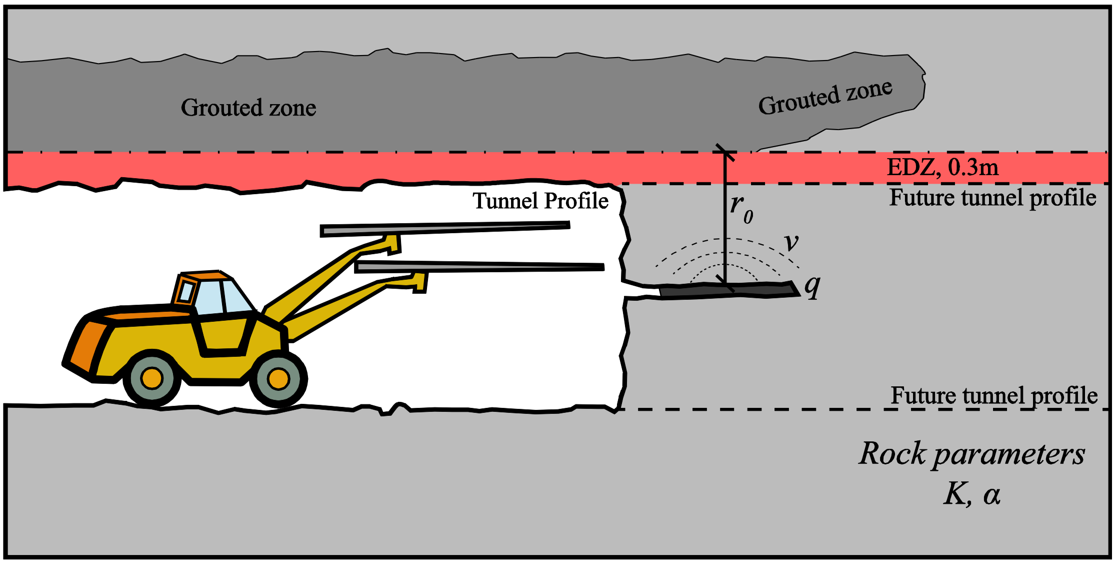

Figure 7 Conceptual model showing the distance (r_0) between a charge (q) and finished grouting as well as the vibration waves (v).

2.5 Blast-Induced Vibrations

To enable tests in a laboratory, the blasting force used in a tunnel project needs to be converted to a more manageable type of wave motion. Although blasting can be performed in a laboratory, it can be expensive, time consuming and somewhat unsafe. In addition, the destructive force of a blast may make it difficult to test the sample after blasting. Hence, a down-scaling of the blast is essential.

In order to generate a vibration wave that resembles a blasting propagation wave and creates the same effects on the grout, the theory behind explosives and vibrations had to be studied thoroughly. For this project, a more simple calculation was performed to analyse the general behaviour of a propagation wave.

The PPV of vibrations from a blast, in the proximity of a charge, can be estimated using equation (1) below and the parameters are explained in Figure 8. The rock parameters K and α are site-specific and should be chosen after test blasting. For this investigation they were set to 0.7 m/s respectively 0.7, since these are considered typical values (Persson, et al., 1993). This equation is the basis for the conceptual model described in chapter 2.4.

$$v = K \cdot \left(\frac{q}{r_0}\right)^{\alpha} \cdot \left[\operatorname{atan}\left(\frac{H+x_s-x_0}{r_0}\right) + \operatorname{atan}\left(\frac{x_0-x_s}{r_0}\right)\right]^{\alpha} \quad (1)$$

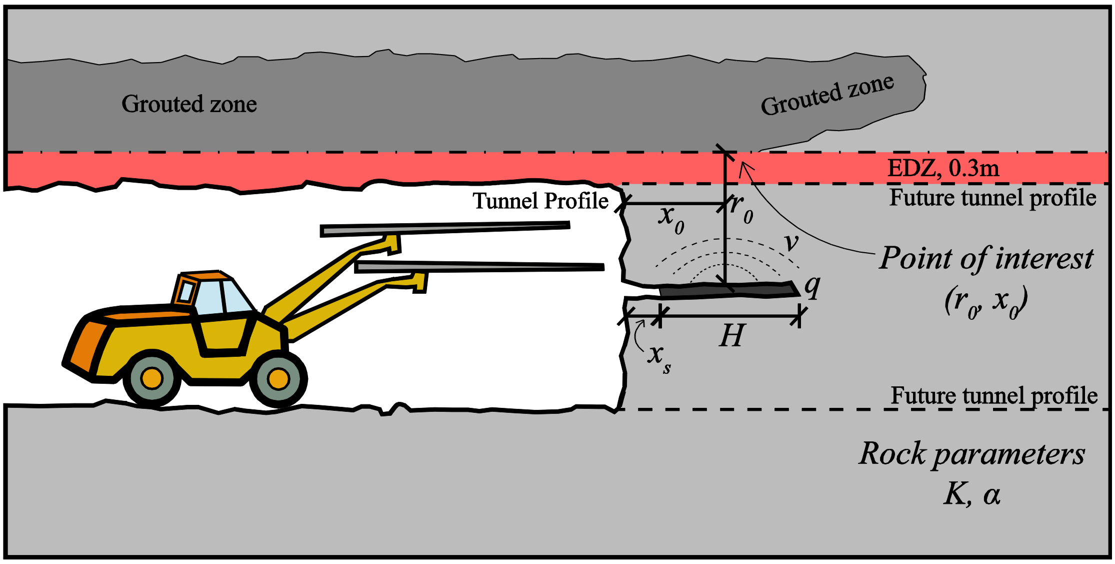

Figure 8 Conceptual model where all parameters in equation (1) are displayed.

2.5.1 Calculations of Blast-Induced Vibrations

When blasting, the tunnel face is divided into five different parts, as shown in Figure 5. Since a larger EDZ in the floor is often allowed in Swedish tunnelling projects, the effects from the floor charges have not been evaluated in this investigation. The blasting is initiated in the cut and the detonations are sequentially timed. Different charge concentrations are used for each part, which has been taken into account in the calculations and they will contribute with different PPV levels at the point of interest (POI). Therefore, the effect of different charges and the PPV's that they will cause in the grouted zone have been evaluated. The hypothesis of this evaluation was that blasting of the contour holes, which are located 0.3 metres from the grouted zone, will have the largest effect.

In accordance with a project concerning the TASS research tunnel in Oskarshamn, different charge concentrations have been chosen for this investigation, which are presented in Appendix A. The charge type Dynotex 17 and concentration 0.2 kg/m is considered a standard setup for smooth contour blasting in Swedish granite (Olsson, et al., 2004). Therefore, this type of charge design was used in the calculation of the PPV. This calculation does not consider what type of explosives that is used, but since this is a common setup it was chosen to enable a comparison to previous investigations.

Before commencing any calculations of the PPV levels, the location where the highest vibration occurs and the size of the linear charge needed to be evaluated. As can be seen in Figure 9 below, the highest PPV occurs at the centre of the charge and a fully filled borehole will produce the highest PPV.

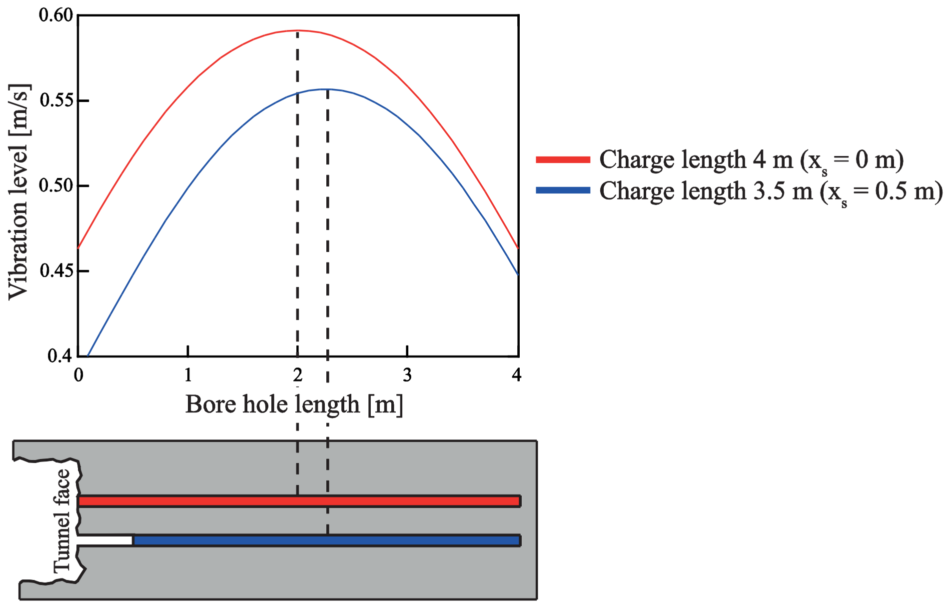

Figure 9 *Vibration level for different designs of the charge. One case where the charge fills the borehole (red) and one where the charge does not completely fill the borehole (blue). In both cases, the highest vibration occurs at the centre of the linear charge.*

Several different PPVs were then calculated in order to evaluate different scenarios, which are displayed in Figure 10. The graph displays how the vibrations are distributed over length for all different charge concentrations and each cross marks the vibration velocity of a charge when that wave reaches the EDZ. The green area represents an undisturbed zone, since the vibrations are lower than 0.7 m/s, the red area is where fracturing of the rock may occur and finally the white area represents fracturing of the rock. The results showed that the contour charge affects the grout the most. Although the other charges are higher, those vibrations will have a smaller velocity outside the EDZ, since they are placed at a further distance. The vibration of a contour charge of 0.2 kg/m gives a PPV of 1.2 m/s in the grouted zone, just outside of the EDZ. The specific distances from each charge to the grouted zone are further explained in Appendix A.

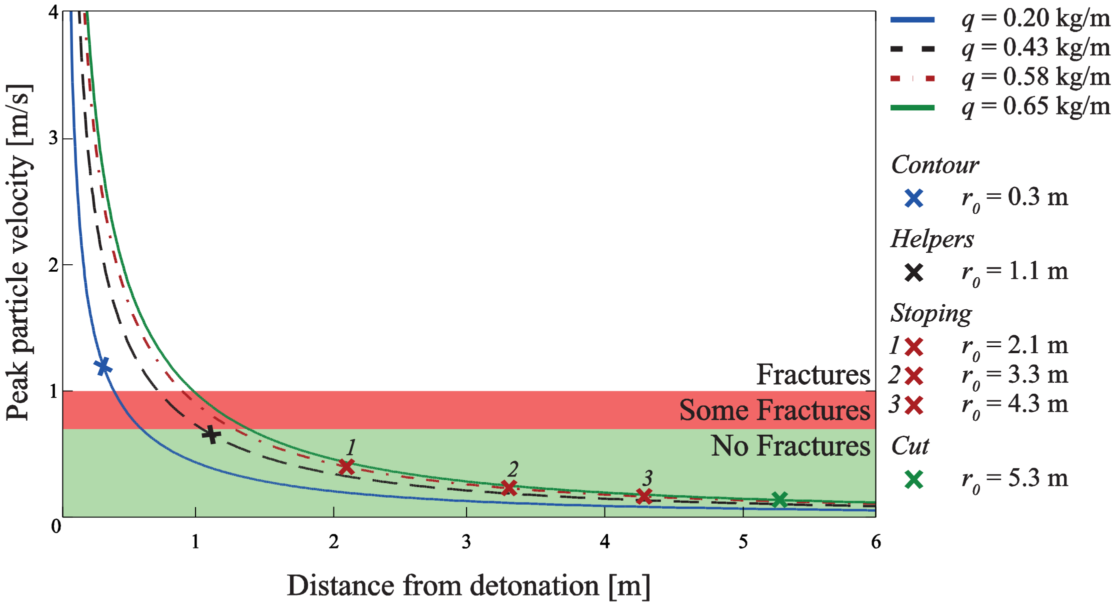

Figure 10 *Vibration level depending on the distance from the charge (r_0) for different charge concentrations. The green area is seen as non-affected by the vibrations, and the red area is where deformations in the rock start to occur.*

In order to compare the calculated vibration levels to the measured accelerations, equation (2) can be used (Konya, 2010). The equation creates a relationship between acceleration and PPV dependent on the gravitational force and the frequency. The distribution of the blast-induced vibrations over time can easily be measured with an accelerometer. Based on measurements from Bårarp; a block quarry outside Halmstad, the frequency of blast-induced vibrations is within a range of approximately 300 to 500 Hz in close proximity to the detonation (Olsson, et al., 2008). In order to create a worst-case scenario for the laboratory tests, the frequency used for the calculations in this investigation was 500 Hz, since a higher frequency results in a higher acceleration. This resulted in a blast-induced peak particle acceleration (PPA) of about 3 700 m/s^2.

$$PPA = \frac{2\pi * f * PPV}{g} \tag{2}$$

2.6 Laboratory Work

To evaluate the relationship between blasting and hardening of grout, laboratory work was executed. The overall aim was to test the resistance of the grout when it is exposed to vibrations and evaluate different test settings. The experiments were developed in an iterative process where different settings were changed until a suitable model was accomplished.

The laboratory work consisted of three main tests, which are explained more in detail in the following sections. The first tests were carried out with the purpose of studying the hardening process of the grout in general and how it reacts when it has been exposed to vibrations in terms of shaking. Secondly, a weight-release equipment was developed through analysis of the behaviour of the vibration waves caused by a detonation as well as testing of weights and dampers. This equipment was then used on a fracture replica, which was grouted to resemble a real-life situation. Hence, the grout was subjected to vibrations from the impact of a falling object.

Before commencing any tests, the grout had to be prepared. First, INJ30 and water were separately weighed. The W/C was held at 0.8 for all tests which is a common mixing ratio. While stirring with a cement mixer, the weighed INJ30 was strewn into the water as to avoid lumps and create a smooth mixture. An accelerating additive called *Cementa Set Control II* was added after about one minute of stirring. It was measured at two percent of the final grout weight. The grout was considered finished after a total of three minutes of stirring. All samples for each test were taken from the same batch of grout. Hence, all undisturbed samples were assumed to have the same rate of hardening and thus, only one undisturbed sample was tested each testing time.

To evaluate the properties of the undisturbed grout, the mud balance and marsh cone devices were applied. These two tests were conducted to ensure that the grout had the same properties for all tests in order to enable a comparison between the results of the different tests. Then, the fall cone test was used for measuring the shear strength of the grout, for both undisturbed and disturbed samples. All measuring equipment is shown in Figure 11.

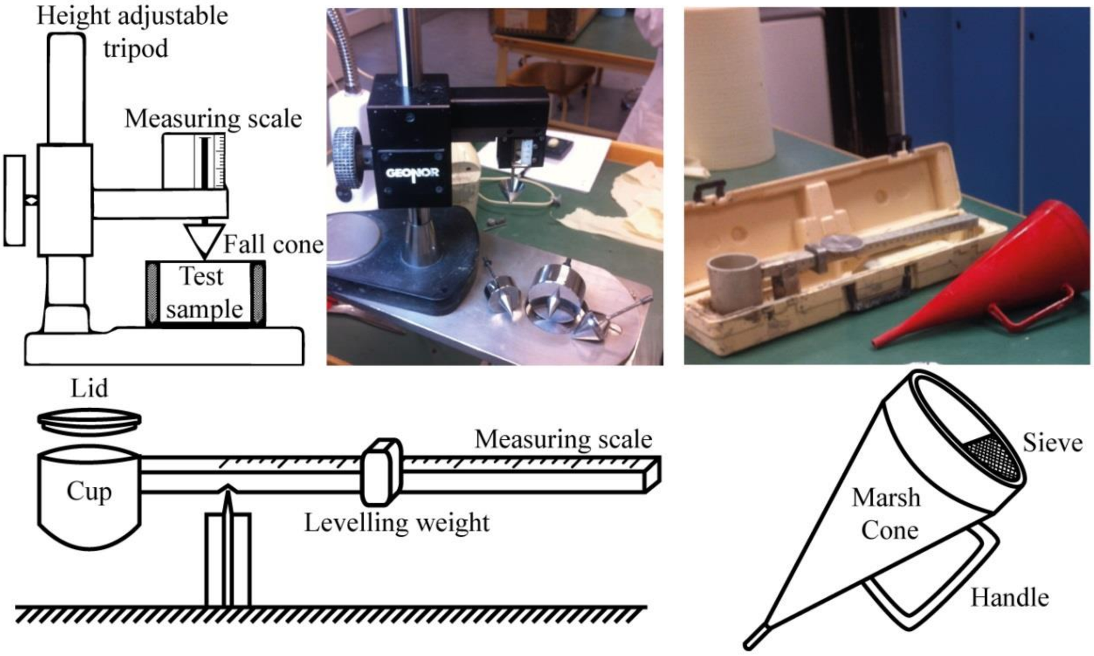

Figure 11 Sketches and pictures of the fall cone apparatus as well as the Marsh Cone and the Mud Balance equipment.

The mud balance device was used to estimate the density of the grout. It consists of a steel cup attached to a graduated beam. The cup was filled to its rim with grout and the lid was put on top. Using a level, the density was then read from the graduated beam. The marsh cone was used to quickly estimate the viscosity of the grout. First, the cone was filled to its edge with grout. Then, one litre was let out through the funnel while the time was measured.

The fall cone test consists of a metal cone with a known weight and tip angle that is mounted to a tripod and released into a sample of grout. The tripod is equipped with a scale and the penetration of the cone should be measured instantaneously after the cone has been dropped. To calculate the shear strength using the fall cone method, equation (3) has been used. This gives the shear strength as a function of the cone tip angle parameter, the gravity, the mass of the cone and the cone penetration into the grout sample.

$$\tau_g = \frac{K_c \cdot g \cdot m}{i^2} \qquad (3)$$

2.6.1 Grout Properties Tests

The initial test of the grout was made using several small cups and the fall cone test was applied once an hour to get a curve of the hardening process, as seen in Figure 12. Only one sample was tested each hour in order to get values of undisturbed grout so that valid measurements could be ensured. Each time, an appropriate drop separation was ensured so that the previous drop did not affect the next one. After three hours, the first sample was stirred with a spoon in order to observe any changes in the hardening process due to the stirring. The rest of the samples were exposed to the same type of stirring in subsequent order, one each hour.

After the initial tests using cups were completed, new tests were carried out where the grout was poured into cylindrical containers, as seen in Figure 12. Once an hour, one sample was shaken in a sieve shaker. The sample was fixed between two sieves, to keep it in place, and then shaken. The shaking motion was used to resemble the vibrations from a blast but only seen as an indicator of how vibrations affect grout. The shear strength of the sample was measured with the fall cone device before *and* after the shaking, to enable a comparison of the shear strength development. Also, one sample was left undisturbed and never shaken throughout the process, so that the hardening process, and thus change in shear strength, could be compared with the shaken samples.

Figure 12 Photo showing the tests of the grout in both cups (left) and cylindrical tubes (right).

The test with tubes was done three separate times. In each test the same grout mixture and identical tubes were used to enable comparisons between each test. The vibration levels of the sieve shaker are not as high as blast-induced vibrations, so the samples were shaken for a longer time instead. Firstly, the samples were put in the sieve shaker for five minutes, secondly for three minutes and in the final trial the samples were shaken for only six to ten seconds.

2.6.2 Weight-Release System

When dropping an object onto a surface of a matter, the impact will cause the spread of vibrations in the matter. This is similar to the detonation of a charge, since that too causes the spread of vibrations. To create an impact force, and thus vibrations, from a falling object, an equipment was designed. The purpose was to create similar vibration waves to those created when a charge detonates.

Although there are different equations for calculating the force of impact of a dropped item, these require the impulse time or the impulse distance, which is the height of a bounce or the decompression of the matter or surface on which it falls. These parameters are difficult to measure accurately, so instead, different weights were dropped from different heights to create a relationship between weight, height and impact. An assumption was made that dropping a certain weight from a specific height will cause the same impact every time. The equipment consists of a steel rod mounted onto a metal plate, see Figure 13. The plate was put on a Plexiglas sheet and an accelerometer was attached *under* and in the centre of the Plexiglas in order to measure the vibrations that will travel through and reach the grout.

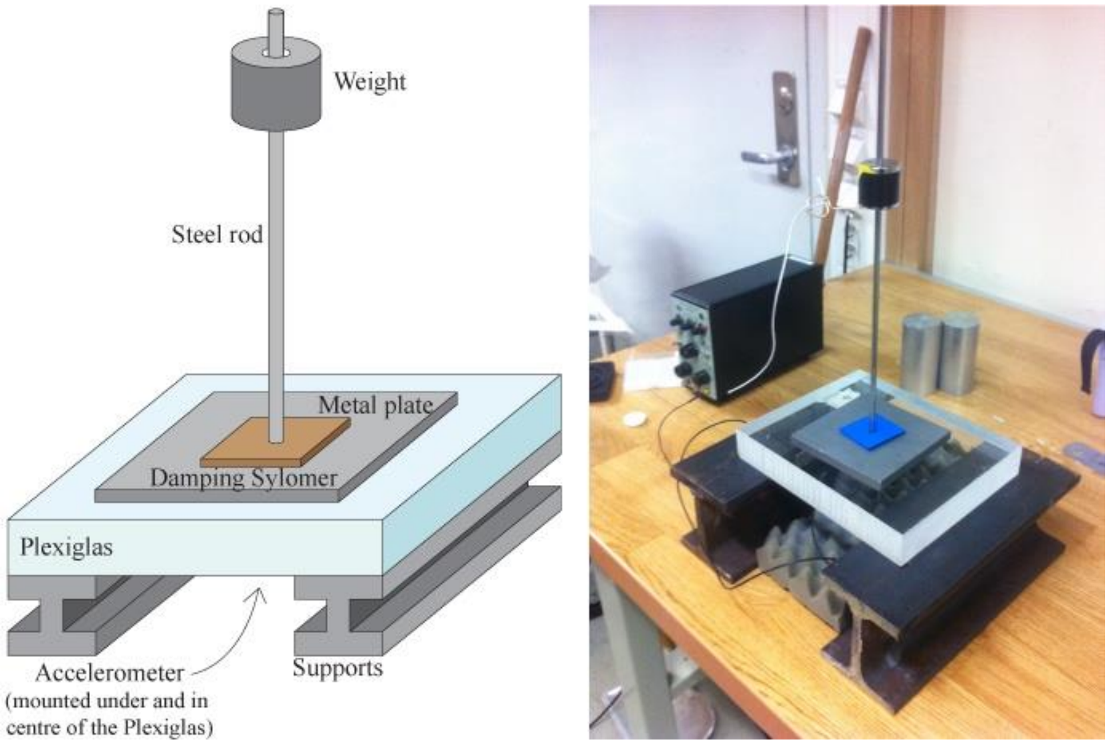

Figure 13 *Model and picture of the weight-release system that represents a small-scale test model of the blast-induced vibrations. A weight is dropped, thus inducing vibrations through the metal plate and the Plexiglas, which are then measured by an accelerometer.*

When a weight was released, the drop of the weight was guided by the steel rod. The wave behaviour of a drop is different from a blast-induced vibration at a distance, since a drop is an instant release of energy and thus has a much higher frequency. Hence, the fall had to be damped to ensure an appropriate spread of the vibrations.

This was established through an addition of a soft rubber, called Sylomer, on top of the metal plate. Different sizes and types of Sylomers were tested in order to create a damped impact and a spread of vibrations similar to that of a blast based on Olsson, et al. (2008).

After the equipment was tested and adjusted to allow reasonable results, it was used to study the effects of vibrations on grout. The final design of the weight-release system consisted of a weight of three kilograms that was released from a height of 0.4 metres. This results in a measured PPA of approximately 4 200 m/s^2, which is in the range of the calculated PPA. This way, a small-scale laboratory investigation was achieved where the properties of the grout were examined before *and* after being exposed to vibrations.

2.6.3 Fracture Replica Tests

The fracture replica consists of two pieces of Plexiglas, that each has a thickness of four centimetres. The purpose of the fracture replica is to resemble a rock fracture with a specific aperture, which can be adjusted to fit a particular purpose. To ensure a certain aperture, thin metal shims are placed in between the sheets, which are then bolted together tightly. It is a common opinion that a grout can penetrate fractures as small as three to five times its d_{95} (Hansson, 1994). This would imply that fractures with apertures larger than 90 to 150 μm can be sealed by INJ30. In these tests, an aperture of 200 μm was chosen. However, due to the pressure against the Plexiglas and the variation in tightening of the bolts, hydraulic measurements showed that the real aperture was approximately 240 μm. This aperture is well within reasonable limits.

After finishing the setup, grout was injected through a packer into the fracture replica using a pressure of 0.5 bar. This pressure was chosen since it gives an appropriate spread of the grout in the fracture replica. Then, water was flushed through the replica at a low pressure in order to measure the permeability of the grout and how this may have been affected by vibrations. A more detailed description of the fracture replica and the setup can be found in Appendix B.

Since the focus of this thesis is the effect of blast-induced vibrations, it is important to remove other parameters that could affect the grout, such as erosion of the grout due to water flow in the rock. In the initial trials of this test, the water washed most of the grout away and diluted what was left. Hence, the pressure was lowered until a setting was found where the water flowed through the grout in developed channels instead of by causing erosion of the grout. Axelsson (2009) studied the effect of erosion of fresh grout and stated that the grout must have a strength that is larger than the stresses from the water. Nevertheless, this test aims at finding *relative* changes between a disturbed and undisturbed grout. Hence, the water pressure is insignificant as long as the rest of the laboratory setup remains the same. The chosen pressure was 0.05 bar (approximately 0.5 metres of water column), since that was visually observed as leaving the major part of the grout unharmed, which easily enabled both visual and hydraulic measurements.

These laboratory tests were conducted in order to measure the hydraulic behaviour of the grout, and how it is affected by vibrations. First, a reference measurement of undisturbed grout was made to enable comparison with the subsequent disturbed tests. Hence, no actual values are significant, only the relative differences. These tests consisted of grouting of the fracture and allowing the grout to harden for different, specific times. The maximum hardening time was three hours, since the functions of the replica could be damaged by hardened grout in pipes and gaps as well as on shims and bolts. After the specified times were attained, the grout was exposed to water, which was flushed into the fracture at a pressure of approximately 0.5 metres, in order to evaluate the sealing effect of the grout without a risk of erosion. Finally, these grouting tests were repeated, but before flushing water into the replica, the grout was subjected to vibrations from the weight-release equipment. The equipment was placed at the centre of the dispersed grout. Hence, an evaluation of the sealing effect of disturbed and undisturbed grout could be made.

During the initial tests using the fracture replica, problems with large channelling in the grout occurred due to the wall slip phenomena, see Figure 14. This phenomenon occurs since the smoothness of the Plexiglas allows an easier flow of the grout which leads to a more dispersed grout in the fracture replica (Barnes, 1995). In addition, there may be some backflow of the grout when the grouting has been finished and the packer was emptied.

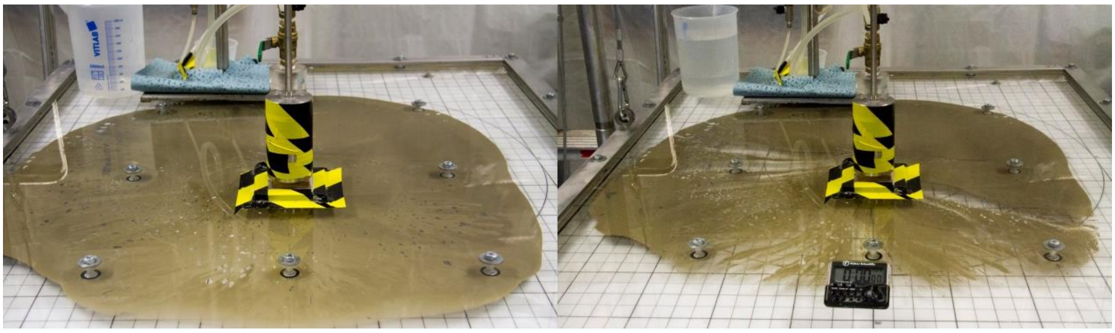

Figure 14 Picture showing before (to the left) and after slip (to the right) occurs in the grout. On the right created slip-channels are visible.

To solve these problems, the bottom surface of the fracture replica was roughened, the grouting pressure was lowered to about 0.4 bar and the packer was not emptied until one hour had passed. These improvements reduced these problems; still channels were formed but to a smaller extent, as seen in Figure 15. Channels were essential for these tests; otherwise permeability measurements would not be possible since no water would have been transported through the grout.

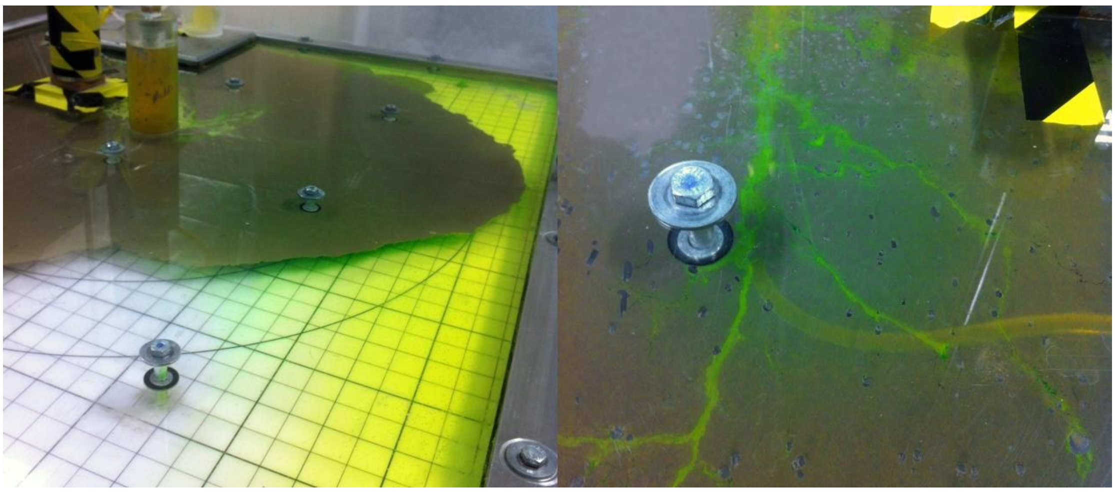

Figure 15 Photo showing the Uranin tests where the flushed Uranin water has been transported through some of the grout (left) and smaller channels filled with Uranin water (right).

To further evaluate how the vibrations affect the grout a chemical agent called Uranin was mixed together with the flushing water. Uranin colours the water and it is also traceable with UV-light. The purpose of this test was to evaluate if any change in transport of water was visible after the grout was subjected to vibrations. The fracture was grouted at a pressure of 0.4 bar, during a time-period of 10 minutes, after which there was nearly any movement of the grout despite the pressure. After one hour, some Uranin water was flushed into the fracture at a pressure of 0.5 metres. Since the water is coloured it is easy to follow the flow of the flushed water, as seen in Figure 15. After a visual assessment of how the Uranin water flowed through the grout, the weight-release equipment was used to disturb the grout and several drops were made. Additional visual assessments were then made to compare the behaviour and identify any changes in the grout or Uranin flow. These tests were repeated on the same batch of grout each hour for a total of four hours.

2.7 Field Study

Currently, a tunnel is being constructed on highway 40 just outside Ulricehamn, led by the contractor Veidekke. There are two separate tubes with two traffic lanes each, and the tunnel will be approximately 400 metres. While conducting laboratory tests, a field study of this tunnel was made. The aim was to deepen the knowledge about the process on-site and also to receive feedback on the conceptual model. These visits helped the evaluation and development of the laboratory tests.

When visiting the tunnel, the general idea and design of the tunnel was explained and discussed. The tunnelling process had just started and they were only about ten metres through. During the visit, bolts were installed in one of the tubes and the other tube was being manually charged in already drilled blast holes. Since this was at an early stage in the tunnelling process, only a small part of the tunnel face was charged. A few hours later, these charges were detonated in one simultaneous detonation using emulsion explosives.

There are several similarities between this project and the made assumptions for calculations and estimations in this thesis. In this tunnelling project a d_{95} of 40 μm or less is allowed and the grout has a W/C of 0.8 to 1. The grouting is made using an overlap of five metres. The drilling of blast holes is allowed to be initiated five hours after the grouting is completed. The blast concentrations are between 0.35 and 1.1 kg/m and the allowed extent of the EDZ is 0.4 metres.

3 Results

After each test was completed, the results were compiled and evaluated. The following sections will display the results of the grout properties test and the fracture replica tests, where the developed weight-release equipment was applied.

3.1 Grout Properties Tests

The results of the grout properties tests show that a shaking motion of a grout sample affects the *rate* of hardening and slows this process down. Nevertheless, the final shear strengths of undisturbed and shaken samples are within the same range, which indicates that vibrations do not have negative effects on the grout's shear strength. In addition, all disturbed samples show similar shear strengths which demonstrates that the time of disturbance is insignificant since the final shear strength is the same.

Figure 16 displays a curve of one disturbed sample, marked in blue, compared to the undisturbed sample, marked in red. The arrow points to the time of disturbance. It is visible that the grout is affected by the vibration, since it causes a direct decrease in shear strength. Nevertheless, the shear strength is recovered and the two samples have similar shear strengths at the end. Specific results of the grout properties tests are displayed in graphs in Appendix C.

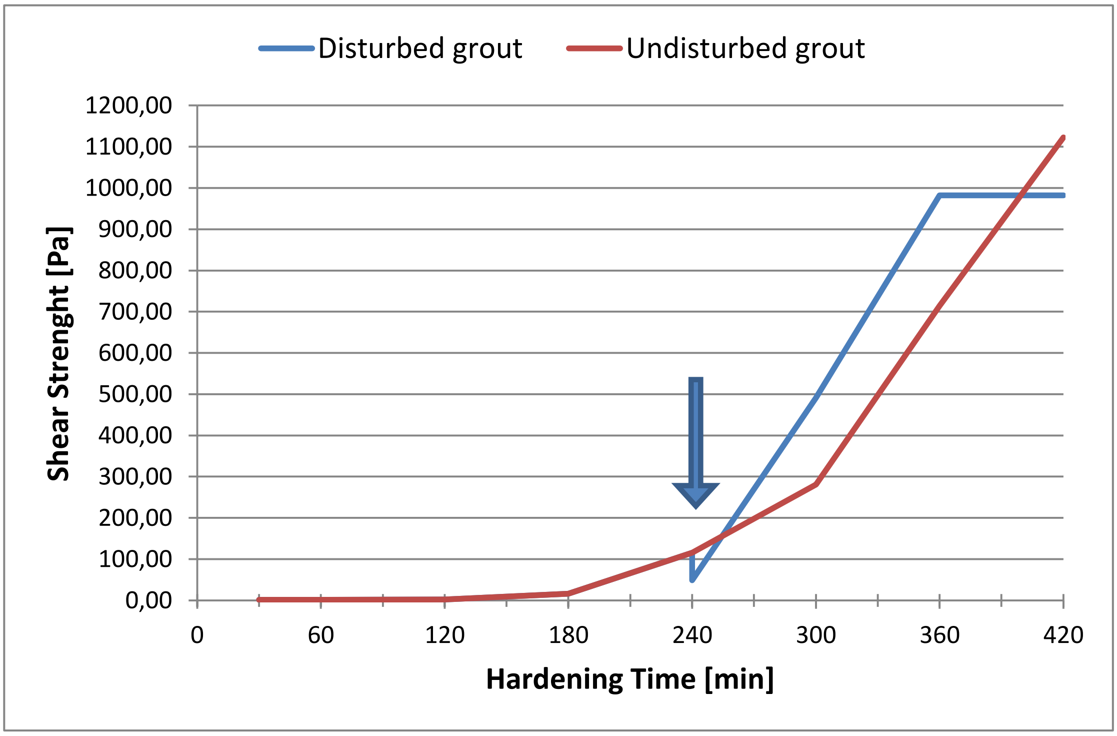

Figure 16 Graph showing the growth of shear strength in one disturbed grout sample (blue) and an undisturbed grout sample (red) over time. The time of disturbance is marked with an arrow.

3.2 Fracture Replica Tests

The fracture replica tests were performed on both undisturbed and disturbed grout of different hardening times. The results have only been considered as relative measurements, which can be seen in Figure 17. It is visible that the disturbance of the grout affects the permeability in a negative way. Specific results of the permeability measurements of the grout in the fracture replica tests are displayed in graphs in Appendix D.

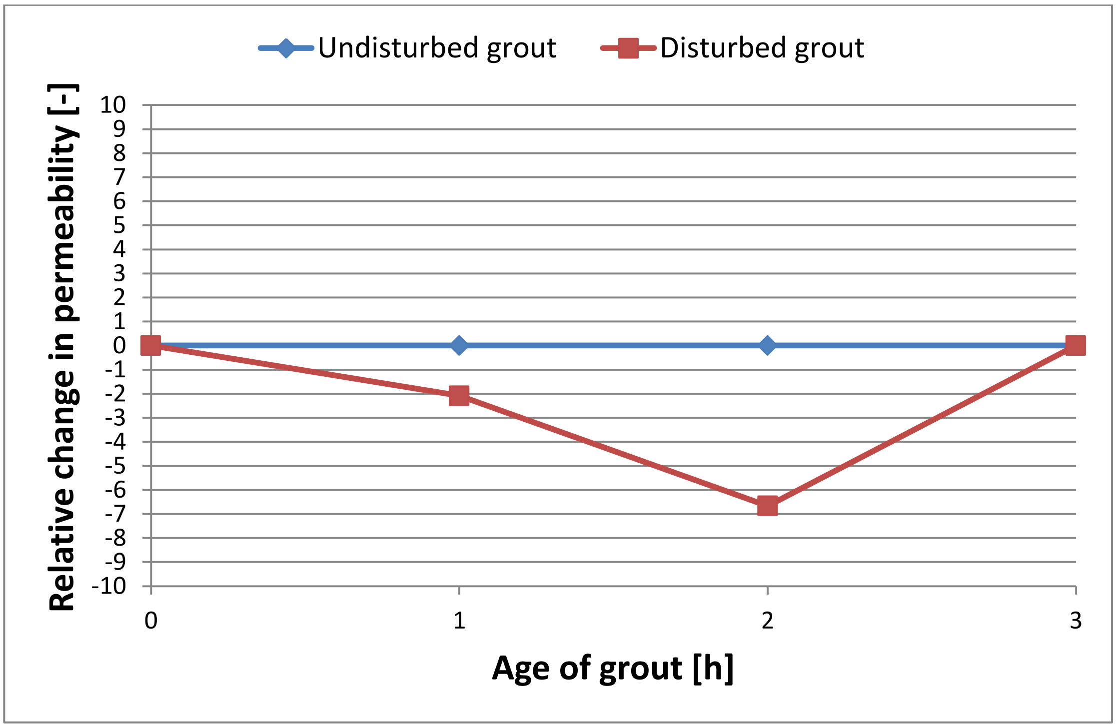

Figure 17 Graph showing the relative change in permeability when grouts of different ages are subjected to vibrations.

The assessment of the Uranin tests show that the vibrations cause a redistribution of some of the cement particles in the grout. The redistribution leads to a change of the channels in the grout, some are widened and some are dispersed, as seen in Figure 18. Also, the flow of water increases visually immediately after the disturbance but the increased flow only lasts for a few seconds.

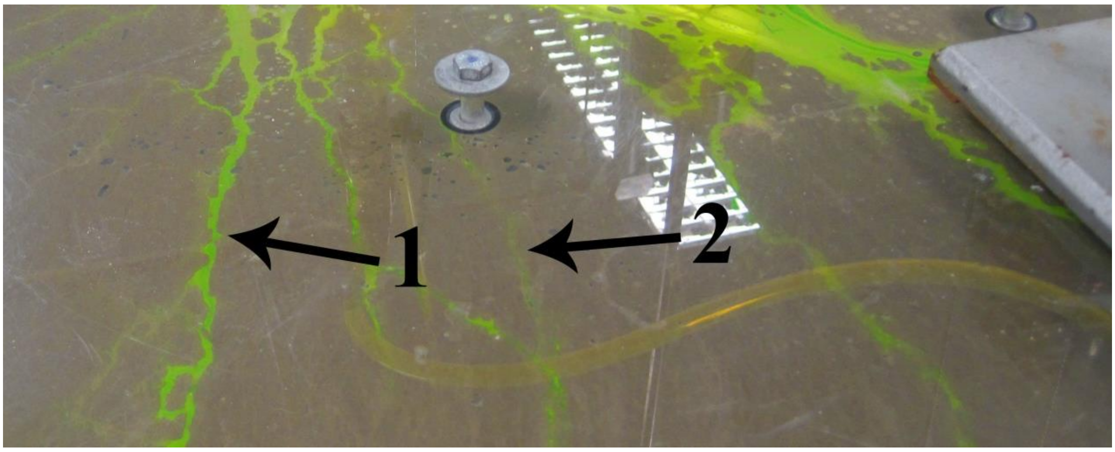

Figure 18 Results from the Uranin tests where the channels are widened (1) and dispersed (2).

4 Discussion and Analysis

The effect of blast-induced vibrations on grout has not been previously studied according to the conducted literature study in this thesis. The laboratory methods have not been applied before and were developed specifically for this thesis. Hence, the process was thoroughly assessed. Although this needs to be investigated further, this thesis creates a basis for deeper studies of blast-induced vibrations and its effects on grout. If the results can be further substantiated, it would mean that time, and thus money, can be saved in tunnelling projects.

4.1 Grout Properties Tests

The grout properties tests show that the shear strength is affected directly after being exposed to a shaking motion, but in the long-term, it is recovered. Misreading of the fall cone apparatus happens easily, which makes it difficult to determine how much the vibrations actually affect the grout. Also, the thickness of the sample is much greater than the grout layer in a fractured rock. Nevertheless, the results of undisturbed and disturbed samples are within the same range. In addition, these tests indicated that the time of disturbance is insignificant. The grout was tested in a ductile (first hours) as well as a brittle (after several hours) stage, but the results were the same or similar either way. The hardening process can be disturbed regardless of at what time the blasting process is initiated since it takes 28 days until hydration is completed. Hence, if the long-term response to vibrations is the same independent of at what time it is disturbed, blasting can be done at an earlier stage.

Although the applied sieve shaker does not create vibrations as high as those from a blast, this test still gives an indication of how grout responds to vibrations. In addition, the vibrations were more enduring, which shows that the grout can handle prolonged vibrations. Stressing the grout for a longer period of time may have a greater impact on the properties of the grout than a short vibration, such as a detonation. Hence, specific duration was applied in each trial of this test to detect any variances in behaviour due to length of shaking. There are slight differences in recovery time between the trials. The recovery time of the third trial is shortest, since it displays that most disturbed samples have the same or higher shear strength than the undisturbed sample after seven hours. Hence, the time that a grout is exposed to vibrations has some influence, but the long-term results are the similar.

In the laboratory test INJ30 has been used since it is one of the most common grout types in Sweden. This cement mixture has a particle size distribution (d_{95}) where 95 percent of the cement grains are smaller than 30 μm. According to Thomas & Jennings (2009) the particle size will determine the hydration time. Hence, a cement grout with smaller particles will hydrate faster. Considering this fact, a finer grained cement grout like Ultrafin 16 or Ultrafin 12 (that has a d_{95} of 16 respectively 12 μm) would be less affected by the blast-induced vibrations since these grouts hydrate faster. Another important parameter is the W/C (Thomas & Jennings, 2009). If the W/C is lowered the hydration time of the grout would decrease which in turn would reduce the effect of the blast-induced vibrations. However, a shorter hydration time could affect the penetration length.

4.2 Vibration Calculations

The calculations of the blast-induced vibrations resulted in a critical PPV of 1.2 m/s in the grout as a result of a blasting at the tunnel contour. Although the contour holes have the lowest charge concentration, they are closest to the POI, which results in the greatest effect. The calculated PPV is higher than the threshold where damage of the rock is incipient (0.7 to 1 m/s), and thus, some damage in the grout should take place. Nevertheless, since the chosen charge type is a typical setup for smooth contour blasting in Swedish tunnelling projects, no damage should occur outside of the EDZ. Furthermore, studies have shown that this charge design causes fractures varying between only 0 and 0.22 metres (Olsson, et al., 2004), indicating that outside an EDZ of 0.3 metres the rock is unaffected. Another study by Kilebrant & Norrgård (2008) has supported that the EDZ does not exceed 0.3 metres if Dynotex is used in the contour holes. In fact, in this study Dynotex 22 was used which resulted in a charge concentration of 0.37 kg/m, since it has a larger diameter (22 mm), compared to the used charge concentration of 0.2 kg/m.

The reason for the short fracture length when using Dynotex 22 is that when blasting the contour hole, the diameter of the charge is smaller compared to the stoping and cut charge diameters, However, the drilled blast holes have the same diameter all across the tunnel face, usually around 40 to 50 millimetres. Hence, the coupling ratio (charge diameter divided by the blast hole diameter) is smallest in the contour holes. For example, in the TASS-tunnel hard rock laboratory, a charge of 17 millimetres was used in the contour but the blast hole diameter was 48 millimetres, which gives a coupling ratio of 35 percent (Karlzén & Johansson, 2010). Thus, a much lower blasting pressure is created when detonating contour holes. However, equation (1) does not consider a coupling ratio, which means that it is not appropriate when the charge diameter is smaller than the blast hole diameter. In addition, the equation assumes that the entire linear charge is blasted simultaneously, but in reality the charge will gradually detonate, starting from the tunnel face to the end of the borehole. Hence, the calculations have resulted in a higher value than a real-life scenario and can be assumed to have been done on the safe side. In-field measurements of the PPV in close proximity to the detonation should in this case be more suitable. However, this is difficult to measure since the short distance to the detonation would induce some damage to the measuring equipment.

When using the equipment, there were some inevitable sources of error. The weight-release equipment was designed so that the impact of the weight would create a spread of vibrations similar to the dispersion of blast-induced vibrations. However, since the vibration levels where not measured for each laboratory experiment, the vibrations may have been higher or lower than the expected levels, which were based on initial tests of the equipment. An assumption was made that each drop would be identical. However, since the impact is affected by the friction of the rod, surface area of the impact and the damping effect of the Sylomer, the impact force may differ. To ensure that the grout was exposed to sufficient vibrations, the weight was instead dropped several times. However, if the appropriate effect was achieved is uncertain.

The weight-release equipment contains many insecure parameters and several assumptions had to be made. For example, the wave behaviour was not thoroughly investigated. The damping Sylomer was adjusted so that the impulse wave would generally resemble a blast-induced vibration wave, but was not adjusted in detail. The impulse time was adjusted to resemble the data from the block quarry in Bårarp measured by Olsson, et al. (2008) and the frequency was similar, as seen in Figure 19. However, the tunnel data was measured at a distance of five metres from the detonation. Due to this distance the size of the PPA were based on calculations instead of this data. In addition, some of the inserted values of rock and grout properties had to be based on typical scenarios of previous tunnel projects. However, these need to be determined for each specific project. Nevertheless, since this thesis aimed to measure effects of vibrations in general, the chosen variables are reasonable and applicable.

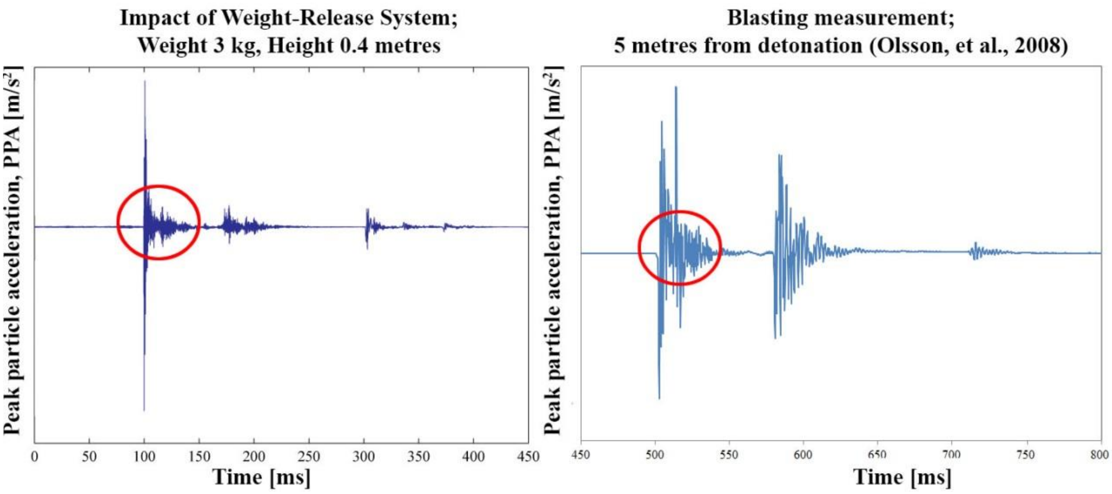

Figure 19 *Comparison of measured impact-vibrations from the weight-release equipment (left) and blast-induced vibrations at the block quarry in Bårarp (right). The impulse time (marked in red) of both vibrations is about 50 ms and the vibration behaviour is similar.*

4.2.1 Sensitivity Analysis of the Vibration Calculations

As a part of the investigation of how blast-induced vibrations affect grout, a sensitivity analysis was made to evaluate how different assumed parameters affect the results. For instance the rock parameters K and α where set to 0.7 m/s respectively 0.7 since these values are considered standard values. However, these values are site-specific and should be chosen after test blasting and vibration measurements have been made at the tunnel site. Therefore, these values were evaluated in a sensitivity analysis. Each parameter was changed with ± 20 percent and the resulting PPV's are presented in Table 1. It can be noted that a slight change does not affect the vibration level considerably and even if both parameters are lowered with 20 percent, the PPV will still be over the threshold value where fracturing of the rock occurs (0.7 m/s).

Table 1 *Sensitivity analysis of the PPV in m/s where the assumed rock parameters K and α vary with ± 20 percent. The PPV in bold text is calculated with the used assumptions in accordance with Section 2.5.*

PPV [m/s]

		K [m/s] - 20 %	- 10 %		+ 10 %	+ 20 %
α [-]	- 20 %	0,86	0,96	1,07	1,18	1,28
	- 10 %	0,90	1,02	1,13	1,24	1,36
		0,95	1,07	**1,19**	1,31	1,43
	+ 10 %	1,00	1,13	1,26	1,38	1,51
	+ 20 %	1,06	1,19	1,32	1,46	1,59

Another parameter that affects the result is the frequency of the vibrations at the POI. This is also site-specific since the vibration propagation will vary in different rock materials. Hence, the frequency should also be investigated in each individual tunneling project. The sensitivity analysis of this parameter shows that a change of ± 20 percent will give a change in acceleration by the same proportion. The highest and lowest velocities from the sensitivity analysis of the PPV, which are highlighted in blue in both Table 1 and Table 2, were taken into consideration as well, see Table 2. The sensitivity analysis shows that the difference between the highest and lowest values of velocity and frequency gives a large difference in acceleration. Hence, this parameter is sensitive to changes. Since several assumptions had to be made for this entire study, the results should only be seen as *indications*. In addition, the values marked in green are accelerations that are lower than the measured accelerations when designing the weight-release equipment. Hence, most of the accelerations in the sensitivity analysis are still on the safe side and only a few are higher than expected acceleration levels.

Table 2 *Sensitivity analysis of the acceleration in m/s^2 where the PPV and frequency vary with ± 20 percent. The acceleration in bold text is calculated with the used assumptions in accordance with Section 2.6.2.*

Acceleration [m/s²]

		PPV [m/s]				
		-20 %	- 10 %		+ 10 %	+ 20 %
f [Hz]	- 20 %	2152	2553	2992	3470	3992
	- 10 %	2421	2872	3366	3904	4491
		2690	3192	**3739**	4338	4990
	+ 10 %	2959	3511	4113	4771	5489
	+ 20 %	3228	3830	4487	5205	5988

4.3 Fracture Replica Tests

It is evident that the permeability of the grout is affected negatively. Nevertheless, the hydraulic measurements are relative to each other, and in numbers, the differences may not be significant. To be able to determine if the negative effects have an impact on the sealing ability of the grout, more detailed tests need to be conducted where it is possible to measure the magnitude of the effects. On the other hand, in actual tunnel projects there is no equipment that can be used to measure if the grout has achieved the required shear strength before the blasting process is initiated. Hence, the effects of an earlier blasting may be minor so that they will not have a noticeable change in sealing. For instance, there may only be a change of inflow of one more drop of water per minute, which will not affect the overall sealing of the tunnel.

In these laboratory tests, the same grout mixture has been used for all trials. However, there were still differences in behaviour to a small extent, since the viscosity and density of the different batches were slightly varying. The dispersal of the grout in the fracture replica may also vary since the grout pressure will not be exactly the same each time due to uncertainties in the pressure gauges and the bolts will vary in tightness. The formation of larger channels in the hardening grout, which may be due to slip and separation between water and the cement particles, may affect the hydraulic measurements. However, some channels are required to enable any measurements. The results from the fracture replica may also be altered by a possible minor change in the water pressure. Nevertheless, the tests were conducted thoroughly and carefully. In addition, in all tests these sources of error existed and the relative relation between the results is still valid.

The conducted measurements displayed a lowered permeability after the grout had been vibrated compared to when it was left undisturbed. These measurements were taken right after the grout was exposed to the vibrations. However, it was not possible to measure if the exposed grout achieved the same final properties as the undisturbed grout after a certain time, since leaving the grout in the replica any longer could damage the equipment. Compared to the grout properties tests, the samples of disturbed grout from that test were first affected by the vibrations, but in the long-term, the shear strength was recovered. Hence, it is possible that the negative effects from vibrations are just short-term and that the grout would have the same hydraulic behaviour in the long run.

Tests using Uranin water made it visible that only minor and instantaneous changes occur when the grout is subjected to vibrations. Although, long-term tests were not possible, it was clear that the grout was only affected during the vibrations and a short time after. Hence, it is unlikely that the long-term effects are significant but further investigations are required. In addition, the small effects only occurred in close proximity to the grout. Meanwhile, it was not obvious where the weights were dropped, since the overall appearance of the grout remained the same.

4.4 Analysis of Previous Studies

In accordance with Zhang, et al., (2005), Ansell (2004) and Ahmed (2012) this investigation has shown that it is possible to disturb a cement-based grout early in the hydration process without negative effects. Since the aim has been to limit the waiting time, only the first hours of the hydration process were studied, but the results indicate that the grout is insignificantly affected.

In accordance with Johansson (1997), this investigation has shown that flushing of water will affect grout, but only if the water pressure is higher than the strength of the grout. Water will always choose the easiest way, so when water is flushed while drilling, the water will flow back through the borehole and not into the fractures. It is much harder for the water to enter a fracture with an aperture of less than one millimetre than going through the borehole with a diameter of more than 40 millimetres. In the laboratory experiments of this thesis, this was seen in the fracture replica where the water would chose to exit through a tube of diameter eight millimetres connected to the replica rather than going through the fracture if the valve to the tube was open. Hence, the flushed water will never enter fractures with a pressure as high as suggested by Johansson (1997), and in reality, flushed water from drilling boreholes should not be an issue.

In accordance with Dalmalm (2004), vibrations from drilling of the blast holes should not have an effect on the performance of the grout. Although it was suggested that drilling should be conducted at a certain distance from the grouted area, these vibrations should not have an effect since the magnitude of the blast-induced vibrations is much larger. The results of the tests of this thesis have shown that blast-induced vibrations have a minor effect on grout and thus, much smaller vibrations will most unlikely have an influence. Nevertheless, the grout is exposed to the drilling during a longer time and therefore they could have an effect anyway. Depending on at what time in the hardening process that drilling is initiated it is possible that it may create a separation in the grout mixture. On the other hand, the grout properties tests using the sieve shaker displayed that the time at which vibration occurs and the duration of the vibrations did not have any major long-term effect.

5 Conclusions

The main aim of this project has been to form a basis for further development of ways of blasting at an earlier stage in the tunnelling process. This thesis has explored the general concepts grouting and blasting as well as the ways in which vibrations may affect the performance of a grout. Through conducted laboratory experiments where the grout has been exposed to different forms of vibrations, the behaviour of grout has been tested and analysed. In addition, a field study to a tunnel outside Ulricehamn gave insight on how a real tunnelling project develops.

The most difficult part of the laboratory experiments has been to find different methods that resemble the stresses that a grout is exposed to during blasting. Although some of the conducted tests are not easily comparable to an actual blasting, they are still indications of how vibrations may affect grout. The comparisons made are based on limited material; other results may therefore be possible if the base of comparisons is extended.

The conducted grout properties tests have shown that vibrations affect the hardening process in that it is slowed down a bit, but in the long-term, the same shear strength as the undisturbed grout is reached. Whether the grout is exposed to vibrations when it is in a ductile or in a more brittle stage is insignificant; the effects are of similar range either way. Although the vibrations from the sieve shaker were not as high as blast-induced vibrations, they were more enduring. In addition, it indicated how the performance of a grout can be altered through the exposure to vibrations.

During the tests where the fracture replica was used, the grout was exposed to vibrations equivalent to blast-induced vibrations. This was a manageable laboratory experiment in which the hydraulic properties of the grout were evaluated and compared. These tests showed changes between disturbed and undisturbed grout, since the hydraulic measurements differed. Hence, grout is affected by blast-induced vibrations. Nevertheless, the extent of these differences and effects as well as how much they will actually influence the sealing of the tunnel is uncertain.

In conclusion, this study has evaluated the effects on grout by blast-induced vibrations. In general, the results indicate that the properties of grout are influenced by vibrations in the short-term. However, indications show that the long-term effects may be minor or close to insignificant, which means that blasting directly after grouting is possible. Nevertheless, further investigations need to confirm these theories.

5.1 Further studies

To further analyse the possibilities of earlier blasting, the limitations of this project need to be evaluated and assessed. Since this report has mainly analysed *if* it is possible to blast before the hardening process of the grout is completed, it is suggested that a more thorough investigation of *when* the optimal blasting time occurs should be performed. In addition, the extent of the effects of blast-induced vibrations should be investigated, since this thesis has only focused on if there were any notable effects in general. If this is done, it can be determined whether or not blast-induced vibrations have any *significant* effect on grout.

Real rock experiments should be conducted in order to analyse how grout is affected by blast-induced vibrations and vibration measurements in close proximity of the detonation should be performed. In addition, other methods that better resemble the force of a blasting should be developed to further display that a grout's shear strength is not significantly affected by vibrations. When calculating the velocity of blast-induced vibrations, several assumptions had to be made. In order to ensure that calculations are correct, they should be performed for each tunnel case since the rock parameters, charge concentrations, tunnel profile and rock properties will differ.

Another study that could be made is if the waiting time between grouting and the blasting process can be shortened from a logistics point of view. Since the waiting time is controlled by removal of the grout equipment and establishment of blasting equipment there may be little time to save anyway. Currently, the planning of a tunnelling project includes the waiting time and resources are distributed to ensure an optimal tunnelling excavation. Hence, the used scheme of procedures may be as efficient as it can be already.

The chemical changes that occur when the grout is exposed to blast-induced vibrations should also be investigated. In addition the effects of removal of rock at an earlier stage should be analysed, since a removal of rock increases the hydraulic gradient and causes a stress redistribution. If this occurs at an earlier stage, the shear strength of the grout may not be sufficient.

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List of Appendices

APPENDIX A

Different charge concentrations are used for each part of the tunnel, which has been taken into account in the calculations. In accordance with a project focused on the hard rock laboratory tunnel, TASS, in Äspö, different charge concentrations have been chosen for this investigation, which are presented in Table A 1. Since these different charges are used in different parts of the tunnel they will contribute with different PPV levels at the POI. The distance from each type of blasting hole to the POI, which is just outside the EDZ, has been estimated in accordance with Figure A 1.

Table A 1 Charge concentrations in the TASS tunnel in Äspö (Karlzén & Johansson, 2010). These concentrations are used in the calculations of the blast-induced vibrations.

Type of hole	Charge type	Charge concentration [kg/hole]	Charge concentration [kg/m]	Approximate distance to maximum EDZ [m]
Cut	Dynorex 25	2.6	0.65	7.3
Stoping	Dynorex 25	2.3	0.58	2.1-5.3
Helpers	Dynotex 22	1.7	0.43	1.1
Contour	Dynotex 17	0.8	0.20	0.3

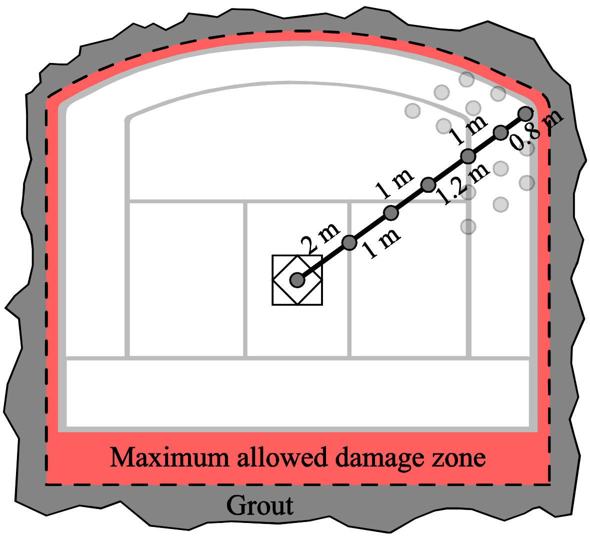

Figure A 1 Approximate distances between each different charge (also stated in Table A 1).

APPENDIX B

The fracture replica consists of two Plexiglas sheets that are sealed using several bolts. A borehole has been made through the Plexiglas sheets and a grouting packer is inserted into the hole at the bottom of the fracture replica. Grout is inserted with a pressure of 0.5 bars and the grouting is considered finished when a spread of 0.4 metres in radius is achieved. The grout has been allowed to harden for different specific times before it is disturbed using the weight-release equipment.

Figure B 1 The fracture replica.

Grouting is done through a packer from under the fracture replica. When a spread of 40 centimetres (the outermost red circle) has been achieved the grouting has been considered finished. To reduce the slip phenomenon, this area was roughened. The placement of the weight-release equipment is seen in the figure, covered in yellow and black.

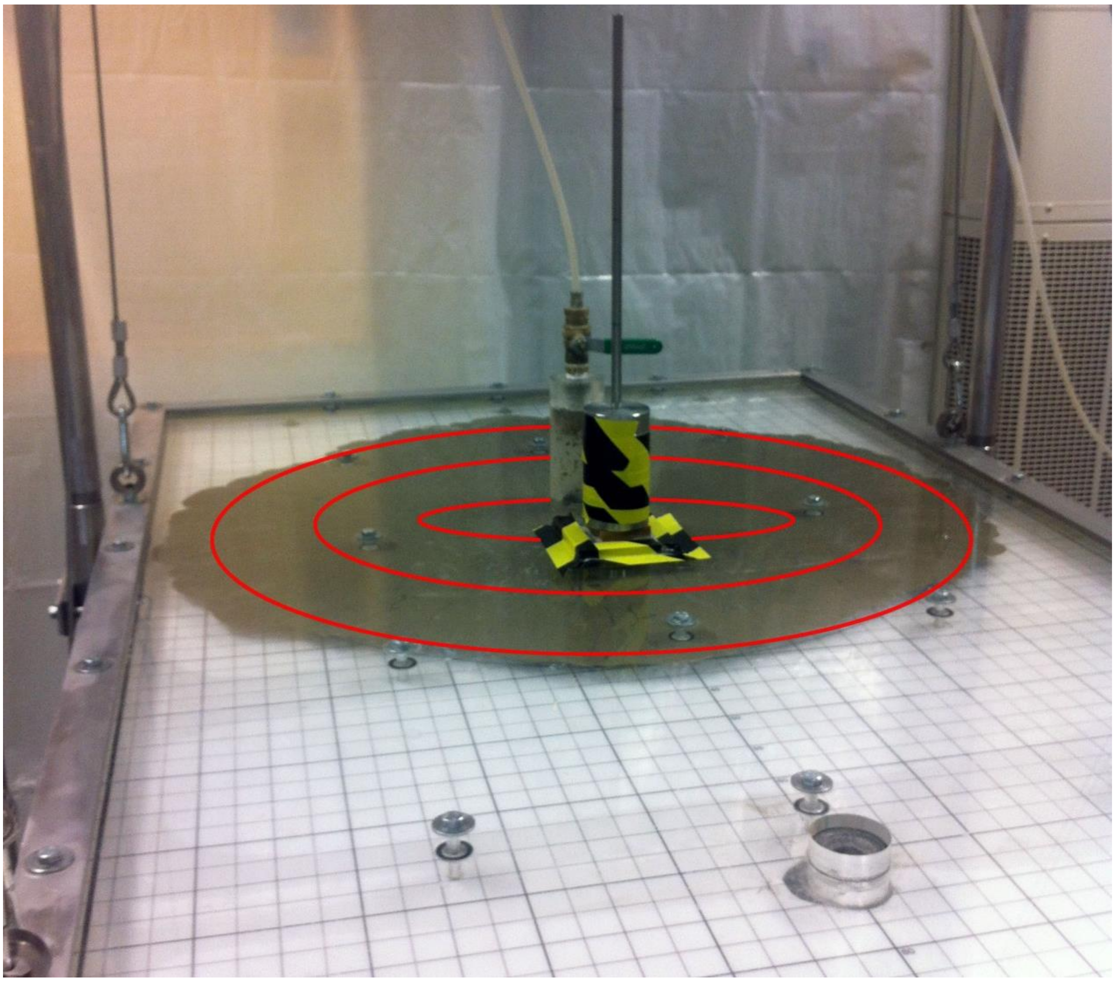

Figure B 2 Grouted fracture replica with the weight-release equipment at centre.

APPENDIX C

The results from the different grout properties tests can be seen in the following graphs. These show the growth of shear strength for the grout and the influence of stirring and shaking of the different samples. The measurements have been made using fall cone tests and the shaking is made using a sieve shaker. In all tests, one sample has been left undisturbed and used as a reference sample.

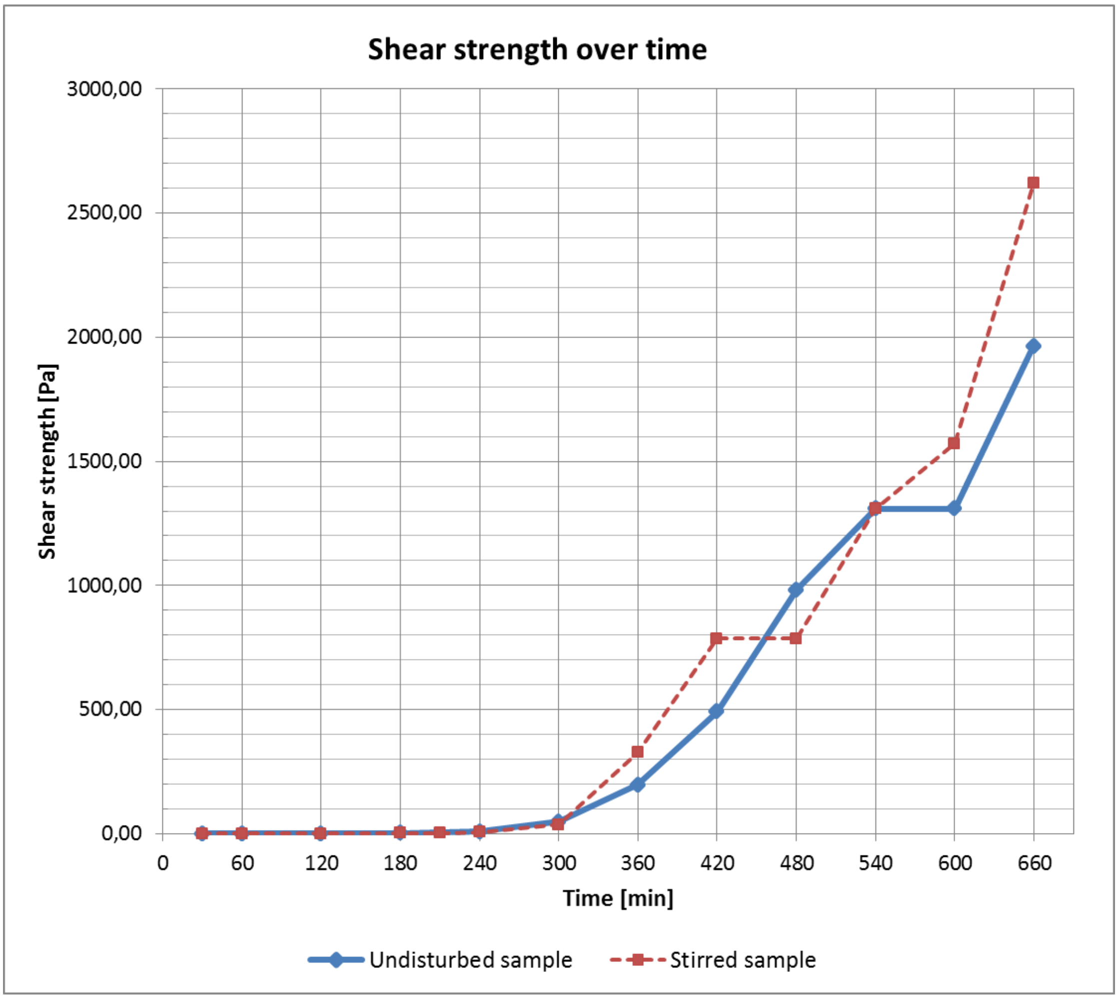

Figure C 1 Initial test of grout properties comparing an undisturbed hardening to lightly stirred samples. The first sample was lightly stirred after three hours.

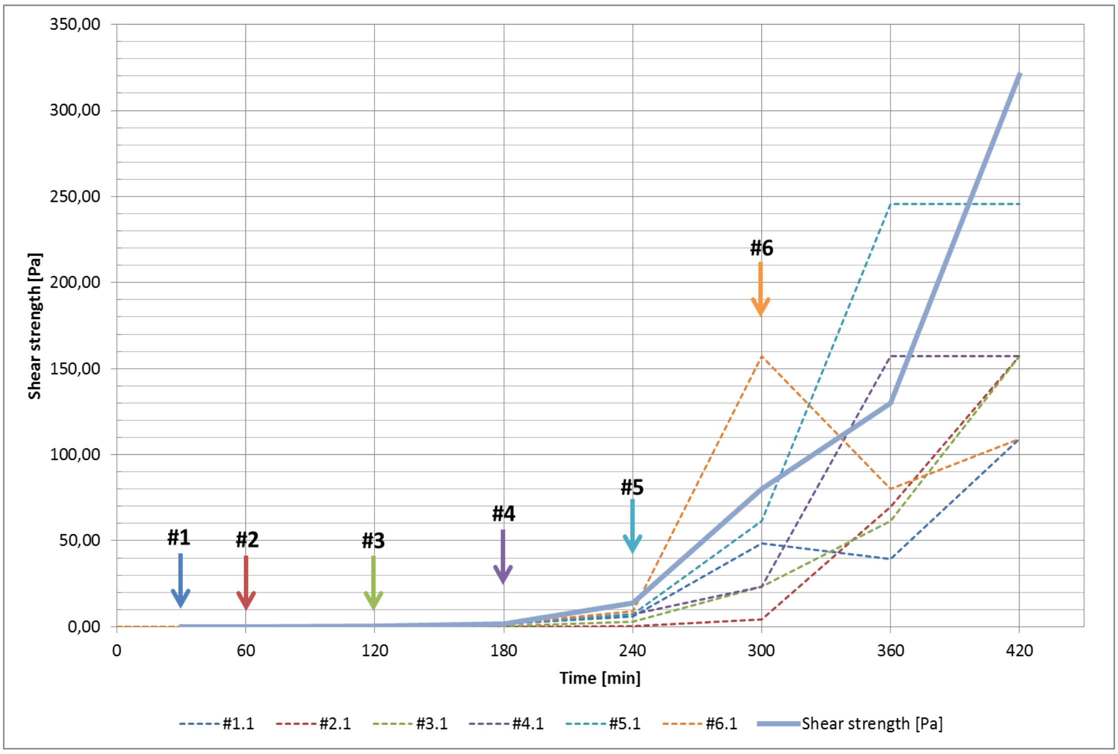

Figure C 2 *The increase in shear strength over time for samples that were shaken for five minutes.*

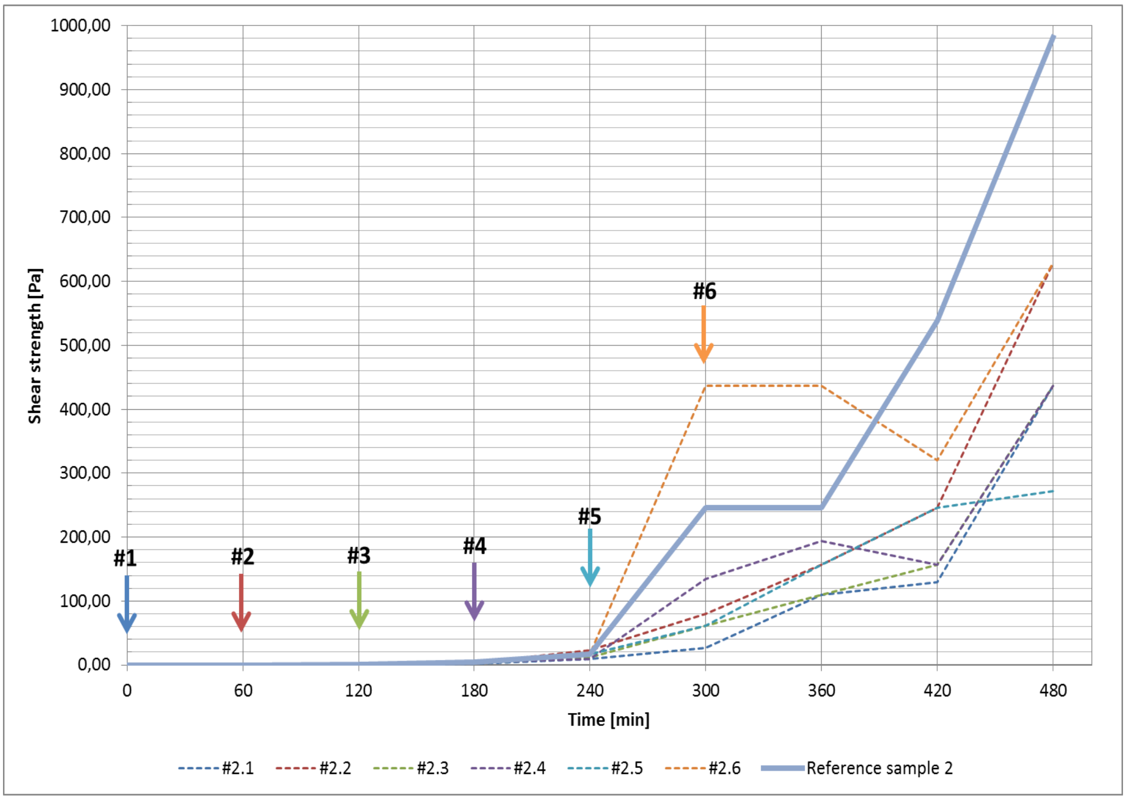

Figure C 3 *The increase in shear strength over time for samples that were shaken for three minutes.*

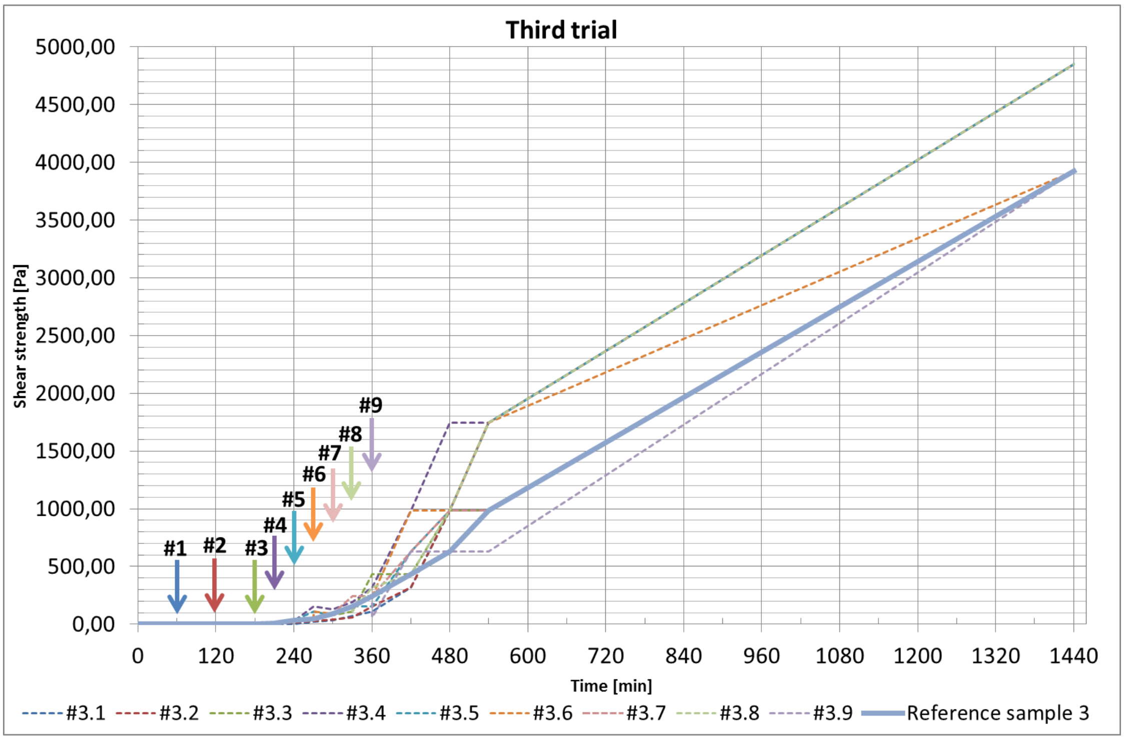

Figure C 4 *The hourly increase in shear strength over time for samples that were shaken for six to ten seconds.*

APPENDIX D

The permeability measurements of the undisturbed and the disturbed grout were made using the fracture replica, as seen in

Figure D 1. The grouted fracture was subjected to a water pressure of 0.5 metres as the valve from the water column was opened. All tests were made on grouts that had hardened for different times. However, reference measurements of the undisturbed grout that had hardened for three hours was made two separate times, but did not give reasonable values. The measurements were only made for 30 minutes; if more than this time had elapsed the grout would be considered to have entered the hardening stage of the following hour (i.e. after 1 hour and 31 minutes the grout was considered to have hardened for to 2 hours).

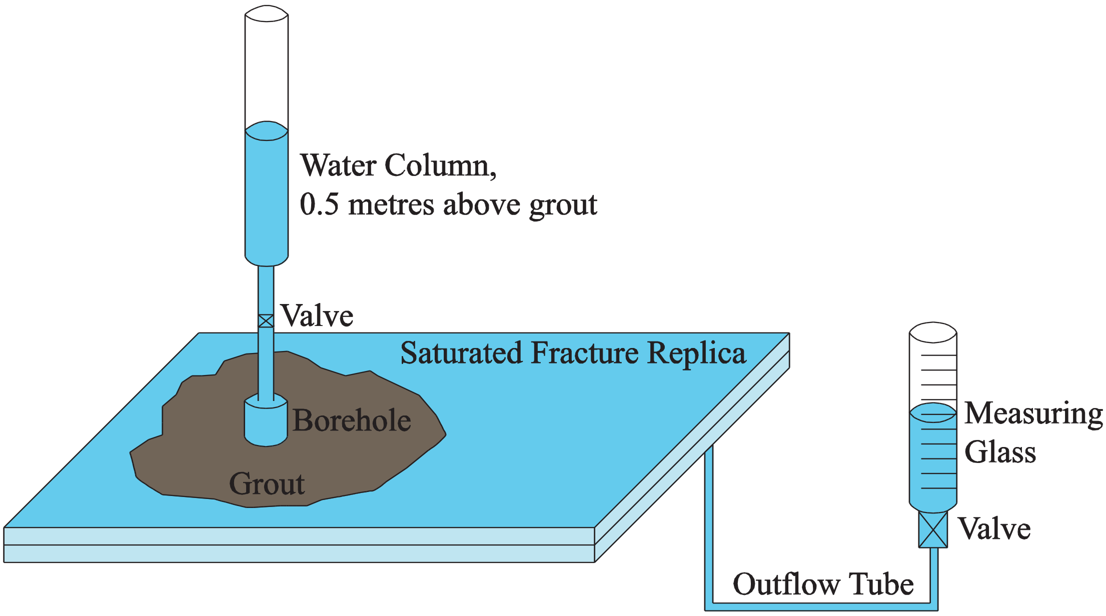

Figure D 1 Sketch of the permeability measurements in the fracture replica.

Two different time measurements were made in order to evaluate the permeability of the grout. First the time from opening the valve at the water column until water entered the measuring glass (this valve was open all the time). These results can be found in Table D 1 and in Figure D 2. The second time measurement was how fast each centimetre (approximately 1.4 ml) was filled in the measuring glass; these results can be found in Table D 2 and Table D 3.

Table D 1 Results of the measurement of time from opening of the valve at the water column until water reached the measuring glass. The measurements of the undisturbed grout that had hardened for three hours were made two separate times but each time unreasonable values were measured. Therefore this value is marked in red.

Time of measurement [h]	Time through undisturbed grout [min]	Relative change of undisturbed grout permeability [-]	Time through disturbed grout [min]	Relative change of disturbed grout permeability [-]
0	-	-	-	-
1	4,6	0,0	2,5	-2,1
2	13,7	0,0	7,0	-6,7
3	34,5	0,0	34,5	0,0

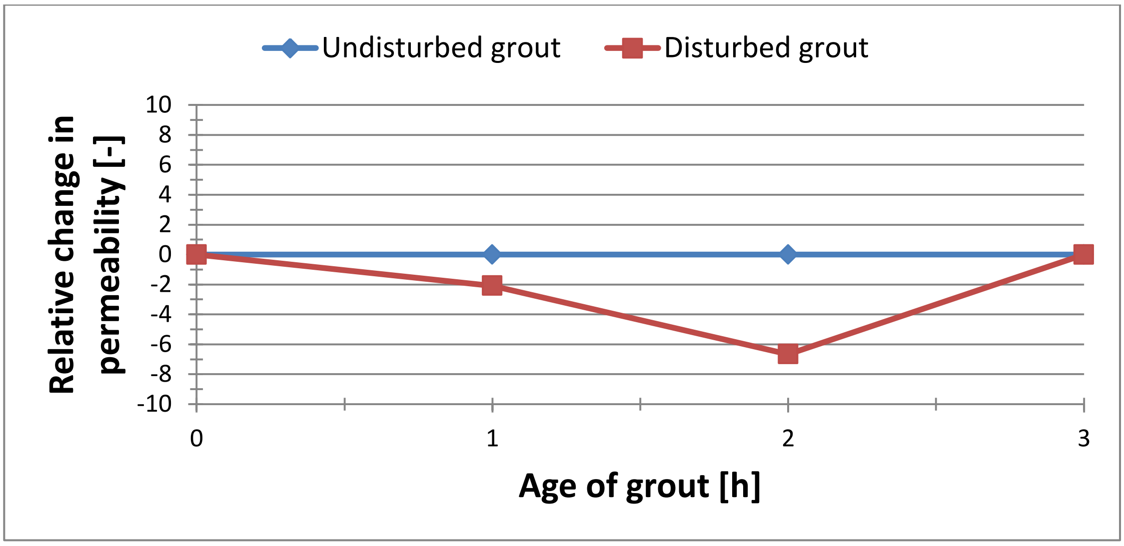

Figure D 2 Graph showing the relative change in permeability when grout of different ages is subjected to vibrations.

Table D 2 Absolut results from the measurements of the permeability of the grout where the times (in minutes) to fill different volumes are shown. The measurements of the undisturbed grout that had hardened for three hours were made two separate times but each time unreasonable values were measured. Therefore these are stated as not available (N/A).

Absolute values [min]							
		Hardening Time					
Measuring glass		1 hour		2 hours		3 hours	
Height [cm]	Volume [ml]	Undisturbed	Disturbed	Undisturbed	Disturbed	Undisturbed	Disturbed
0	-	-	-	-	-	-	-
1	4	1,3	0,3	1,5	0,5	N/A	-
2	7	2,9	0,7	3,5	0,8	N/A	-
3	11	4,8	1,1	6,5	1,3	N/A	-
4	14	8,0	1,3	11,0	2,3	N/A	-
5	18	13,0	1,8	-	2,8	N/A	-
6	21	30,0	2,0	-	3,3	N/A	-
7	25	-	2,2	-	3,8	N/A	-
8	29	-	2,5	-	4,3	N/A	-
9	32	-	2,9	-	5,0	N/A	-
10	36	-	3,1	-	5,5	N/A	-
11	39	-	3,4	-	6,2	N/A	-
12	43	-	3,8	-	6,8	N/A	-
13	46	-	4,3	-	7,5	N/A	-
14	50	-	4,8	-	8,1	N/A	-

Table D 3 Relative results from the measurements of the permeability of the grout where the times (in minutes) to fill different volumes are shown. The measurements of the undisturbed grout that had hardened for three hours was made two separate times but gave never reasonable values, therefore these are stated as not available (N/A).

Relative values [-]							
		Hardening Time					
		1 hour		2 hours		3 hours	
Height [cm]	Volume [ml]	Undisturbed	Disturbed	Undisturbed	Disturbed	Undisturbed	Disturbed
0	-	-	-	-	-	-	-
1	4	0,0	-1,0	0,0	-1,0	N/A	-
2	7	0,0	-2,3	0,0	-2,7	N/A	-
3	11	0,0	-3,8	0,0	-5,2	N/A	-
4	14	0,0	-6,7	0,0	-8,7	N/A	-
5	18	0,0	-11,3	0,0	-	N/A	-
6	21	0,0	-28,0	0,0	-	N/A	-
7	25	0,0	-	0,0	-	N/A	-
8	29	0,0	-	0,0	-	N/A	-
9	32	0,0	-	0,0	-	N/A	-
10	36	0,0	-	0,0	-	N/A	-
11	39	0,0	-	0,0	-	N/A	-
12	43	0,0	-	0,0	-	N/A	-
13	46	0,0	-	0,0	-	N/A	-
14	50	0,0	-	0,0	-	N/A	-