Report
P-17-10
November 2017

Sealing of investigation boreholes

Laboratory investigations of sealing components

Torbjörn Sandén
Ann Dueck
Mattias Åkesson
Lennart Börgesson
Ulf Nilsson
Reza Goudarzi
Viktor Jensen
Ola Karnland

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

SVENSK KÄRNBRÄNSLEHANTERING

ISSN 1651-4416
SKB P-17-10
ID 1573856
November 2017

Sealing of investigation boreholes

Laboratory investigations of sealing components

Torbjörn Sandén, Ann Dueck, Mattias Åkesson,
Lennart Börgesson, Ulf Nilsson,Reza Goudarzi,
Viktor Jensen, Ola Karnland
Clay Technology AB

Lars-Erik Johannesson
Svensk Kärnbränslehantering AB

Keywords: Investigation boreholes, Seal, Bentonite, PSU17, KBP1013.

Abstract

This report describes the laboratory investigations performed on different candidate materials that have been considered to be used for sealing of deep investigation boreholes. The recently proposed so-called Sandwich-concept includes that the main part of a borehole is filled with granular material (sand, crushed rock), while sealing sections are strategically positioned in sections with good rock i.e. where there are no water bearing fractures present. The number and position of sealing sections in a borehole can be decided after a characterization of the borehole so that interaction between water bearing fracture zones at different depths can be minimized. A sealing section consists of a certain length of dense bentonite with quarts based concrete positioned on both sides. In order to facilitate the installation and also in the long term to prevent interaction between the different materials, special copper expanders (bridge plugs) are suggested to be positioned in the transitions between the different materials. In this report, the results from different laboratory investigations on the different sealing components are described. A mockup test, including all components suggested in the Sandwich-concept, has also been started within the project.

In addition, an investigation has been made on two other possible sealing materials, Sandaband and Barite. Sandaband is a commercial sealing material used in the gas and oil industry while Barite has been suggested mainly because of its high density, 4480 kg/m^3. The investigation has included laboratory tests of Sandaband, a literature study of the two materials and also an assessment of the properties of the two materials regarding post closure safety.

The investigations are a first step before a borehole sealing test in full scale can be performed.

Granular materials

Four granular materials with different origins and with different grain size distribution have been investigated. The investigations have included both material properties such as compressibility and hydraulic conductivity but also methods of installation in laboratory scale. These materials are planned to be installed by gravity i.e. settling through the standing water column in a borehole.

Quartz based concrete

A recipe for quartz based concrete has been developed earlier within another SKB project. It is a low pH concrete with a cement content of about 4 % which means that also after long time when all cement has leached, there will be a remaining core of quartz grains left in the borehole. In the present laboratory tests both compressibility and hydraulic conductivity have been performed on a mixture where no cement has been added i.e. the properties of the remaining quartz core have been tested.

Special tests have been made to investigate the adhesion between the quartz based concrete and the rock. A few of the drilled investigation boreholes are positioned very close to the planned extension of the SFR repository and it is judged that there is a risk that a sealed borehole could be crossed during the tunnel excavation. It has been suggested that the boreholes in the sections positioned close to the SFR tunnels possibly could be sealed with the quartz based concrete. If a borehole should be crossed, it is of great importance that all installed sealing components in the borehole stays in place. The installation of quartz based concrete must probably be installed in boreholes using a dump bailer depending on the viscous consistency. This installation method have been tested earlier and is also planned to be tested in a full scale test. Tests are ongoing in Finland with the development of a pumpable concrete of similar type. The results of these tests may influence the final design of the Sandwich-concept.

Bentonite

The bentonite used in the tests is MX-80 from American Colloid Company. This bentonite has for long time been SKB's reference material and has been investigated in a large number of projects. The investigations performed within this project have focused on three properties: erosion during

installation (with and without coating), the influence of using coating on the hydraulic conductivity and the swelling pressure, and also tests on the homogenization of the bentonite in a simulated borehole section. The bentonite is planned to be installed by lowering long sections, L = 2−10 m, into the borehole by use of the drill rig.

Copper expander

Different designs of a copper expander have been tested within this project. The principal idea with two parts, one inner part made of hard copper (Rp 0.2 = 250–350 MPa) and an outer part made of annealed copper (Rp 0.2 = 40–120 MPa) that could be expanded have been proven to work well. Further work on the design will, however, be necessary to develop a copper expander which can be used in the full scale tests.

Mockup test

A mockup test (large scale laboratory test), including all sealing components have been installed and started at the Äspö laboratory. The simulated borehole section has a length of 4 meters. The test layout and the installation are described in this report but no results have been available at the time for this report. One of the main objectives with this test is to demonstrate the installation of all components included in the Sandwich-concept and how they interact with each other. Another important objective is to demonstrate the homogenization of the bentonite seal and the resulting properties regarding swelling pressure and hydraulic conductivity.

Sandaband and Barite

Sandaband is a patented material produced by Sandaband Well Plugging AS, Stavanger, Norway. The material is mainly used for sealing of wells, temporary or permanently. A minor laboratory investigation has been performed on this material together with a literature study.

Barite is a material that is interesting as a seal material mainly depending on its high density which facilitates installation (sedimentation through standing water) and also makes the filling self-compacting with time. Another advantage is that it is almost chemically inert. A literature study has been performed also on this material.

Sammanfattning

Denna rapport beskriver de undersökningar som genomförts på olika kandidatmaterial som har övervägts att kunna användas som förslutningsmaterial för djupa borrhål. Det nyligen framtagna så kallade Sandwichkonceptet innebär att huvuddelen av borrhålet fylls med friktionsmaterial till exempel sand eller krossat berg, medan speciella tätsektioner placeras strategiskt i sektioner med bra berg det vill säga där det inte finns några vattenbärande sprickzoner. Antalet tätsektioner i ett borrhål bestäms efter att borrhålet har karakteriserats och de placeras så att risken för att vattenförande sprickor på olika nivåer kan interagera med varandra minimeras. En tätsektion består av en bestämd sträcka med bentonit med hög densitet där kvartsbaserad betong är placerat på ömse sidor. För att underlätta installationen och för att under lång tid förhindra att de olika materialen interagerar med varandra, föreslås att speciella kopparexpandrar placeras vid alla materialövergångar. I denna rapport beskrivs resultaten från de olika laboratorieundersökningar som genomförts på de olika komponenterna. Ett större så kallad Mockup test där alla komponenter som ingår i Sandwichkonceptet har installerats har också startats.

En undersökning har också genomförts på två andra möjliga förslutningsmaterial, Sandaband och Barite. Sandaband är ett kommersiellt material som är tänkt att användas vid förslutning av borrhål främst inom gas och oljeindustrin medan Barite har föreslagits att användas främst på grund av dess höga densitet, 4 480 kg/m^3. Undersökningen har innefattat laboratorieförsök med Sandaband, en litteraturstudie av de båda materialen samt en bedömning av de båda materialens egenskaper när det gäller långtidssäkerheten.

De genomförda undersökningarna är ett första steg innan ett förslutningstest i full skala genomförs.

Friktionsmaterial

Fyra friktionsmaterial (sand, krossat berg) med olika ursprung och med olika kornstorleksfördelning har undersökts. Undersökningarna har innefattat både materialegenskaper som kompressibilitet och hydraulisk konduktivitet men också installationstester i laboratorieskala. Dessa material är planerade att installeras genom att de får sedimentera ner i de vattenfyllda borrhålen.

Kvartsbaserad betong

Ett recept på kvartsbaserad betong har tidigare tagits fram inom ett annat SKB projekt. Det är en låg pH betong med ett cementinnehåll på cirka 4 % vilket betyder att även om cementen efter lång tid har lakats ur kommer en kärna av kvartskorn att finnas kvar i borrhålet. I de laboratorieförsök som genomförts har tester gjorts både när det gäller hydraulisk konduktivitet och kompressibilitet på en blandning där ingen cement har tillförts det vill säga egenskaperna hos den återstående kvartskärnan har testats.

Försök har också genomförts för att undersöka friktionen mellan betong och berg. Det finns ett antal borrhål som passerar tunnlarna väldigt nära i den planerade utbyggnaden av SFR och det har bedömts att det finns en risk att man i samband med tunneldrivningen kan korsa redan förslutna borrhål. Det finns förslag på att de aktuella borrhålen möjligen kan förslutas med betong de sträckor som ligger nära tunnlarna. Om man skulle korsa ett sådant borrhål är det viktigt att de installerade förslutningskomponenterna stannar kvar i borrhålet.

De kvartsbaserade betongpluggarna måste installeras med hjälp av den så kallade containermetoden på grund av dess trögflytande konsistens. Denna metod har testats tidigare och är också tänkt att användas vid ett planerat fullskaletest. Tester pågår emellertid i Finland där man har utvecklat en pumpbar betong av liknande typ. Resultatet från dessa tester kan komma att påverka den slutliga designen av Sandwichkonceptet.

Bentonit

Bentoniten som använts i testerna har det kommersiella namnet MX-80 och levereras av American Colloid Company. Denna bentonit har under lång tid varit SKB:s referensmaterial och har undersökts inom ett stort antal projekt. De undersökningar som har gjorts inom detta projekt har fokuserat på tre egenskaper; erosion i samband med installationen (med och utan skyddslack), inverkan av skyddslack på svälltryck och hydraulisk konduktivitet samt hur bentoniten homogeniseras efter installationen i ett borrhål. Bentoniten är planerad att installeras genom att sektioner med en längd på mellan 2 och 10 meter sänks ner i borrhålet med hjälp av borriggen.

Kopparexpander

Olika typer av kopparexpandrar har tagits fram och testats inom projektet. Principen för expandrarna bygger på att det finns två delar, en inre tillverkad av hård koppar (Rp 0.2 = 250–350 MPa) och en yttre som är tillverkad av glödgad koppar (Rp 0.2 = 40–120 MPa) som kan expandera utan att spricka. Systemet med de två delarna har testats med gott resultat. Det kommer dock att krävas en del ytterligare utveckling för att få fram en slutlig design som kan användas vid installation i fält.

Mockup test

Ett så kallat mockuptest (storskaligt laboratorieförsök) som inkluderar alla ingående komponenter i Sandwichdesignen har installerats och startats på Äspölaboratoriet. Det simulerade borrhålssektionen har en längd på fyra meter. Testdesignen samt installationen är beskrivna i rapporten men inga resultat finns tillgängliga vid tidpunkten för denna rapport. Ett av huvudmålen med försöket är att demonstrera installationen av alla komponenter som ingår i Sandwichkonceptet och hur de fungerar tillsammans. Ett annat viktigt mål är att demonstrera homogeniseringen av bentonittätningen och hur svälltrycket byggs upp. Den hydrauliska konduktiviteten hos bentoniten kommer att bestämmas efter att bentoniten har homogeniserat.

Sandaband och Barite

Sandaband är ett patenterat material som tillverkas av Sandaband Well Plugging AS, Stavanger, Norge. Materialet används av gas- och oljeindustrin i samband med tätning av olika borrhål, tillfälligt eller permanent. En laboratorieundersökning samt en litteraturstudie har genomförts med detta material.

Barite är ett material som är intressant för förslutning av borrhål huvudsakligen på grund av dess höga densitet som både underlättar installationen (sedimenterar snabbt genom vatten) och som också gör det självkompakterande. En annan fördel är att det är kemiskt stabilt. En litteraturstudie har genomförts på detta material.

Contents

1 Introduction

A large number of investigation boreholes have been drilled in both the area for the planned Spent Fuel Repository and for the Final Repository for Short-Lived Radioactive Waste (SFR), both located in Forsmark in Östhammar municipality. Due on the planned start of the construction of above-ground buildings for the Spent Fuel Repository (a number of investigation boreholes starts here) and the planned extension of the SFR repository (at least six boreholes are assessed to interact with the extension), and since it has been assessed that these boreholes should be sealed before starting the construction work, methods and techniques for sealing of the investigation boreholes will be developed.

The present reference method for sealing of investigation boreholes (SKB 2010) includes that the boreholes are filled with highly compacted bentonite plugs placed in perforated copper tubes in the main part of the borehole while the parts of the borehole that includes water bearing fracture zones will be filled with quartz based concrete plugs that prevents erosion of the clay.

Development work regarding other possible techniques has been going on during a period mainly depending on the following reasons:

- A need of optimizing and simplifying the reference method (SKB 2010) has been identified. The reference method was mainly developed for sealing of deep investigation boreholes and it is therefore desirable to develop a new, simpler method that can be used for both deep boreholes and also for short boreholes positioned far from the repository area.
- The effect of nearfield hydrology for SFR has been studied with hydraulic modelling of the SFR3 area. When the boreholes have been sealed so that the hydraulic conductivity is 10^{-6} m/s or lower, the modelling gives the same water flow through the rock vaults as if no boreholes where present (Abarca et al. 2013).
- Analyses performed within SR-Site regarding the Spent Fuel Repository (SKB 2011) shows that the present requirement on low hydraulic conductivity of the sealing can be mitigated. The design requirement is at present that a hydraulic conductivity of less than 10^{-8} m/s should be achieved along the whole borehole length. Since also open boreholes seems to have a limited influence on the groundwater flow at repository depth the conclusion is that the present requirement is high enough.
- A study regarding closure of ramp, shafts and investigation has shown that instead of having a sealing that restores the hydraulic conductivity of the rock, it will be enough that the hydraulic conductivity of the sealing along the borehole length is less than 10^{-6} m/s boreholes (Luterkort et al. 2012). This has also been suggested as a design requirement regarding borehole sealing at the Spent Fuel Repository in Forsmark.

As a result of the ongoing development work, a new design for sealing of deep boreholes has been suggested, referred as the” Sandwich concept”, see detailed description in Chapter 2. This report describes the tests and investigations made on the different components included in the Sandwich concept, where the different properties of the components related to their function in the concept are investigated, see Chapter 4 to 7. A Mockup test where all the suggested components are included, have also been made, see Chapter 8. In addition, laboratory investigations and a literature study have been made on an alternative sealing material, Sandaband, see Chapter 10. A minor literature study has also been performed on another sealing candidate material, Barite. The work has been performed within the SKB projects PSU-17 and KBP1013.

2 The Sandwich-concept

2.1 General

The new modeling results, see description in Chapter 1, show that the tightness of the sealed boreholes only marginally affects the groundwater flow at the depth of a repository and this has resulted in suggestions for mitigated requirements on the borehole sealing.

The new concept (in this report denominated the "Sandwich-concept") implies that the main part of a borehole is filled with a permeable material such as sand or gravel, which is chemically and mechanically stable, while strategically positioned bentonite seals are placed in specially chosen sections with good rock i.e. there are no water bearing fractures, see the schematic drawing provided in Figure 2-1. The number of sealing sections in a borehole can be decided after a characterization of the borehole so that interaction between water bearing fracture zones at different depths can be minimized. In order to prevent interaction between the different materials, quartz based concrete is positioned a certain length in the transition zones between bentonite and sand. In addition, bridge plugs made of copper are positioned at all transition zones. This will facilitate the installation of the different materials and e.g. prevent concrete from flowing into the annular gap between bentonite plugs and rock but they will also prevent mixing of different materials in the long term. The uppermost part of the borehole is filled with bentonite pellets to ensure that no surface water is transported via the borehole down to water bearing zones. An upper end seal is placed in the uppermost part of the rock. The end seal has a larger diameter than the borehole and will serve as a mechanical lock of the borehole.

There are a number of boreholes positioned close to the planned extension of SFR and for these boreholes it will be necessary to also have concrete in the length passing close to the planned extension.

The development work of the Sandwich-concept has implied investigations and laboratory tests on the four main components included in the design:

1. Sand/gravel filling
2. Bentonite plugs
3. Quartz based concrete
4. Copper expanders (Bridge plugs)

The results from the performed investigations and tests on these components are provided in this report.

2.2 Hydraulic conductivity

As described, the Sandwich-concept includes that the main part of the borehole is filled with sand which have a high hydraulic conductivity, in the order of 10^{-5} m/s while bentonite seals are placed at strategically chosen sections with good rock. The hydraulic conductivity of the seals will be in the order of 10^{-12} – 10^{-13} m/s. This implies that a requirement of a certain hydraulic conductivity along the whole borehole length of 10^{-8} m/s not will be fulfilled, but locally the hydraulic conductivity will be much lower.

Instead of hydraulic conductivity one can calculate that the hydraulic resistance (R) for the borehole fill:

- Assume that the requirement of the hydraulic conductivity (hw) for a borehole with the length (L) of 1 000 m is 10^{-8} m/s. The resistance for water flow through the hole can then be calculated as: $R = L/(h_w) = 1\,000/(10^{-8})\ s = 10^5\ s$.
- Assume that 980 m of the borehole is filled with sand with a hydraulic conductivity of 10^{-5} m/s. The rest of the borehole is filled with bentonite with a hydraulic conductivity of 10^{-13} m/s. The resistance for this borehole will then be: $R = L_{sand}/(h_{w,\,sand}) + L_{bent}/(h_{w,\,bent}) = 980/10^{-5} + 20/10^{-13} \sim 2 \times 10^{14}\ s$.

With this way of looking at the requirements on the borehole sealing, the sealing can be substantially simplified.

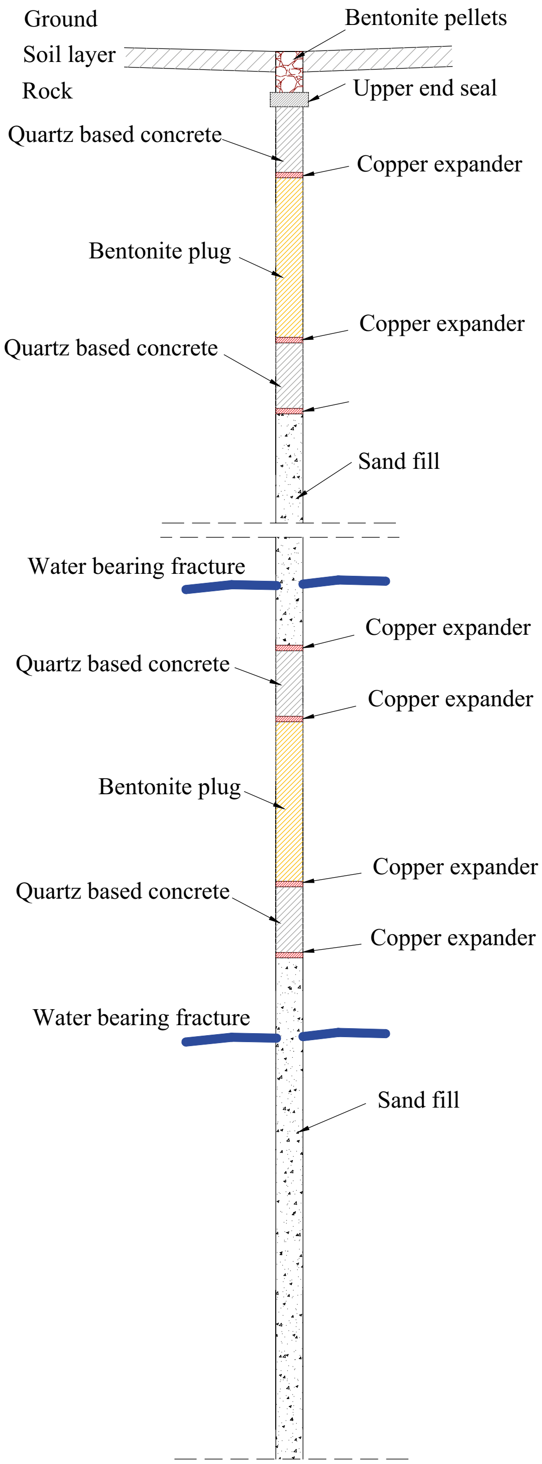


Figure 2-1. *Schematic showing the suggested principle for sealing of deep investigation boreholes, the so called "Sandwich-concept". The design includes dense bentonite plugs positioned in sections with good rock. Permeable sand is filling up the main part of the borehole. Quartz based concrete is positioned in the transition zones between bentonite and sand. Copper expanders are positioned at all transitions between different materials.*

3 Summary of tests performed

3.1 General

In this chapter an outline of the report are presented together with definitions of basic geotechnical parameters used in the report.

3.2 Outline of the report

In the investigated Sandwich-concept for sealing of boreholes four components are included. The tests made on these components are described in Chapter 4 to 7 and summarized in Table 3-1. In addition to the tests of the components, a mockup test has been started at the Äspö Bentonite Laboratory. The plans and realization of this test is described in Chapter 8. Chapter 9 contains the results from a theoretical analysis of the friction between the components installed in the borehole and the wall of the borehole. An investigation on alternative materials which can be used for sealing of boreholes has been made and is presented in Chapter 10. The conclusions of the work are summarized in Chapter 11 together with suggestions for further studies.

Table 3-.1 Determined properties or types of tests performed to test the four components included in the Sandwich-concept.

Part of the project-tests of components	Property or type of test	Comments
Granular materials		Four different materials have been investigated
	Grain size distribution and densities	
	Methods of installation	
	Settlement at water saturation	
	Compressibility	
	Hydraulic conductivity	
Quartz based concrete plug		Recipe according to Pusch and Ramqvist (2006)
	Friction between rock and concrete	
	Compressibility	
	Hydraulic conductivity	
Copper plug (Bridge plug)		Development of design
	Installation tests in laboratory	
Bentonite plugs		MX-80 bentonite
	Erosion during installation	
	Swelling pressure and hydraulic conductivity	
	Homogenisation and demonstration	

3.3 Basic geotechnical parameters

The base variables water content w (%), dry density ρ_d (kg/m^3), void ratio e (–) and degree of saturation S_r (%) were determined according to Equation 3-1 to 3-4.

$$w = 100 \cdot \frac{m_{tot} - m_s}{m_s} \qquad \text{(Eq 3-1)}$$

$$\rho_d = \frac{\rho}{1 + w/100} \quad \text{(Eq 3-2)}$$

$$e = \frac{\rho_s}{\rho_d} - 1 \quad \text{(Eq 3-3)}$$

$$S_r = \frac{\rho_s \cdot w}{\rho_w \cdot e} \quad \text{(Eq 3-4)}$$

where

m_{tot} = total mass of the specimen (g)
m_s = dry mass of the specimen (g)
ρ = bulk density of the specimen (kg/m^3)
ρ_s = particle density (kg/m^3)
ρ_w = density of water (kg/m^3)

The dry mass of the specimen is obtained from drying the wet specimen at 105 °C for 24 h. The bulk density is calculated from the total mass of the specimen and the volume determined by weighing the specimen above and submerged into paraffin oil.

4 Tests of components – granular material

4.1 General

In the Sandwich-concept, the main part of the borehole lengths will be filled with granular materials which, in this report is used as denomination for sand and crushed rock. Four different materials have been tested, one natural sand and three different types of crushed rock. The main difference between the materials is the grain size distribution. The installation techniques and properties of these materials in the long term are thus an important part of the borehole sealing. In this project the following have been investigated:

- Installation tests. Installation tests have been performed in laboratory scale at both dry and water filled boreholes in a simulated section (L = 2 m) of a borehole made of Plexiglas.
- Settlement at water saturation. It has been investigated whether installation of granular material in a dry borehole that later was water filled, could lead to settlements.
- Compressibility. The compressibility of the granular material is an important factor in order to ensure that the neighboring sealing components stays in position also in the long term.
- Hydraulic conductivity. It was expected that the hydraulic conductivity of the granular materials should be high. These tests were made in order to get an overall picture of the hydraulic situation of the borehole seal.

4.2 Materials

The following granular materials were tested:

- Fogsand < 2 mm. A natural sand with grain size less than 2 mm.
- MakPak, 0–5 mm. A combination of crushed rock < 5 mm and rock flour > 0.063 mm. The product is manufactured by Sydsten AB in Dalby, Sweden.
- Ballast 2–4 mm. Crushed rock with grain size between 2 and 4 mm. The product is manufactured by Sydsten AB in Dalby, Sweden.
- Ballast 4–8 mm. Crushed rock with grain size between 4 and 8 mm. The product is manufactured by Sydsten AB in Dalby, Sweden.

The denominations used in this report are the same as the commercial names. Photos of the four materials are provided in Figure 4-1.

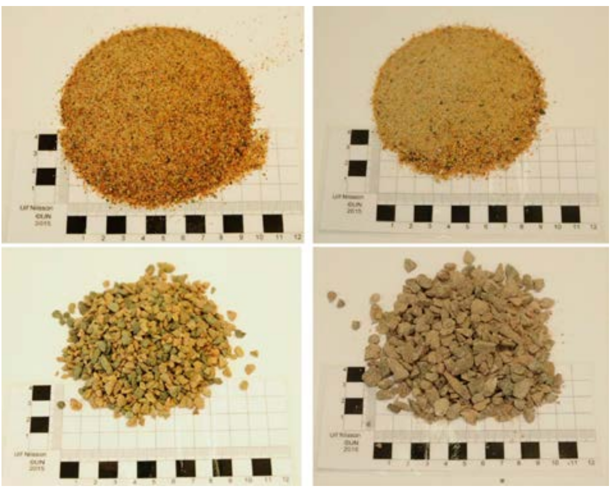


Figure 4-1. *Photos of the four tested materials. Upper left: Fogsand < 2 mm Upper right: MakPak 0–5 mm Lower left: Ballast 2–4 mm Lower right: Ballast 4–8 mm*

4.2.1 Grain size distribution

The grain size distribution of the four materials was determined by sieving of the dry material. The results from the sieving are shown in Figure 4-2. The two ballast materials and the Fogsand are all three containing granules of a few sizes while the variation is larger for the MakPak. The variation for the MakPak should be even higher according to the name "MakPak 0–5 mm", however, the results from the sieving showed no grains larger than 2 mm.

4.2.2 Density of the filling

The dry density, determined as a bulk density (ρ_b), of the different materials was determined according to Equation 4-1. The material was poured into a graduated cylinder (1 dm^3) with a known volume (V). A laboratory balance was used to determine the mass (m_b)

$$\rho_b = \frac{m_b}{V} \qquad \text{(Eq 4-1)}$$

Measurements were performed at conditions simulating both dry and water filled boreholes, and the filling has also been installed as "loosely filled" i.e. poured into the measuring cylinder but also as "manually shaken" (where the cylinder was carefully vibrated or tapped into the table). The results from the measurements are provided in Table 4-1. It is obvious that all materials are very sensitive to small vibrations regarding the achieved density. The reason for this is probably that when pouring the material loosely into a cylinder, a grain skeleton is created where the grains are standing on top of each other and the result of a small vibration is that many grains then fall into the neighboring voids resulting in a much denser filling.

Table 4-1. Dry densities of the tested materials under different conditions.

Material	Loosely filled kg/m^3	Vibrated kg/m^3	Loosely filled, saturated kg/m^3	Vibrated, saturated kg/m^3
Fogsand < 2 mm*	1509	1666	1485	1696
MakPak 0–5 mm	1527	1709	1456	1772
Ballast 2–4 mm	1388	1576	1375	1603
Ballast 4–8 mm	1339	1558	1296	1415

*The average of five measurements.

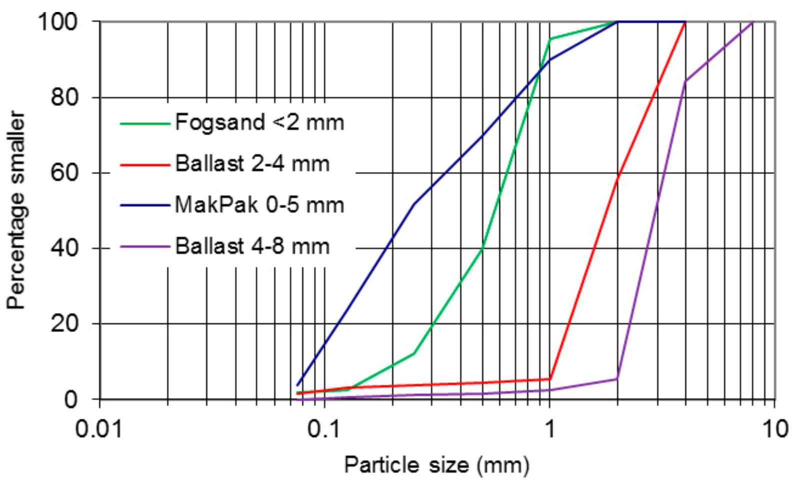


Figure 4-2. *Grain size distribution curves of the four tested materials.*

4.3 Installation tests

4.3.1 General

Gravimetric installation of granular materials has been tested in laboratory scale at both dry and water filled conditions. This is the technique that is expected to be used in a full scale installation.

4.3.2 Test equipment

The borehole has been simulated using Plexiglas tubes with a length of 2 meters and with an inner diameter of 80 mm (most of the investigation boreholes have an inner diameter of 76 mm). The tubes are equipped with a water tight bottom lid. The tests have included installation in both dry and water filled boreholes. The water used in the tests was tap water.

4.3.3 Installation flow rates

In order to control the installation flow rate of the different materials during the installation tests, funnels with different diameters on the outflow pipe were used, see Figure 4–3. The tests were performed using four different funnel diameters: 18 mm, 43 mm, 57, mm and 68 mm respectively. The tests started by putting about 13–14 kg of the current material into the funnel having a stop sheet blocking the outflow. When the stop sheet was removed, the timer was started and the time for emptying the funnel was determined. The flow rates were measured for all tested materials at different funnel diameters.

4.3.4 Installation in dry boreholes

These tests simulated installation of granular materials in dry boreholes. The installations were made in two meter long Plexiglas tubes with an inner diameter of 80 mm. The tests were performed by pouring materials from buckets into the funnels (with different diameters on the outflow side) positioned above the simulated borehole. The amount of material installed was determined by weighing. The installation time for each test was measured and used for calculating the installation rate.

After and during the installations, observations were made regarding possible bridge structures in the simulated borehole or separation of the installed material. Dust extraction and respiratory protection were used during the installation tests.

4.3.5 Installation in water filled boreholes

Installation tests have also been performed in simulated water filled boreholes. These installation tests were made using the same equipment as used for the dry boreholes and also the same methodology.

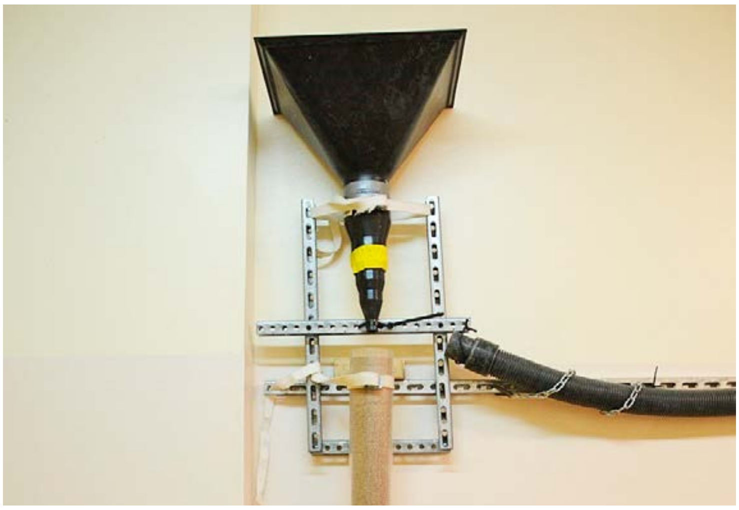


Figure 4-3. *Photo showing one of the funnels used in order to achieve a certain installation rate of the material into the borehole.*

At test start, the boreholes were filled with water. This led to water flowing out from the boreholes as material was poured in. The outflowing water brought parts of the installed material, the finer grains, up and out from the borehole. The loss of material was strongly depending on the installation rate. This phenomena only applies if using material containing fine grained material.

4.3.6 Results

Installation flow rates

The method used for the control of the installation flow rate was tested with a small amount of each material to determine the maximum flow rate of each combination of funnel diameter and material type. A compilation of the test results is provided in Table 4-2. The two materials "Ballast 2–4 mm" and "Ballast 4–8 mm" were not possible to test in the smallest diameter since stops occurred almost immediately for these materials in the material flowing through the funnel.

Table 4-2. Measured installation rate in kg/min for the different funnel diameters.

	Funnel diameter			
Material	18 mm	43 mm	57 mm	68 mm
Fogsand < 2 mm	9.7	73.4	140.8	181.9
MakPak 0–5 mm	8.6	62	125.4	148.4
Ballast 2–4 mm	n/a	52	98.4	160.1
Ballast 4–8 mm	n/a	37	77.5	170.5

Installation in dry boreholes

A compilation of the measured installation rates and the achieved installed dry density is provided in Table 4-3.

Table 4-3. Measured installation rates in dry boreholes for the different funnel diameters. The table also shows the measured installed densities in the simulated borehole.

	Funnel diameter							
	18 mm		43 mm		57 mm		68 mm	
Material	Flow rate kg/min	Dry density kg/m³	Flow rate kg/min	Dry density kg/m³	Flow rate kg/min	Dry density kg/m³	Flow rate kg/min	Dry density kg/m³
Fogsand < 2 mm	9.4	1480	60	1492	60	1493	90	1500
MakPak 0–5 mm	8.7	1522	68	1577	64	1590	64	1601
Ballast 2–4 mm	n/a	n/a	32	1346	67	1318	150	1299
Ballast 4–8 mm	n/a	n/a	36	1343	87	1306	100	1335

Some comments to the test results:

- No tendencies to bridge structures in the simulated borehole were observed from any of the tested materials at any of the tested installation rates.
- When installing material with the lowest flow rates i.e. with the funnel diameter 18 mm, there was a tendency that the two finest materials i.e. Fogsand 0–2 mm and MakPak 0–5 mm separated and that layers of fine material were created in the simulated borehole, see photos provided in Figure 4-4.
- It was noticed that the Fogsand 0–2 mm material was very sensitive to vibration after installation in the simulated borehole. A small vibration of the tube led to a settlement of the sand of approximately 5–10 cm in the in two meter long tube.
- The installation rates where in general lower than in the pre-tests, see Table 4-2. This depended on that a larger amount of material was used and an extra filling of the funnel was necessary.

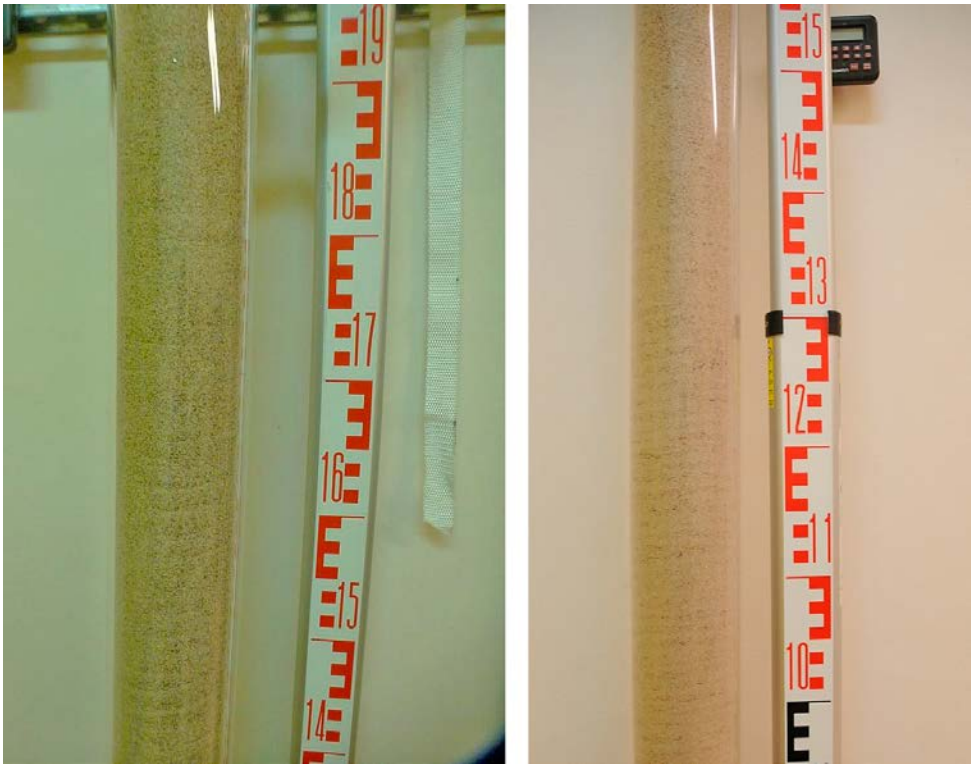


Figure 4-4. *Photos taken after installation in simulated dry boreholes. Left: Photo showing Fogsand < 2 mm after installation. The photo shows that there is a small separation of the material (finest material in layers). Right: Photo showing MakPak 0–5 mm after installation. Also for this material it was possible to see a minor separation.*

Installation in water filled boreholes

A compilation of the measured installation rates, the achieved installed dry density and the measured material losses during installation is provided in Table 4-4. Note that it was not possible to test the lowest installation rates (small funnel diameter) with the material containing coarse grains.

The results from these tests were somewhat difficult to interpret, mainly depending on the large loss of material when increasing the installation rate. Some comments to the test results:

- Installation of material containing a lot of fines led to a loss of material via the outflowing water from the borehole. The material loss was strongly dependent on the installation rate. For this reason it was decided not to perform tests with the highest installation rates.
- It was not possible to see any tendencies to bridge structures of the materials in the simulated borehole.
- There was a very evident separation of the MakPak 0–5 mm material, the coarser fractions in the bottom and the finest at the top, see Figure 4-5. Samples were taken from the material flowing out from the borehole in order to determine the grain size distribution and from the results shown in Figure 4-6 it is obvious that the material loss was from the finest fraction of the material.
- Two test series where performed with the MakPak material. In the A test series, the mouth of the funnel was just above the water (as for the other materials as well) while in the B test series the mouth was lowered down in the water. The results from these tests where, however, rather similar.

Table 4-4. Measured installation rates in water filled boreholes for the different funnel diameters. The table also shows the measured installed densities, the material loss during installation and the total installed mass.

Material	Funnel diameter			
	15 mm			
	Flow rate kg/min	Dry density kg/m³	Material loss, kg	Total installed mass, kg
Fogsand < 2	3.4	1448	0.055	14.6
MakPak 0–5, A	n/a	n/a	n/a	n/a
MakPak 0–5, B	n/a	n/a	n/a	n/a
Ballast 2–4	n/a	n/a	n/a	n/a
Ballast 4–8	n/a	n/a	n/a	n/a
	Funnel diameter			
	18 mm			
	Flow rate kg/min	Dry density kg/m³	Material loss, kg	Total installed mass, kg
Fogsand < 2	9.2	1448	0.475	14.6
MakPak 0–5, A	2.9	1430	1.516	14.4
MakPak 0–5, B	4.6	1367	2.508	13.7
Ballast 2–4	n/a	n/a	n/a	n/a
Ballast 4–8	n/a	n/a	n/a	n/a
	Funnel diameter			
	43 mm			
	Flow rate kg/min	Dry density kg/m³	Material loss, kg	Total installed mass, kg
Fogsand < 2	3.88	1411	7.202	14.2
MakPak 0–5, A	4.5	1402	4.988	14.1
MakPak 0–5, B	6.9	1418	5.768	14.2
Ballast 2–4	12.8	1275	0.6	12.8
Ballast 4–8	33.9	1241	0.0	12.5

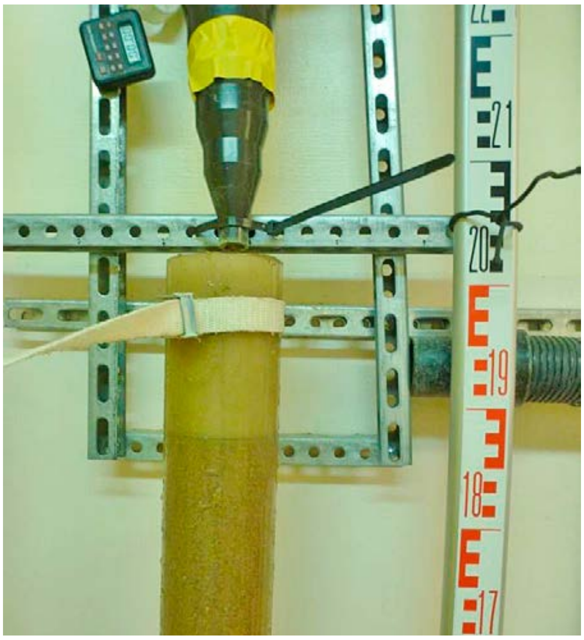


Figure 4-5. *Photo showing the separation of material when installing MakPak 0–5 mm in a water filled borehole. The uppermost 15 cm are filled with fine material while the coarser grains are at the bottom.*

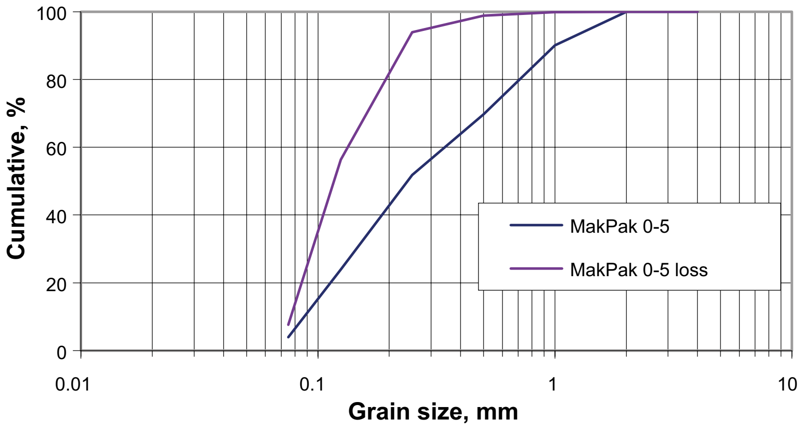


Figure 4-6. *Graph showing the grain size distribution for the installed MakPak 0–5 mm material together with the sampled material flowing out from the borehole. It is obvious that it is the finest material that flows out.*

4.3.7 Discussion

From the tests with installation in a dry or water filled simulated borehole of acrylic plastic the following was observed:

- The maximum dry density of the four materials was achieved when the installation was made in a dry borehole with installation rates between 32–90 kg/min, depending on material.
- The installation in a water filled borehole was limited to rates between 2.9–33.9 kg/min, depending on material, to avoid blockage in the borehole and to minimize the loss of material with outflowing water.
- From the installation in the simulated borehole at dry and water filled conditions, and the installation rates mentioned above no tendency to bridge structures were observed.
- Separation in different fractions was observed for Fogsand 0–2 mm when installed in a dry borehole and for MakPak 0–5 mm after installation in both dry and water filled borehole.
- The maximum dry density achieved for each material after installation in a dry borehole:
- Fogsand < 2 mm 1 500 kg/m^3
- MakPak 0–5 mm 1 601 kg/m^3
- Ballast 2–4 mm 1 346 kg/m^3
- Ballast 4–8 mm 1 343 kg/m^3
- The maximum density achieved for each material after installation in a water filled borehole (in brackets are the corresponding installation rates):
- Fogsand < 2 mm 1 448 kg/m^3 (9.2 kg/min)
- MakPak 0–5 mm 1 430 kg/m^3 (2.9 kg/min)
- Ballast 2–4 mm 1 275 kg/m^3 (12.8 kg/min)
- Ballast 4–8 mm 1 241 kg/m^3 (33.9 kg/min)
- It was noticed that the Fogsand was very sensitive to vibration after installation and with this taken into account the maximum density was 1 580 kg/m^3 and 1 530 kg/m^3 installed in a dry and a water filled borehole, respectively.
- Compared to the density achieved in the small lab scale tests, see Table 4-1 (loosely filled material), the maximum dry densities achieved in the simulated boreholes was of the same magnitude for the dry borehole tests and somewhat lower for the water filled boreholes (4–8 % lower).

4.4 Settlement at water saturation

4.4.1 General

The objective with these tests was to study what happens when the granular materials are installed in a dry borehole which then is filled up with water. The tests were made to study a scenario where the material settles in the borehole during the water filling, leaving an empty pocket at the top.

4.4.2 Test equipment

The borehole was simulated with the same type of Plexiglas tubes that were used in the other tests i.e. two meter long and with an inner diameter of 80 mm. The tube was connected to a bottom plate with an inlet connection which made it possible to apply a constant point inflow into the borehole.

4.4.3 Test procedure

The simulated borehole was filled with the material at a rather low inflow rate at dry conditions (funnel diameter 18 mm for Fogsand and MakPak, and diameter 43 mm for the Ballast 2–4 material). After having filled the simulated borehole to the brim with the current material, a constant water inflow was applied at the bottom of the borehole. During the saturation, the installed material was studied especially to detect any settlements. The wetting rate was chosen to avoid problems with uplifting or separation of grains.

4.4.4 Results

The test results are shown in Table 4-5 where the density and the water filling rate of each material are shown. The water filling rate of the first test on Fogsand (A) was found to be too high since uplifting of the sand column was observed and lower rate was therefore used for the other tests. The results of Fogsand (B), MakPak and Ballast 2–4 mm are shown in Figure 4-7, Figure 4-8 and Figure 4-9, respectively. For each material the results are shown with three photos showing the dry material (to the left), half of the material being saturated (in the middle) and all material being saturated (to the right). In the photos to the right the settlement, if any, can be seen.

Table 4-5. Compilation of data on the settlement tests.

	Installed dry density	Water filling rate	Water filling rate	
Material	**Density kg/m³**	**Liter/min**	**Meter borehole/min**	**Remark**
Fogsand < 2 mm-A	1474	0.48	0.12	The sand column was pushed upwards
Fogsand < 2 mm-B	1501	0.28	0.07	Small initial settlement
MakPak 0–5 mm	1538	0.24	0.06	Small initial settlement
Ballast 2–4 mm	1351	0.24	0.06	No settlement
Ballast 4–8 mm	n/a	n/a	n/a	n/a

4.4.5 Discussion

The installed densities are of the same magnitude as the one achieved in the installation tests at dry conditions, see Section 4.3.6. After the water filling the small settlements in Fogsand and MakPak gave a slightly higher density of the material but also a small gap with water at the top (due to the settling) corresponding to approximately 1 % of the length.

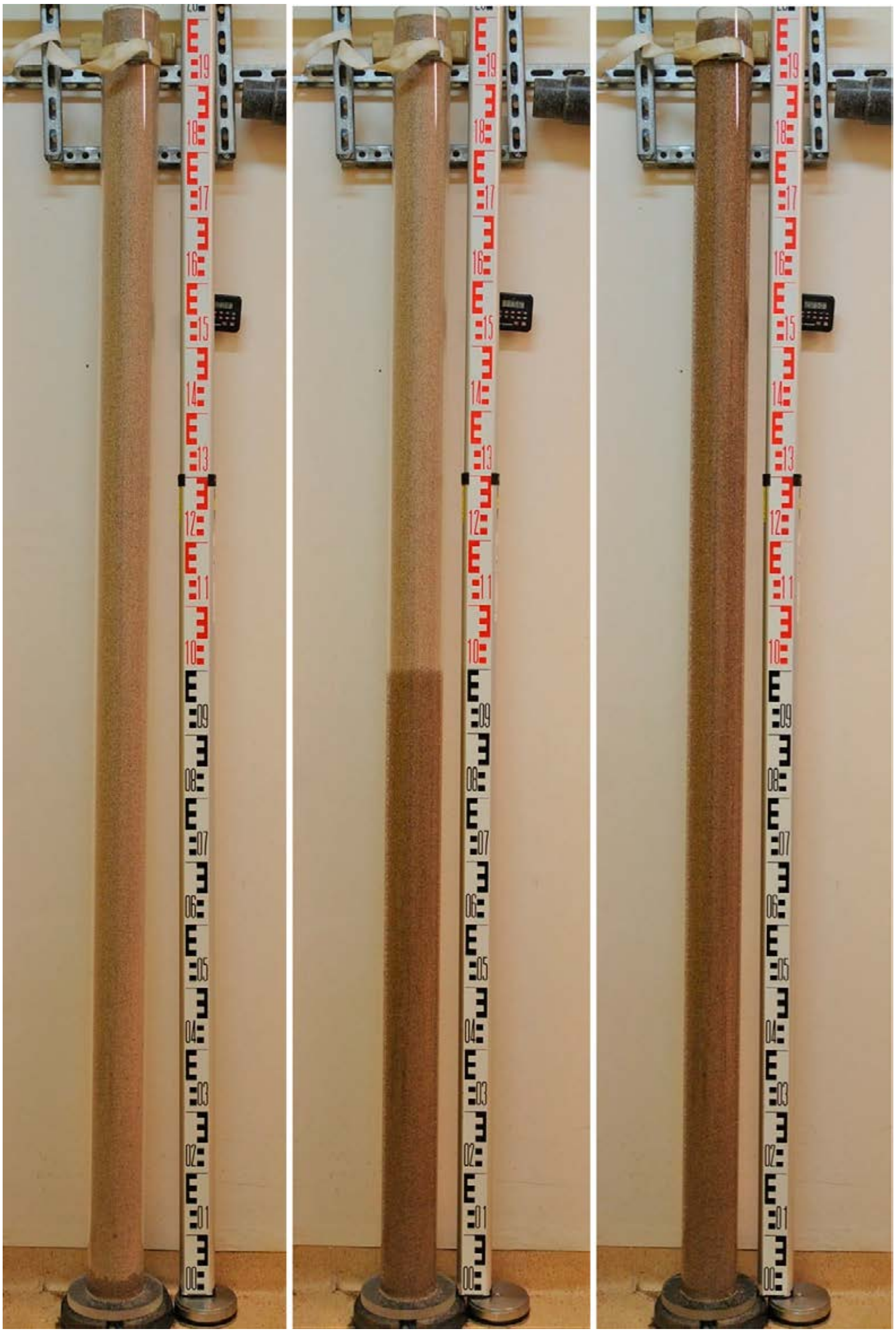


***Figure 4-7.** Photos taken during the water filling of the Fogsand 0–2 mm installed in a dry borehole. Left: The dry material Middle: Half of the material has been water filled Right: All material has been water filled.*

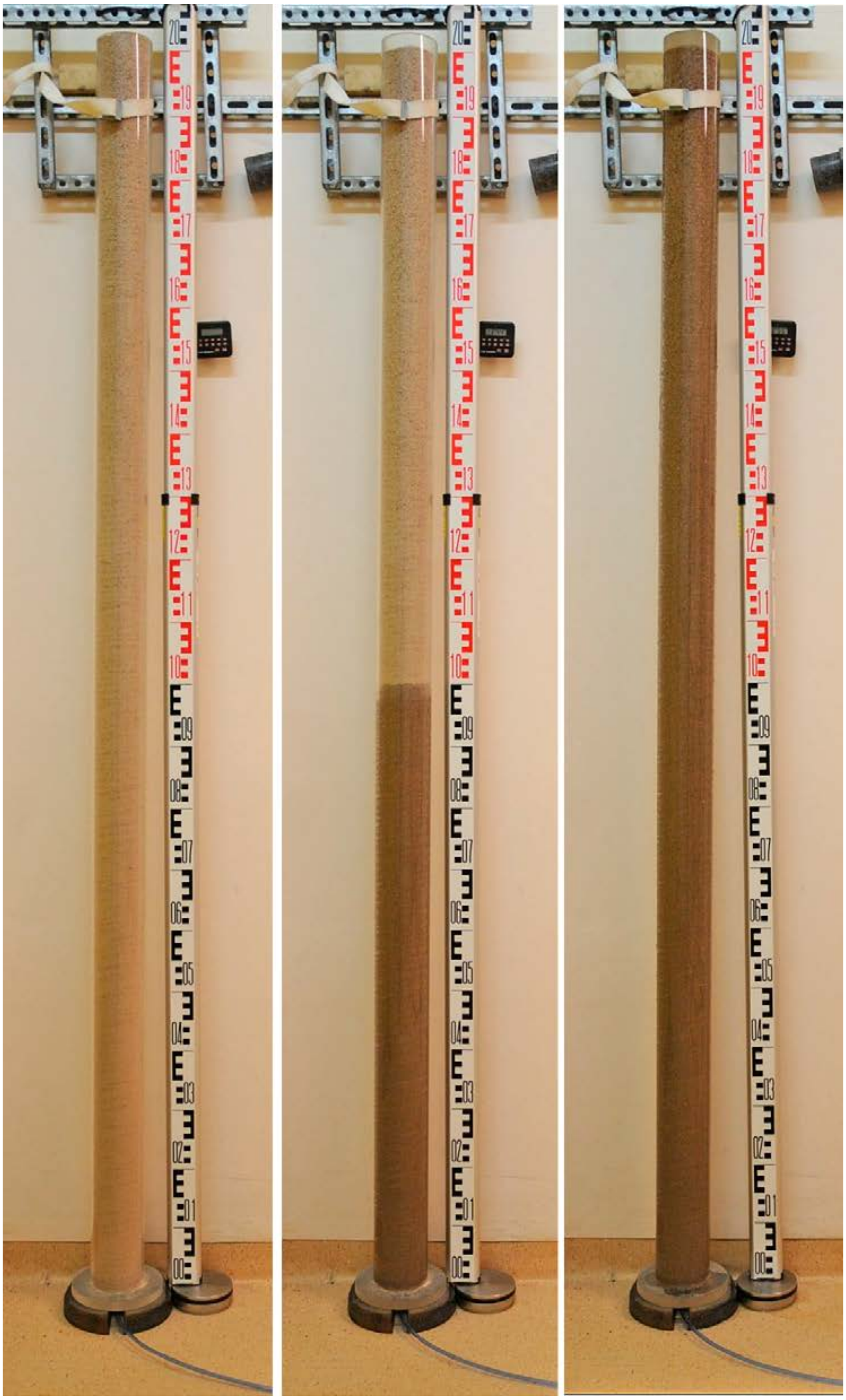


***Figure 4-8.** Photos taken during the water filling of the MakPak 0–5 mm installed in a dry borehole. Left: The dry material Middle: Half of the material has been water filled Right: All material has been water filled.*

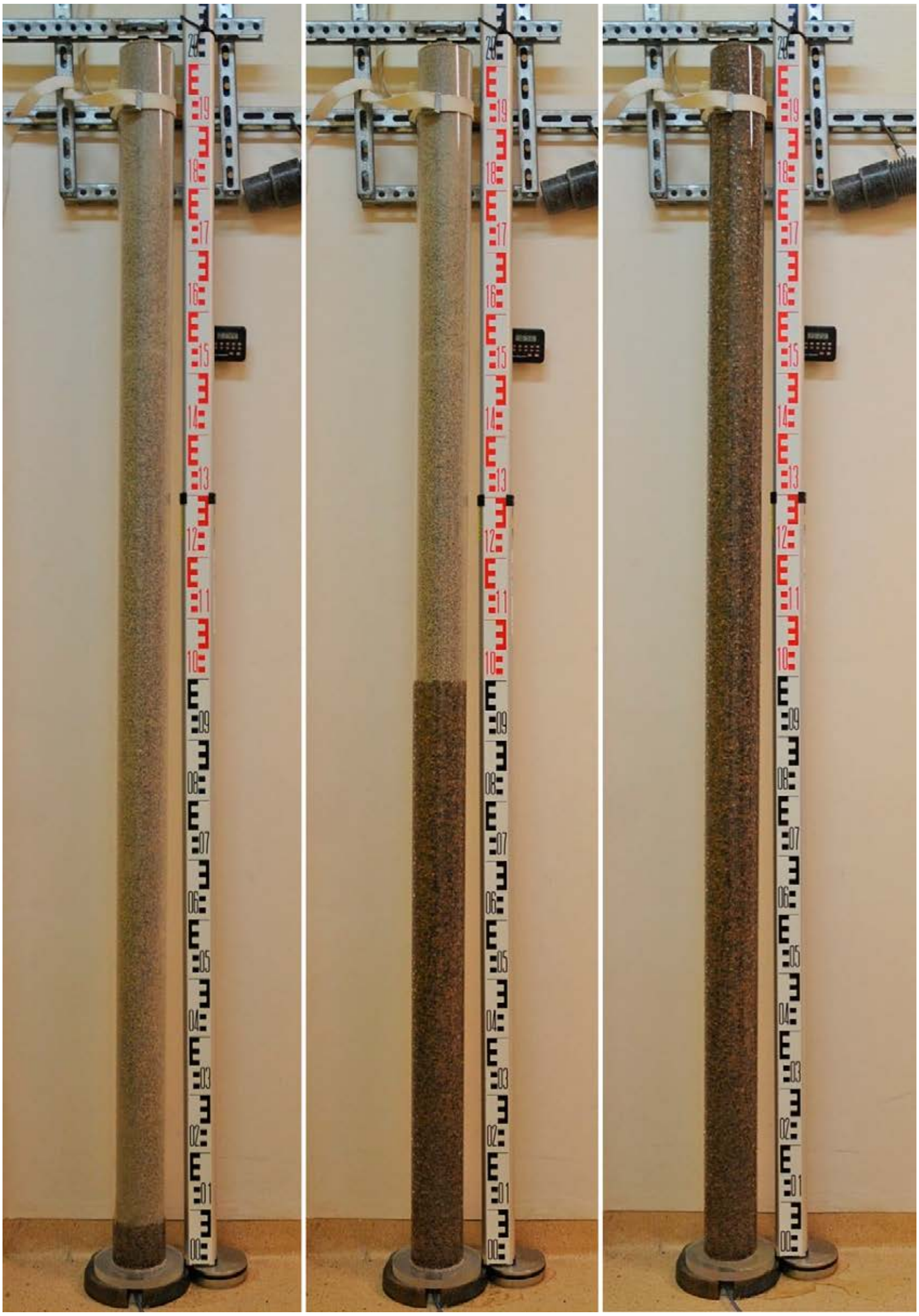


***Figure 4-9.** Photos taken during the water filling of the Ballast 2–4 mm installed in a dry borehole. Left: The dry material Middle: Half of the material has been water filled Right: All material has been water filled.*

4.5 Compressibility

4.5.1 General

The compressibility of the materials is important to be able to secure that the bentonite plugs stay in position also after some swelling and swelling pressure from the bentonite towards the granular material has been developed. This is, however, a scenario that only may occur after long time if the two following hypothesis are fulfilled:

- The cement in the concrete has leached leaving a core of coarse and fine grained quartz in the borehole.
- The copper expander has disappeared due to corrosion or if it is not working as intended i.e. the copper is not locking against the rock wall.

4.5.2 Test equipment and test procedure

The compressibility of the four investigated granular materials were determined with a constant rate of strain test where the sample was placed in a rigid ring. The equipment consisted of a steel cylinder with an inner diameter of 50 mm, a bottom plate fixed to the steel ring and a movable piston placed above the sample, see Figure 4-10. The device was put in a mechanical press where the rate of deformation was controlled. During the tests the deformation and the force were measured with a deformation transducer and a load cell, respectively.

The material was poured into the steel cylinder to a height of 40 mm and then the piston was put in place. The friction was minimized by lubrication of the piston and the inner surface of the steel ring. The device was put into the mechanical press where the piston was forced onto the granular material with a rate of 0.5 mm/min.

4.5.3 Test matrix

The tests were performed according to Table 4-6. In general the materials were tested both at a dry and saturated state. The tests were made both from a low density, resulting from pouring the material into the sample holder, and from a higher density, resulting from vibration (Fogsand) or initial compression (MakPak 0–5, Ballast 2–4 and Ballast 4–8). The ordinary tests were made in the equipment shown in Figure 4-10 with the height H = 40 mm, the diameter D = 50 mm and at a rate of 0.5 mm/min. In addition, some tests were made on specimens with deviating height and diameter; on short specimens (H = 20 mm and D = 50 mm), on tall specimens (H = 200 mm and D = 50 mm) and on wide specimens (H ≈ 85 mm and D = 100 mm). One test was performed at a slower rate than 0.5 mm/min (0.04 mm/min).

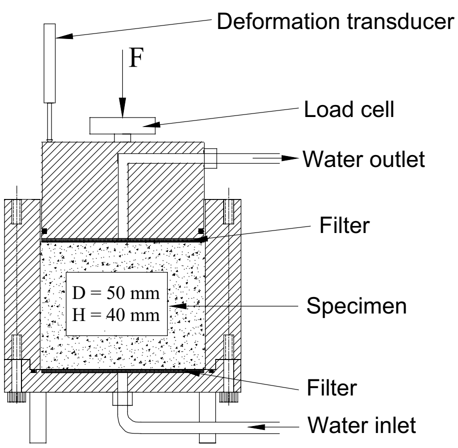


Figure 4-10. *Sketch of the set-up used for the tests of the compressibility.*

Table 4-6. Test conditions and test ID for all tests on compressibility of the materials Fogsand (FS), MakPak 0–5 (MP), Ballast 2–4 (B) and Ballast 4–8 (BB) where the letters in brackets are used in the final part of the test ID. The test rate was 0.5 mm/min for all but one test marked (M16MP).

Material		Fogsand (FS)		MakPak 0–5		Ballast 2–4		Ballast 4–8	
Start conditions		**Dry**	**Sat.**	**Dry**	**Sat.**	**Dry**	**Sat.**	**Dry**	**Sat.**
Density	**Equipment**								
Low	Ordinary (H = 40 mm D = 50 mm)	M11FS M13FS	M21FS M23FS	M11MP M13MP M14MP M15MP[2] M16MP[3]	M21MP	M11B	M23B		
	Wide (H ≈ 85 mm D = 100 mm)	M14FS						M11BB	M21BB
	Tall (H = 200 mm D = 50 mm)	M16FS	M24FS[1] M25FS						
Higher	Ordinary	M12FS	M22FS	M12MP	M22MP	M12B	M22B		
	Wide	M15FS							
	Tall	M17FS							

[1] Uncertain values. [2] Short specimen with H = 20 mm and D = 50 mm. [3] Slow test with the test rate 0.04 mm/min.

4.5.4 Results

In total 26 tests were run, according to Table 4-6; twelve on Fogsand, eight on MakPak, four on Ballast 2–5 and two on Ballast 4–8. The test results are presented in separate diagrams in Figure 4-11, Figure 4-12 and Figure 4-13 where the different colors (green/yellow, blue/black, red/purple) denote the different materials (Fogsand, MakPak, Ballast). The different line types (dotted line, solid line) denote the test conditions (dry, wet). The majority of the specimens were compressed to a maximum of 10 MPa but the wider specimens (marked with thicker lines) were only compressed to a maximum of 5 MPa. Test ID for the tests of compressibility contains M and a running digit and it ends with the letters (FS, MP, B, BB) denoting the different materials (Fogsand, MakPak 0–5, Ballast 2–4, Ballast 4–8).

Good repeatability was seen in the results from the tests on Fogsand. The highest final density was achieved when starting from a high initial density. Starting with a higher density gave also a lower compressibility than else. The lowest compressibility was seen in the test results from the tall specimens having a height four times the diameter. No influence of different diameters was seen as long as the ratio between height and diameter was kept to 0.8. The effect of testing the material dry or wet was small. An analysis of the friction forces along the specimens is given in Chapter 9.

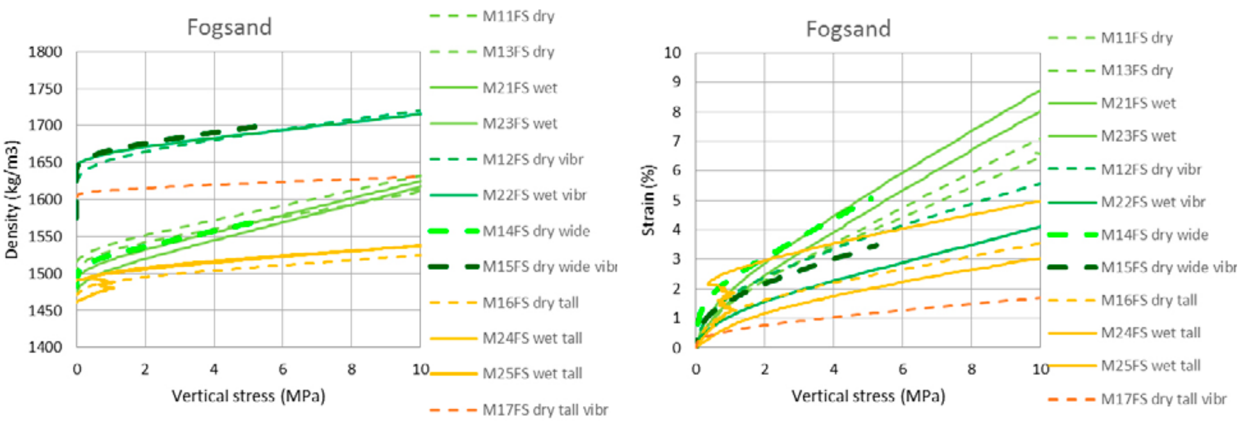


Figure 4-11. *Density (left) and strain (right) plotted as a function of vertical stress from tests on Fogsand (FS). The legends contain information about the Test ID and the text (tall, wide, vibr, dry, wet) denotes the test conditions (five times the ordinary height, double the ordinary diameter, vibrated to get higher initial density, dry material, and wet material).*

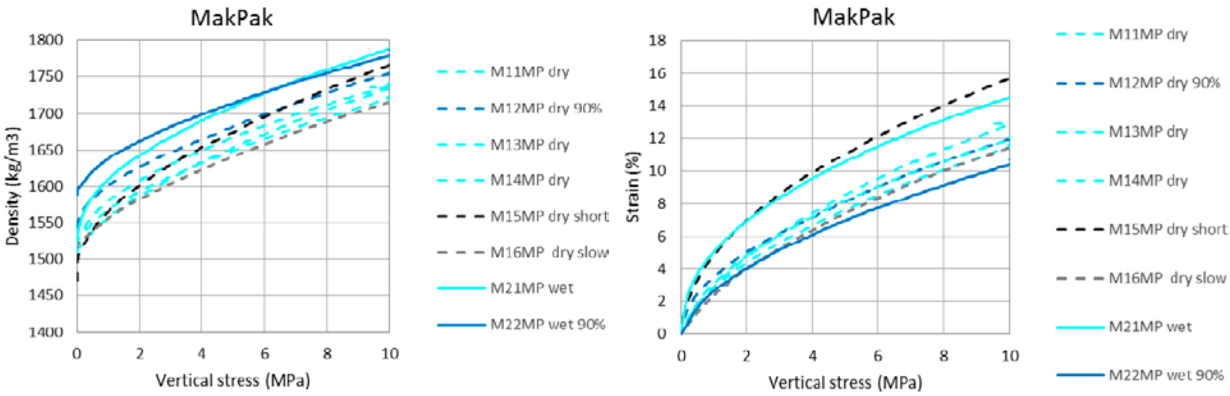


Figure 4-12. *Density (left) and strain (right) plotted as a function of vertical stress from the tests on MakPak (MP). The legends contain information about the Test ID and the text (90 %, short, slow, dry, wet) denotes the test conditions (initially compacted to 90 % of the final density of the low density test, half the ordinary height but the same diameter, rate of 0.04 mm/min, dry material, wet material).*

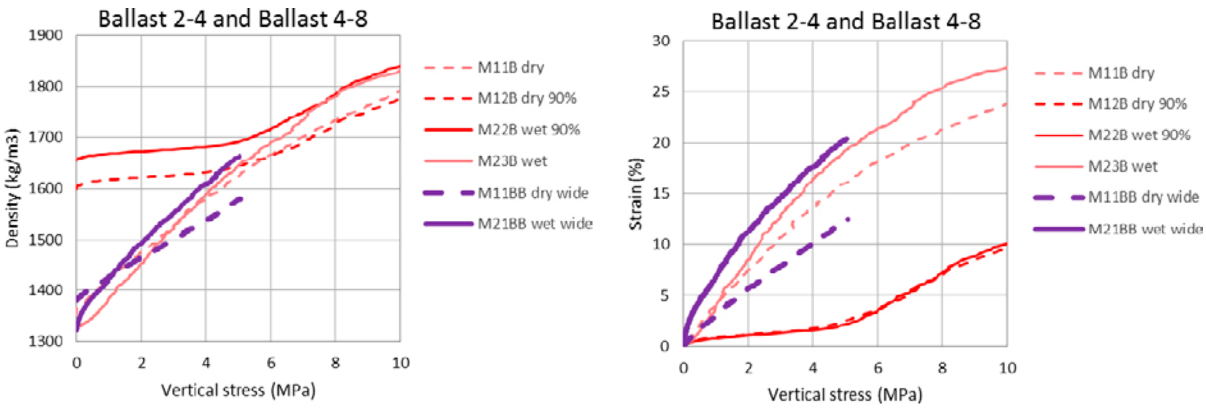


Figure 4-13. *Density (left) and strain (right) plotted as a function of vertical stress from the tests on Ballast 2–4 and Ballast 4–8. The legends contain information about the Test ID and the text (90 %, dry, wet) denotes the test conditions (initially compacted to 90 % of the maximum density of the low density test, dry material, wet material). The final letters of the Test ID (B, BB) denote the two materials (Ballast 2–4, Ballast 4–8).*

Good repeatability was seen in the tests according to the test repeated three times (M11MP, M13MP, M14MP) and no large deviation from this was seen in the results from the comparable specimen tested at a lower test rate (M16MP). However, an indication of higher compressibility when using shorter specimen (M15MP) was seen. The highest final density was achieved when testing wet material but a relative small difference was seen comparing all tests on MakPak.

No large difference was seen between the two different Ballast materials, Ballast 2–4 mm and Ballast 4–8 mm. The highest final density was achieved when testing water saturated material. The lowest compressibility was observed when starting from a higher initial density which was only tested on Ballast 2–4 mm (M12B, M22B).

4.5.5 Discussion

In general, good repeatability was seen in the test results. Test results from comparable tests on saturated specimens of Fogsand, Ballast 2–4, Ballast 4–8 mm and MakPak 0–5 mm are shown in

Figure 4-14 together with results from saturated Fogsand vibrated before the test. Comparing all four materials the highest density at high pressure was observed in the Ballast and MakPak materials while the lowest compressibility was observed in the Fogsand, especially when starting from an initially vibrated state. The very lowest compressibility was observed from the tall specimens of Fogsand, see

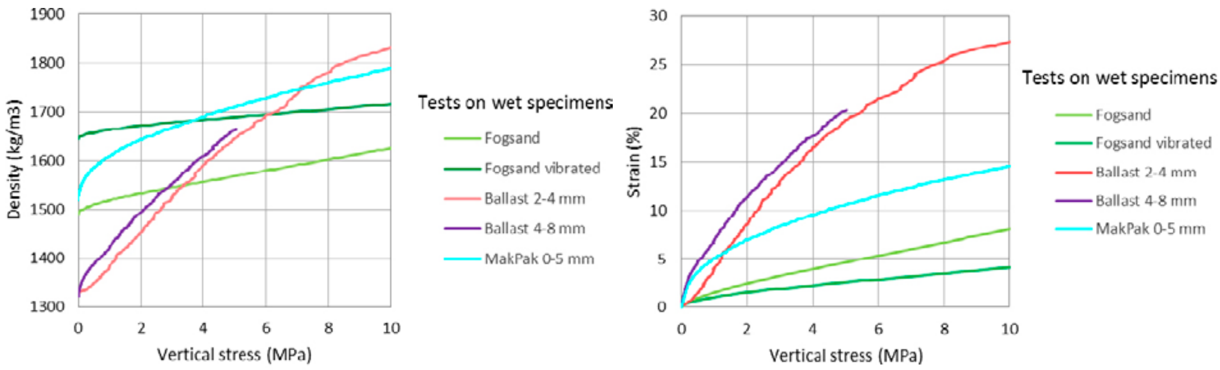


Figure 4-14. *Density (left) and strain (right) plotted as a function of vertical stress from the tests on saturated Fogsand, Ballast 2–4 mm, Ballast 4–8 mm and MakPak 0–5 mm. In addition saturated Fogsand initially vibrated is also shown. The specimens, test ID, are marked bold in Table 4–6.*

Figure 4-11, but in combination with a rather low final density, probably due to high friction along the specimens which is further commented on in Chapter 9. It can also be observed that there is a difference in the densities resulting from the small scale laboratory tests (Table 4-1) and the initial densities of the compressibility tests.

4.6 Hydraulic conductivity

4.6.1 General

The hydraulic conductivity of the granular material has small influence after installation in the borehole since the main sealing is maintained by strategically placed bentonite plugs. However, to get a total picture of the hydraulic condition of the borehole, the hydraulic conductivity of the granular material is also important to know.

4.6.2 Test equipment and test procedure

A sketch of the setup used for the determination of hydraulic conductivity is shown in Figure 4-15. The equipment consisted of a steel cylinder with an inner diameter of 100 mm and a bottom plate and a piston was fixed to the steel cylinder to keep the volume constant during the tests. Plastic filters were used below and above the specimens.

The material was installed in the sample holder at different densities. A constant water pressure of 0.8 m water column was applied to the water inlet below the specimen and the volume of the outflowing water was registered as a function of time. The dry density was determined as an average over the sample before the test.

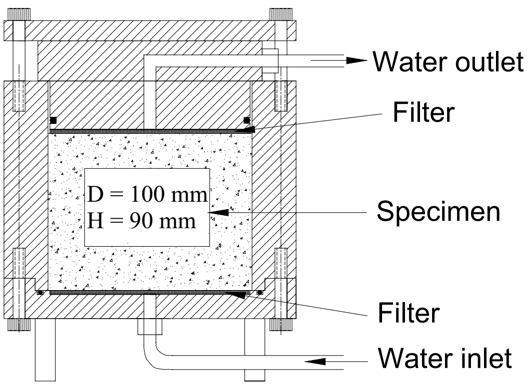


Figure 4-15. *Sketch of the setup used for the determination of hydraulic conductivity.*

4.6.3 Test matrix

The hydraulic conductivity of the materials was determined at the relatively low density achieved by pouring the dry material into the sample holder. For some of the materials the hydraulic conductivity was also determined at higher densities achieved by initial compaction.

4.6.4 Evaluation of data

The hydraulic conductivity k (m/s) was evaluated according to Darcy's law and Equation 4-2. The accumulated outflow of water was evaluated when the outflow was constant with time and over a period of minutes.

$$k = \frac{Q}{A \cdot t \cdot I} \qquad \text{(Eq 4-2)}$$

where

Q = accumulated outflow during the test duration (m^3)

t = test duration (s)

A = cross section area of the specimen (m^2)

I = water pressure gradient over the specimen height (m/m)

4.6.5 Test results

The test results are presented in Table 4-7 and in Figure 4-16. The hydraulic conductivity was determined with a gradient of 9 m/m and the outflow was measured during a couple of minutes.

Table 4-7. Hydraulic conductivity of the granular materials at different dry densities and measured at a pressure gradient of 9 m/m.

Material	Dry density kg/m^3	Hydraulic conductivity m/s
Ballast (4–8 mm)	1400	8.9×10^{-5}
Ballast (2–4 mm)	1430	2.5×10^{-5}
	1610	1.3×10^{-5}
	1890	1.1×10^{-5}
MakPak (0–5 mm)	1580	4.9×10^{-5}
	1750	1.1×10^{-5}
	1890	0.6×10^{-5}
Fogsand (< 2 mm)	1530	6.6×10^{-5}
	1680	1.1×10^{-5}
	1820	0.6×10^{-5}

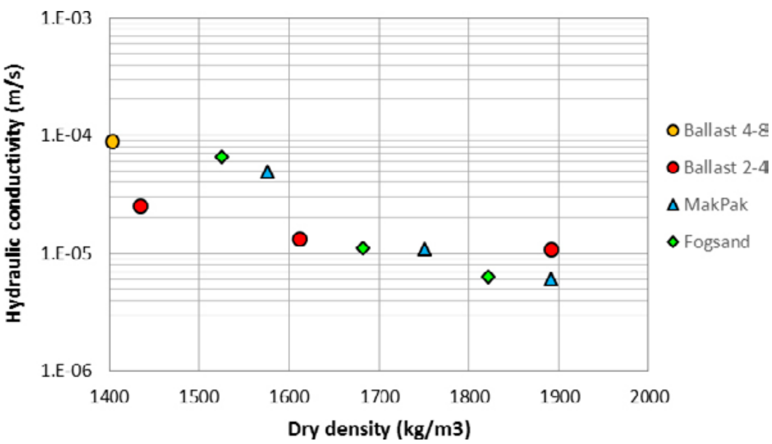


Figure 4-16. *Hydraulic conductivity as a function of dry density for Ballast (4–8 mm), Ballast (2–4 mm), MakPak (0–5 mm) and Fogsand (< 2 mm).*

4.6.6 Discussion

The hydraulic conductivity at low density are the most interesting and the four tested materials all have hydraulic conductivities of the same range, i.e. $1 \times 10^{-5} – 9 \times 10^{-5}$ m/s.

4.7 Comments and discussion

In the Sandwich-concept, the main part of the borehole length will be filled with granular materials. The most important behavior of the granular material is to secure that the bentonite plugs stay in position also after some swelling and swelling pressure from the bentonite towards the granular material. To optimize the properties of the installed granular material the requirements of the material and the installation can be further specified according to the following:

- the chosen material should be possible to install to a density similar to what is possible to achieve for the actual material,
- the material should be as homogeneous as possible after installation, i.e. the risk of separation and bridge structures should be minimized,
- the material should have low compressibility and as low hydraulic conductivity as possible.

From the tests the following advice can be given regarding of the choice of the granular material and since installation in a water filled borehole seems to the most plausible the comments below are concentrated on this condition. However, neither flowing water nor hydraulic gradients during the installation have been taken into account.

- Densities after installation in a borehole were shown to be of a magnitude comparable to the lowest densities achieved in the small scale tests (see Table 4-1) and some efforts to increase the density at installation will be valuable. This is valid for installation in water filled as well as dry boreholes.
- Sensitivity of vibrations was observed in some of the materials (see e.g. Table 4-1) and for the final density it could be valuable to use vibrations or similar already during the installation. This seems to be especially important for Fogsand, which was observed as extra sensitive in the results presented in Section 4.3.6, but efforts of vibration will be gained also for MakPak and Ballast 2–4.
- The effects of vibrations on Fogsand seems to be of the same magnitude or greater than compression to high pressure, see Figure 4-17 below, where the green line and the green solid square denote the compression test and the density after vibration in the small scale tests, respectively. Some effects of vibration was also observed in the results on MakPak (blue line and blue solid square) and to some extent also on Ballast 2–4 (red line and red solid square). In the diagram also the maximum density achieved of each material in the installation tests are marked.
- Tendencies of separation during installation in a water filled borehole were seen in tests on MakPak (Figure 4-5) and at dry conditions observations of separation were seen in both MakPak and Fogsand (Figure 4-4).
- After installation a low compressibility will be important and the lowest compressibility was seen in the test results of Fogsand and of MakPak. The sand used, Fogsand, is a poorly graded sand having a specific grain size which is suitable for effective compaction which gives low compressibility. On the other hand the MakPak material has a low compressibility since it is well graded with a specific gradation to get low compressibility. Both the gradation and the specific grain size are thus of importance for the compressibility.
- Tendencies to form bridge structures might be minimized by lowering the installation rate of the materials into the borehole. Especially at installation of Fogsand and MakPak into a water filled borehole it seems to be important to use a low installation rate, well below 10 kg/min (10 kg/min corresponds to approximately 1.5 m borehole/min for a borehole with an inner diameter of 76 mm. The fastest installation into a water filled borehole could be made with Ballast 4–8 which in addition seems not to be sensitive to vibrations, however, has a rather high compressibility.
- For all materials in the actual range of densities the hydraulic conductivity will be between $1 \times 10^{-5} – 9 \times 10^{-5}$ m/s.

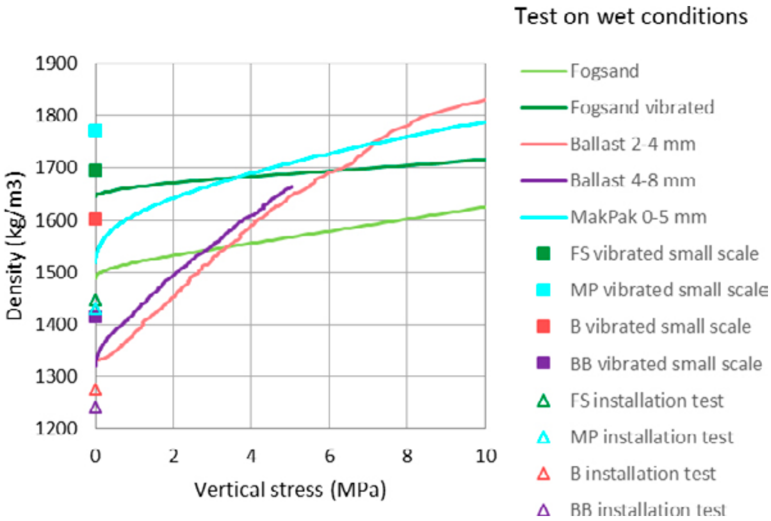


Figure 4-17. *Density plotted as a function of vertical stress from tests on Fogsand (FS), MakPak (MP), Ballast 2–4 mm (B) and Ballast 4–8 mm (BB).*

5 Tests of components – quartz based concrete plug

5.1 General

In the suggested Sandwich-concept, quartz based concrete plugs are used as delimiters between the bentonite filled sealing sections and the sections filled with granular materials. The main function of the concrete plugs is to prevent the bentonite from swelling in axial direction into the rather large voids in the filling i.e. the concrete plugs should work as a filter. If the bentonite is allowed to swell, the density will decrease and by that the hydraulic conductivity will increase which thus results in an impaired function.

Except some simple casting tests in laboratory, a number of material properties have been investigated:

- The adhesion between concrete and rock as function of curing time.
- Compressibility of the remaining quartz core assuming that all cement has leached.
- Hydraulic conductivity of the remaining quartz core assuming that all cement has leached.

The concrete is viscous and is recommended to be installed in deep boreholes using a dump bailer. This has also been made in conjunction with a borehole sealing test performed in Olkiluoto, Finland (Pusch and Ramqvist 2006).

5.2 Material

A recipe for quartz based concrete plugs was suggested in Pusch and Ramqvist (2006), see Table 5-1. It is a low pH concrete with a cement content of about 4 % which means that also after a long time, when all cement has leached, there will be a remaining core of quartz grains of different sizes left in the borehole.

The recipe also includes a small amount of flowing agents, superplasticizer, which is needed in order to achieve a suitable viscosity of the mixture. The superplasticizer contains organic material which is something that should be considered when investigating the post closure aspects on this material.

The long term safety aspects of the materials used in recipe needs thus to be considered. The suitability of the concrete recipe is a part of the design, and therefore the amount of cement is minimized, the pH is low, and the content of admixtures is kept low. The recipe also contain a lot of pozzolans.

Table 5-1. Components of the quartz based concrete plug (Pusch and Ramqvist 2006).

Components	kg/m^3 concrete
Cement (Aalborg Portland)	60
Water	150
Silica Fume	60
Fine sieved a quartz (M 300, Sibelco)	200
Fine sieved christobalite quartz (M 600, Sibelco)	150
Superplasticizer (Glenium 51)	4.38
Ballast 0–4 mm (Underås Jehanders Grus)	1679

5.3 Casting test

The recipe for the concrete presented in Table 5-1 prescribes quartz with different grain size but the coarser ballast is not very precise in description e.g. the grain size distribution is not given, only “Ballast 0–4”. Some initial tests were performed where specimens were cast using two different ballast materials, “Fogsand 0–2 mm” and “Ballast 2–4 mm”, see material description in Section 4.2. The photos provided in Figure 5-1 show two specimens cast with the two different ballast materials. After a visual inspection it was decided to use the “Fogsand 0–2 mm” as ballast material for the further tests since it was judged that this ballast should result in a more homogenous concrete that should stick better to the borehole rock walls.

The bulk density of the concrete was determined by casting a sample in a vessel with known volume (about 0.5 litres). The exact volume of the vessel was determined by filling the vessel with water and then determine the mass of the water. The bulk density of concrete cast with the ballast “Fogsand 0–2 mm” was determined to 1 972 kg/m^3. This density was then used as a target density when performing the compressibility and the hydraulic conductivity tests, see Section 5.5 and 5.6.

5.4 Friction between concrete and rock

5.4.1 General

The adhesion between concrete and rock is an important parameter to be tested. In conjunction with the construction of new tunnels in the extended SFR there may be a risk that some of the closest boreholes will be crossed and in that case it is important that all installed sealing material stays in the borehole. The concrete has earlier been investigated regarding strength (Unconfined compressive strength) and shrinkage (Pusch and Ramqvist 2006).

5.4.2 Test equipment and test procedure

In order to achieve as realistic values as possible regarding the friction between concrete and rock it was judged that the tests should be performed using the suggested quartz based concrete and a rock surface. Casting in a prepared borehole and then determine the friction forces is, however, rather complicated and in order to facilitate the testing it was decided to do the opposite i.e. casting around a central core of rock, see photos provided in Figure 5-2, and then push the core out while measuring the force needed and the displacement.

Figure 5-1. *Left: Concrete using Ballast 2–4 mm Right: Concrete using Fogsand 0–2 mm.*

Figure 5-2. *Photos showing the test principal of the friction tests. Left: A granitic core was cast into the center of a mould. Middle: After a decided time the core was pushed out from the concrete. During the pushing, the needed force and displacement were registered. Right: The granitic core and the holder with concrete after having finished the test.*

The test equipment consisted of a central granitic core with a diameter of 71.5 mm and a height of 100 mm which was cast into the center of a sample of concrete in a holder with an inner diameter of 149 mm and a height of 100 mm. The sample holder was after preparation placed on a pedestal where the lower concrete surface was almost fully supported. A piston made of steel was placed on the upper surface of the rock core together with a load cell, see photos provided in Figure 5-2. The complete arrangement was placed in a press and a constant deformation rate was applied (0.01 mm/min in the beginning of the test and then increased in steps). The test matrix has included different time of curing for the concrete. The specimens were during the curing time, stored wrapped in plastic and the relative humidity was kept close to 100 % by wet rags placed inside the plastic. During the test time, the vertical load and the displacement were measured continuously.

From the test results the maximum shear stress was evaluated according to Equation 5-1.

$$\tau_{max} = \frac{F_{max}}{A} \qquad \text{(Eq 5-1)}$$

where

τ_{max} = Maximum Shear stress (kPa)

A = Envelope surface of the rock core sample (m^2)

F_{max} = Maximum applied vertical load (kN)

The calculated maximum shear stress was then used to calculate the force needed to push out one meter of sealing material from a borehole with an inner diameter of 76 mm (common diameter of SKB investigation borehole).

5.4.3 Test matrix

In total seven tests were performed. All specimens were cast at one time and then they were tested at different times after casting (1, 2, 5, 8, 16, 33 and 49 days).

5.4.4 Results

The graph provided in Figure 5-3 shows an example of the measurements made during the test. The shown data is from the test performed after 1 day curing of the concrete. As shown in the graph, the applied constant rate was very low in the beginning of the test, 0.01 mm/min but after having reached the maximum force the rate was increased in steps. No clear influence of the rate on the residual force was seen. There was a very clear decrease in force with time independent of the rate. The corresponding graphs for all performed tests are provided in Appendices 1 through 3.

Figure 5-4 shows a compilation of the results from all tests. The calculated maximum shear stress is plotted versus the curing time of the concrete. It is obvious that the friction increases with time, from about 150 kPa after 1 day curing up to above 300 kPa after 8 days.

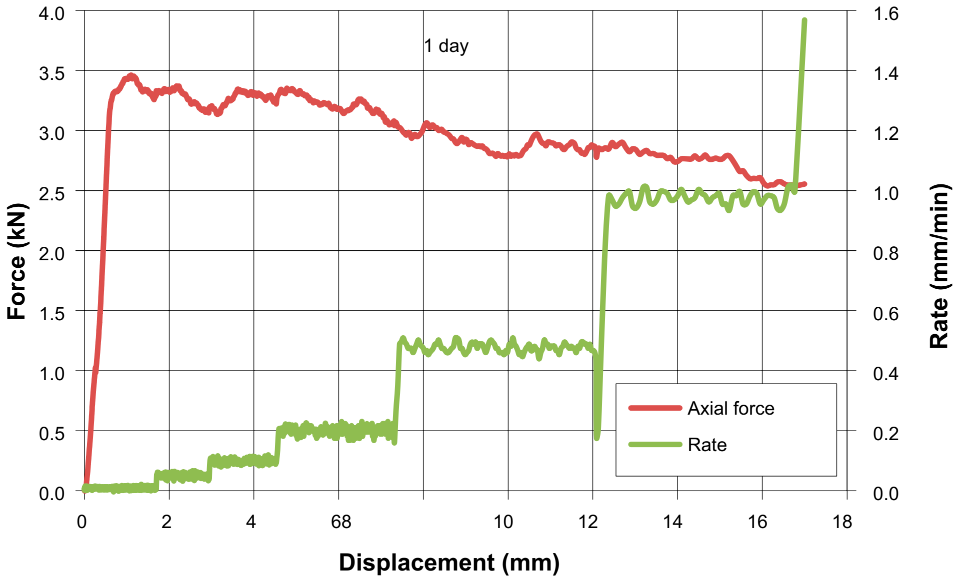


Figure 5-3. The graph shows the measured force and test rate plotted versus displacement for the test with a curing time of 1 day.

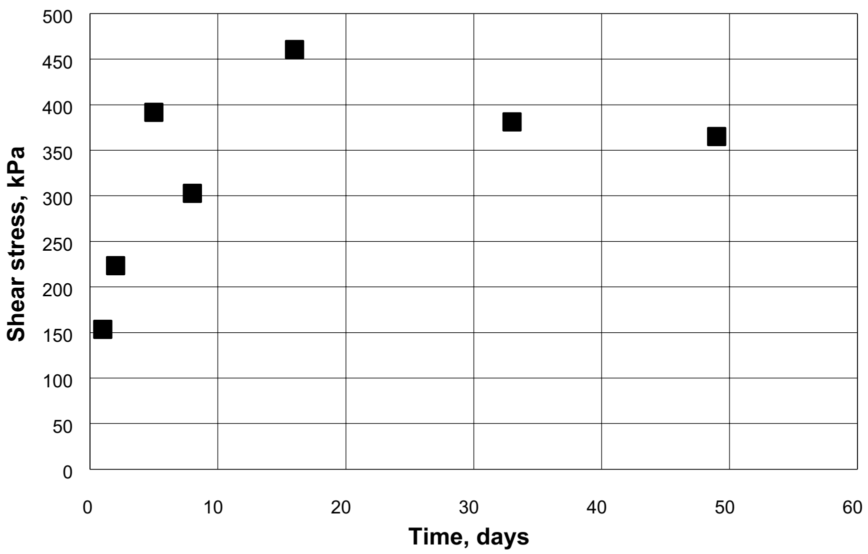


Figure 5-4. The maximum shear stress during test plotted versus curing time for the concrete/rock specimens.

5.4.5 Discussion

The performed tests show that the suggested quartz based concrete will have high adhesion against the borehole walls. A maximum shear stress between concrete and rock of 300 kPa is reached after five to eight days. This means that a concrete filled borehole section with a length of 1 meter, after about one week, can withstand to an overload of 72 kN. This load corresponds to an axial swelling pressure from a bentonite section of more than 15 MPa.

The maximum shear stress used in the calculation represents the peak value, mobilized at no or small deformations. However, after additional deformation there will still be a residual strength which, according to the test results, is approximately half of the peak value. Based on the residual strength the concrete filled borehole section will then be able to withstand an overload of approximately half of the overload and half of the swelling pressure compared to the values based on the peak value above.

The tests show that as long as the concrete is in good condition i.e. no cement has leached, it will function as a very good delimiter between different materials.

5.5 Compressibility

5.5.1 General

A conservative assessment is that the cement component in the concrete plugs will leach with time, leaving a core of coarse and fine grained quartz based material left in the borehole. The material of such core was used for determinations of compressibility and hydraulic conductivity in order to get a conservative estimation of the properties of what will be left of the concrete after long time. The determination was thus made on specimens consisting of all components of the quartz based concrete plug, Table 5-1, except the cement.

5.5.2 Test equipment and test procedure

The compressibility was determined according to the description in Section 4.5 but on specimens with the height H = 80 mm and diameter D = 100 mm. The tests were performed at a rate of 0.5 mm/min. It was important to study the mentioned properties at a relevant density which was considered to be the bulk density of the concrete after casting, i.e. 1 972 kg/m^3.

5.5.3 Results

Two specimens with different densities were tested; one with lower density and one with higher density compared to the density of the concrete after casting, i.e. 1 972 kg/m^3. The lower density was achieved by loosely pouring the material into the test device and the higher density was achieved by an initial compaction of the material after installation. Both tests were made with all components except the cement mentioned in Table 5-1 which gave a relatively dry material.

The results from the two tests (specimens M11Q and M21Q) are shown in Figure 5-5, where the letter Q denote the quartz based material. The results are shown with results from comparable tests on Fogsand (M14FS and M15FS) previously shown in Figure 4-11.

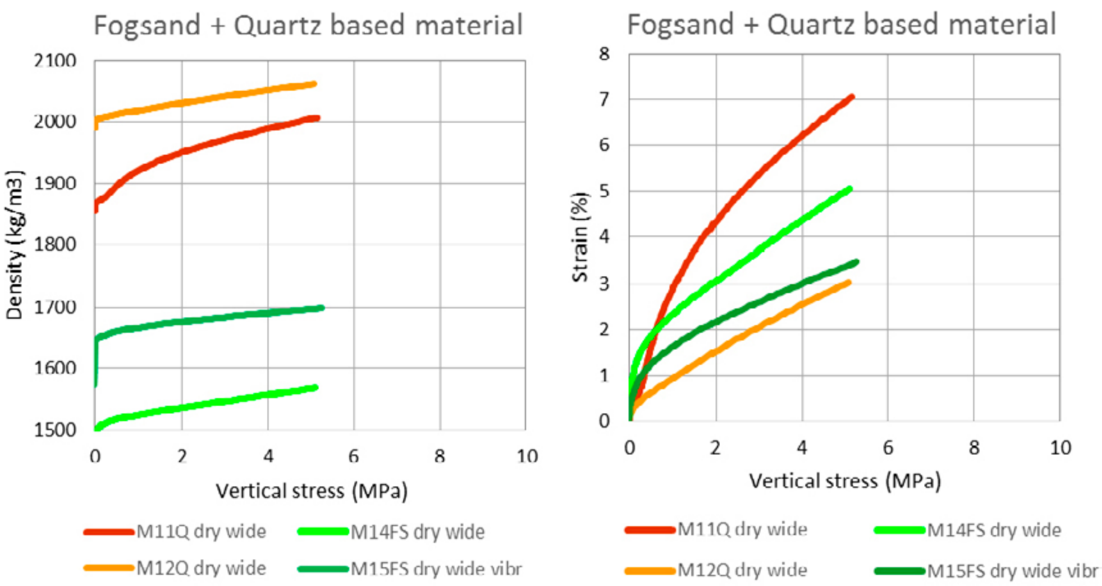


Figure 5-5. *Bulk density (left) and strain (right) plotted as a function of vertical stress from the tests on the quarts based concrete material in Table 5-1 but without cement (Q). The results are presented with results from comparable tests on Fogsand (FS) presented in Figure 4-11. The legends contain the same information as in Section 4.5, e.g. wide means that the tests were made in a device with D = 100 mm.*

5.5.4 Discussion

The compressibility of the core of coarse and fine grained material without cement (Q-material) is of the same range as that of Fogsand which, is logical since the main part of the tested material consisted of Fogsand. The high final strain of M11Q (lower graph, red line) was a result of starting from a relatively low density compared to the relevant density, i.e. 1 972 kg/m^3.

5.6 Hydraulic conductivity

5.6.1 General

The hydraulic conductivity was determined on the same material as was used for the compressibility test i.e. on an assumed left core of the concrete consisting of coarse and fine grained quartz based material.

5.6.2 Test equipment and test procedure

The determination of hydraulic conductivity was made according Equation 4-2 and the description in Section 4.6. In accordance with the determination of the compressibility it was considered to aim at the bulk density of the concrete after casting, i.e. 1 972 kg/m^3.

5.6.3 Results

Two tests were run with initial bulk densities of 1 861 kg/m^3 and 1 963 kg/m^3. The installed material had an initial water content of 6 %. The results are shown in Table 5-2 and in Figure 5-6. In the diagram the results are shown together with the results of Fogsand from Figure 4-16.

Table 5-2. Hydraulic conductivity of the quartz based material without cement at two different dry densities and measured at a pressure gradient of 9 m/m.

Material	Dry density kg/m^3	Hydraulic conductivity m/s
Q-material	1 756	0.4×10^{-5}
	1 852	0.8×10^{-5}

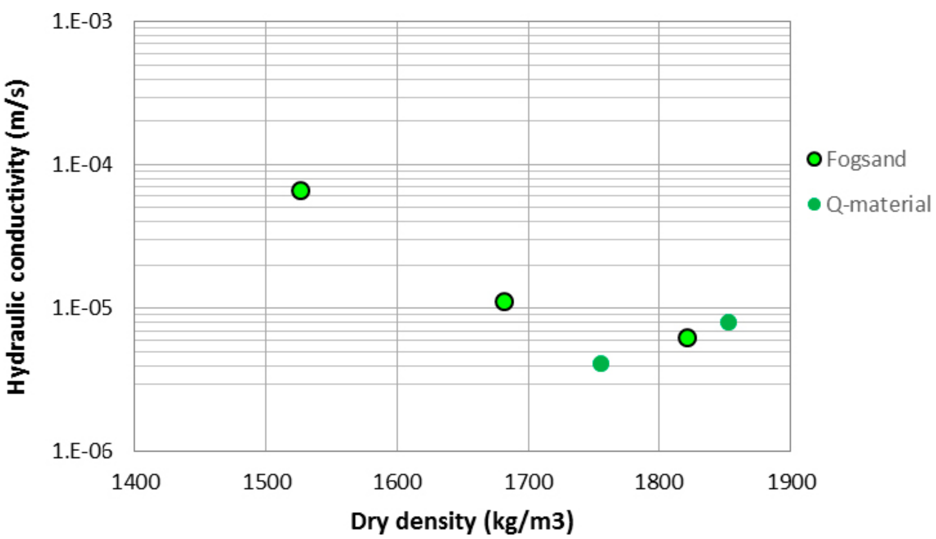


Figure 5-6. Hydraulic conductivity as a function of dry density of the components of the quartz based concrete plug without cement (Q-material). The results are presented together with the results of Fogsand from Figure 4-16.

5.6.4 Discussion

The hydraulic conductivity of the quarts based concrete material without cement was of the same range as that of Fogsand at the same density.

5.7 Comments and discussion

The main function of the concrete plugs is to prevent the bentonite from swelling into the sand filling. To decide if this can be achieved the adhesion between concrete and rock was studied together with determinations of the compressibility and hydraulic conductivity of a core of what is assumed to be left of the concrete after long time.

- The tests show that as long as the concrete is in good condition i.e. no cement has leached, it will function as a very good delimiter between different materials.
- Based on the peak values from the test results a concrete filled borehole section with a length of 1 meter can, after about one week, withstand an overload of 72 kN. This load corresponds to an axial swelling pressure from a bentonite section of more than 15 MPa.
- Occurrence of residual strength gives that still after additional deformation the concrete filled borehole section can withstand an overload which, however, is only half of the value calculated from the peak value.
- The compressibility and hydraulic conductivity of what is left of the concrete after long time was estimated from tests on a quartz based material with the ingredients of the concrete plug except the cement. The results resembles that of the main component which in this case was Fogsand.

After long time when the cement has leached out of the concrete, the content of Silica Fume and Superplasticizer are also assumed to have leached from the concrete. This was not considered in the preparation of the material used for the prediction of the behavior of concrete after long time. However, based on the proportion of the Silica Fume and Superplasticizer in the concrete this should not have a dominant influence on the properties which, should be further verified.

6 Tests of components – copper expander (bridge plug)

6.1 General

The main purposes with the copper expander are to:

- During installation prevent concrete from flowing into either the rather large voids of the sand/gravel filling or into the annular gap between bentonite plugs and rock.
- During long time limit the interaction between different sealing materials (during the post-closure phase).

Three prototypes of copper expander have been developed and tested within the framework of this project.

6.2 Design of a copper expander

The main idea with the design of a copper expander was to have an inner part made of hard copper (Rp 0.2 = 250–350 MPa) and an outer part made of annealed copper (Rp 0.2 = 40–120 MPa) that could be expanded. The expansion should be made by pushing a cone into another, see schematic drawings in Figure 6-1. Three different designs have been tested:

I. (Left in Figure 6-1). This expander was designed to be used in a borehole with a diameter of 80 mm. The diameter of the expander was 75 mm and the length 191 mm. In this design the angle of the outer cone (2) and the inner cone (1) was the same, 7°.

II. (Middle in Figure 6-1). Same design as I, but the angle of the outer cone (2) was changed to, 9° while the outer (1) still was 7°. This change was made in order to decrease the force needed for the expansion.

III. (Right in Figure 6-1). New design where the outer "cup" (2) is cylindrical with a rather thin wall, 3 mm. The inner cone has an angle of the 9°. The design is adapted for a borehole diameter of 84 mm (Mockup test at Äspö, see Chapter 8).

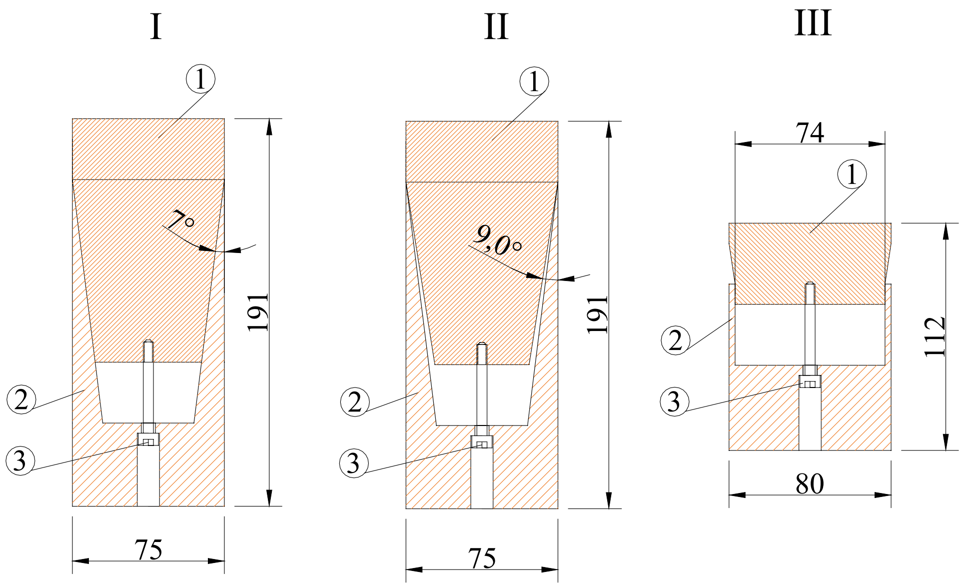


Figure 6-1. Three different designs (I, II, III) of copper expanders have been tested. Each design consists of three parts: 1 Inner cone made of standard copper (hard). 2 Outer cone or cup made of annealed copper. 3 Connecting screw.

6.3 Test equipment and test procedure

The initial tests of the copper expanders were done in a very simple way. The expander was placed in a hydraulic press and an axial force was applied. During the test, the applied force and displacement were registered. The radial expansion was measured with a caliper. In the first test, performed with the copper expander design I, the expander was placed in a tube simulating a borehole, but it was decided to remove the tube during the coming tests to facilitate the measurement of the expansion. In the test of the third design of a copper expander the radial expansion was measured continuously during the compression.

In all tests, the contact surfaces were lubricated with copper grease in order to decrease the friction during compression. The long term safety aspects of the grease needs to be considered.

6.4 Results

Copper expander I

The photos provided in Figure 6-2 show the test setup (left and middle) and also the copper expander after compression with a force of 100 kN (right). During the test, the applied force and the displacement of the inner cone was registered, Figure 6-3. In this test the maximum displacement was about 4.8 mm at a compression of 100 kN. At this time the diameter of the expander had increased from 75 to 77.85 mm i.e. the diameter had increased with 2.85 mm. This expansion was not enough to lock the copper expander in the simulated borehole section (inner diameter 80 mm). The copper expander was after the initial test placed in a larger hydraulic press and a force of 250 kN was applied. This action did not result in any additional expansion of the copper.

***Figure 6-2.** Left: Copper expander positioned in the hydraulic press. The outer tube, simulating a borehole section will be thread over the expander. Middle: The complete test setup Right: The copper expander after test.*

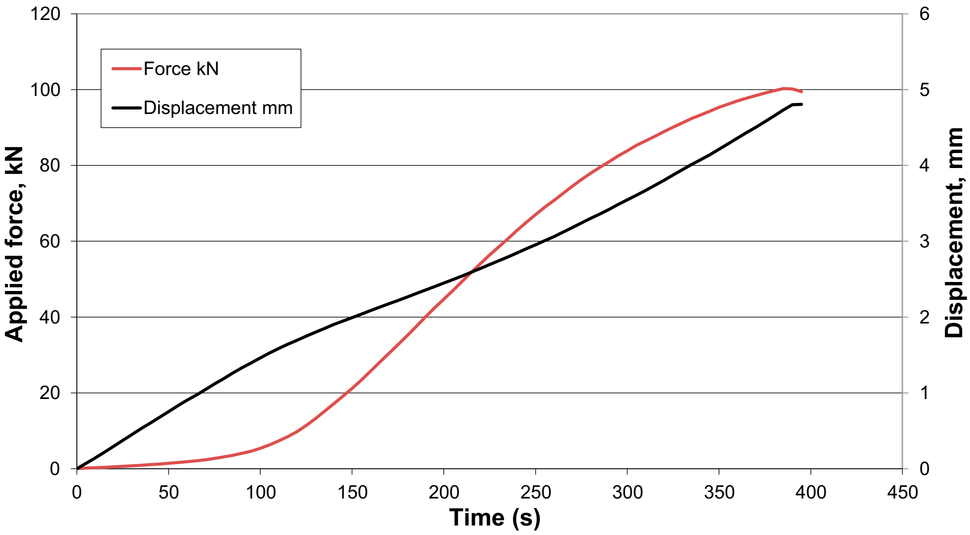


***Figure 6-3.** Applied force and displacement of the inner cone plotted versus time for the tests with Copper expander I.*

Copper expander II

The next test was performed with a slightly modified copper expander where the inclination of the inner cone was changed to 9°, see design II in Figure 6-1. The behavior of this modified copper expander was different. The test was performed without using any outer tube, Figure 6-4. When the maximum force of 100 kN was applied, the axial displacement was about 16 mm, Figure 6-5, i.e. about three times more than in the earlier test. The diameter of the expander had at this time increased from 75 mm to 78.5 mm i.e. 0.65 mm more than in the previous test. The expansion was, however, still too small in order to seal off a borehole with a diameter of 80 mm.

***Figure 6-4.** Copper expander after compression with 100 kN.*

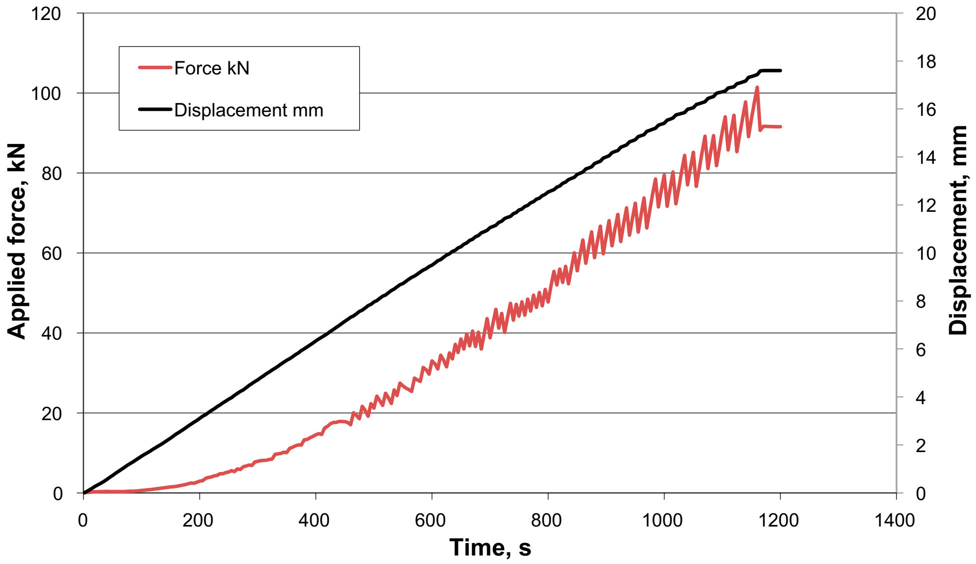


Figure 6-5. *Applied force and displacement of the inner cone plotted versus time for the tests with Copper expander II.*

Copper expander III

The third design of a copper expander was quite different, see design III in Figure 6-1. It should be noted that the dimensions of this copper expander are adapted to the planned Mockup test where this design of expander was used, see description in Chapter 8. The inner part made of hard copper has still a conical shape while the cup, made of annealed copper, has a cylindrical shape with a wall thickness of 3 mm. In this test, the radial expansion of the outer cup was registered continuously during the expansion, at two different levels. One displacement sensor was placed on the edge of the cup and one sensor five mm from the edge, see photo of the test setup in Figure 6-6. The two sensors measuring the radial expansion can be seen to the left in the photo.

Figure 6-6. *Photo showing the test setup just before starting the compression. Note that the conical part is at the bottom. This part is also lubricated with copper paste in order to decrease the friction additionally.*

The graph provided in Figure 6-7 shows the axial applied force and the displacement during compression. The force needed for expansion was much lower than for the two earlier tests, less than a fifth. The radial expansion at the edge of the copper cup was about 3.7 mm which is well above the needed 2 mm in the Mockup test. During the early expansion at the edge, it can be noted that the radial expansion five mm above is negative, see black line in Figure 6-8. However, after a total axial compression of about 8 mm, the copper at this level also starts to expand. Figure 6-9 shows a photo of the copper expander after having finished the test. The radial expansion can be seen very clearly at the lower part of the expander.

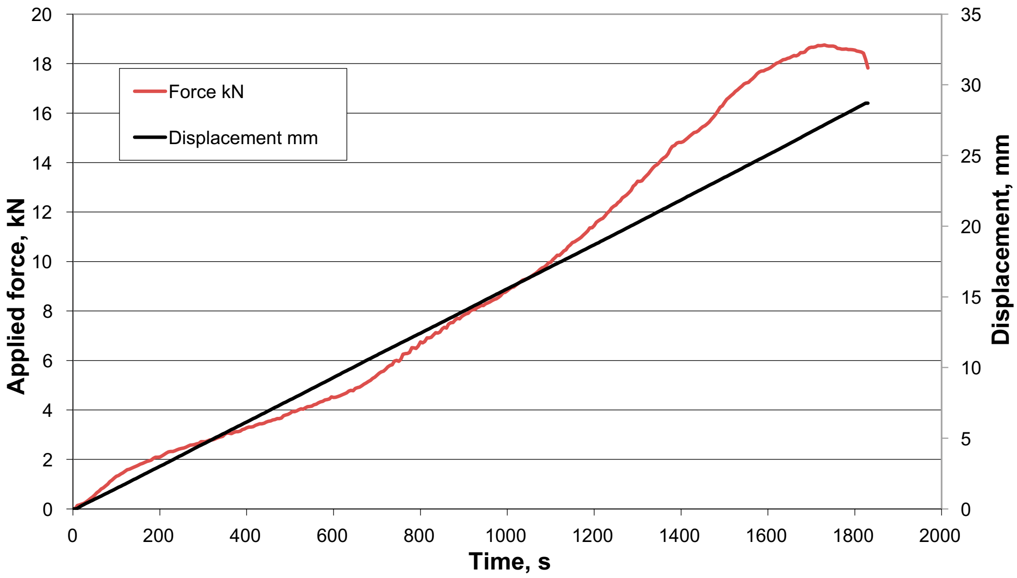


Figure 6-7. *Applied force and displacement of the inner cone plotted versus time for the tests with Copper expander III.*

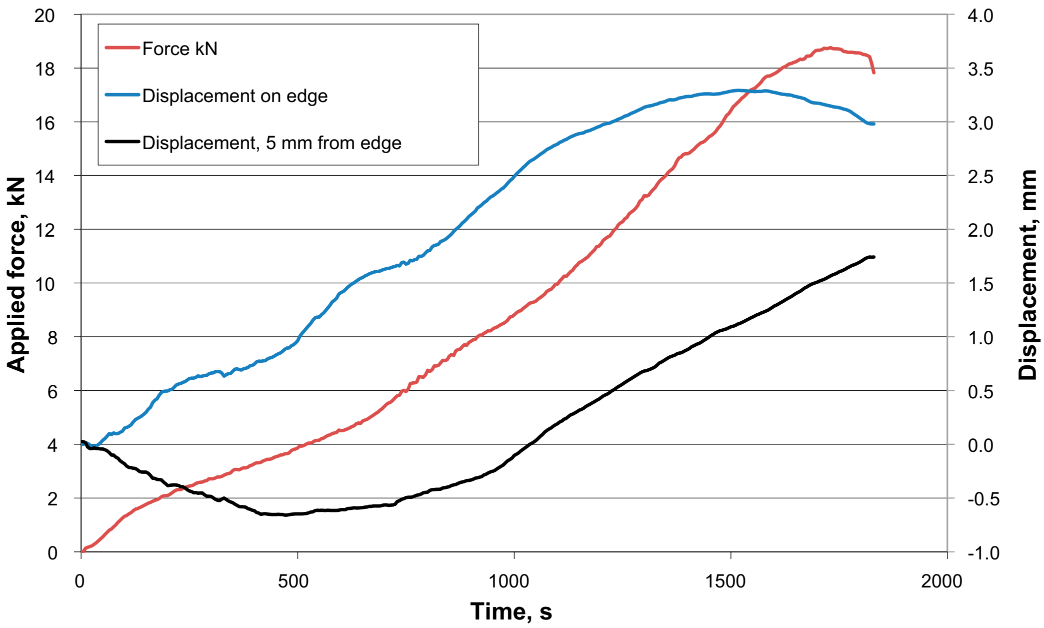


Figure 6-8. *Applied force and displacement measured on the edge of the expandable part of the copper expander. One sensor is positioned right on the edge (blue line) and one is positioned 5 mm from the edge (black line).*

Figure 6-9. Photo showing the copper expander after compression. The lower part has been clearly expanded.

6.5 Comments and discussion

The first two designs of a copper expander that were tested required a high load to expand and the radial expansion was also judged to be too small to be practical i.e. the initial dimensions of the expander would have to be rather close to the borehole diameter (about 3 mm less than the borehole diameter).

The third design tested required much less force to expand, less than 20 kN (2 tons) and the radial expansion was much higher. It is judged that a copper expander with the tested dimensions can be installed in the Mockup test and be expanded to reach the simulated borehole walls at a force of about 10 kN. Complementary laboratory tests are required in order to study the expansion when the expander is installed in a borehole i.e. there will be an anvil when the copper reach the borehole wall. It is also judged that the design can be further improved so that a longer section can expand e.g. the design can be improved so that there are conical parts at both ends which will result in a radial expansion on both ends of the copper expander.

6.6 Alternative expander materials

Annealed copper is a favorable material, for some parts of the expander, due to the low yield strength. However, in a long term perspective, corrosion of the installed plugs may be a problem. The copper canisters in the KBS-3 concept are protected from groundwater by bentonite on all sides. In contrast, a copper plug in a borehole is more or less exposed to groundwater flow and bacterial activity dependent on the adjacent materials. At depth in a borehole, the main threat to a copper plug is expected to be sulfide, either supported by groundwater flow, or locally produced by sulfate reducing bacteria (SRB). Reaction between copper and sulfide takes in principle place instantly, and the magnitude of such corrosion will be dependent on the sulfide concentration and transport capacity of the groundwater, alternatively dependent on the access to sulfate and bacterial activity. It is consequently not possible to determine the level of this potential problem in a generic way. Geochemical modelling may be used to estimate the effect of groundwater sulfide.

Aluminum and stainless steel packers have been tested by e.g. NAGRA, but there are long term concerns for both materials. Aluminum is generally not stable in saline conditions and stainless steel may be attacked by pitting corrosion. Generally, titanium is highly resistant to general corrosion and pitting also in the sulfide environment. However, SRB are reported to promote pitting corrosion of ASTM grade 2 titanium by formation of titanium sulfide (Rao et al. 2005). Still, titanium is one of the interesting materials for better long term performance. Titanium ASTM grades 1 and 11 seem to be the most favorable grades with respect to installation, since they have yield strength not far from that of copper (Table 6-1).

Table 6-1. Typical properties for annealed metals, which may be used in expanders (Howatson et al. 1972).

Element	Young's modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)
Steel	211	80 –100	350
Titanium	120	100–225	246–370
Copper	130	70–120	210

7 Tests of components – bentonite plug

7.1 General

The bentonite plugs are an essential part of the "Sandwich-concept". Three types of test, directly related to the Sandwich-concept have been performed within this project:

- Erosion tests. The bentonite plugs are planned to be installed as packages that are lowered down in a water filled borehole. The standing water in the borehole will have to pass the annular gap between rock and bentonite which means that there will be an erosion of material.
- Swelling pressure and hydraulic conductivity tests. If coating (shellac) is used as an erosion protection there will be remaining impurities also after installation. The effect of these impurities on the swelling pressure and on the hydraulic conductivity have been investigated.
- Homogenization test. The homogenization of the bentonite after installation is important. A small scale test simulating a section of a borehole, L = 0.25 m, have been performed. The radial swelling pressure built up as function of the test time is continuously registered.

7.2 Materials

7.2.1 Bentonite

The material used for the bentonite plug tests was MX-80 bentonite from American Colloid Company.

7.2.2 Water

Hydraulic conductivity and erosion properties have been determined using water with a salinity of 1 % by weight (NaCl/CaCl 50/50). In addition, the erosion tests were also performed using tap water, simulating that the original borehole water had been exchanged before installation.

7.2.3 Shellac

Shellac is an organic resin harvested from the lac bug secretions. It is dissolved in ethanol to form the varnish that is used, i.e. it is not water soluble. Since the coating is not perfect any weakness or damage will lead to swelling of the bentonite, a local swelling will lead to increased water exposure and ultimately resulting in a fully saturated bentonite.

Shellac has been used in the erosion tests as a protecting shield during the installation phase. The coating material will, however, remain as an impurity and a few tests have been performed in order to test how this impurity will affect the swelling pressure and the hydraulic conductivity.

7.3 Erosion

7.3.1 General

One of the main problems when installing high density bentonite blocks in a water filled deep borehole is erosion during emplacement. All water standing in the borehole must pass the annular gap between the rock and the bentonite blocks resulting in a relatively high water flow (depending on the lowering rate) which will tear off and erode bentonite that will flow away with the water flowing out from the borehole.

7.3.2 Method

Bentonite blocks were manufactured and machined to correct dimensions in a lathe. The compaction pressure was 60 MPa for all blocks. The height of a single block was 50 mm. Two sets of five blocks with no coating were used, denoted Normal in the tables, and two sets of five blocks were lacquered with three layers of shellac, denoted Coated in the tables. The blocks were place in a flow rig simulating a section of a borehole, see Figure 7-1, with cones covering the end surfaces so that only the mantle surfaces of the bentonite blocks were exposed to the flowing water. Water was then flushed along the blocks for one hour with a speed of about 1 l/s. The gap between the wall and the block was 3 mm and strings with a diameter of 2 mm were inserted to center the block during the test.

The water flow was measured with a flowmeter that was read before and after the tests. To verify the flow rate, tests with bucket and watch were conducted. There was a small flow variation between the tests, and the results have been recalculated to a flow of 1 l/s. The variation of flow was due to the use of a centrifugal pump that was affected by the varying flow resistance and water level.

A flow rate of 1 l/s during 1 h corresponds to lowering bentonite blocks into a borehole with the diameter 80 mm (used in the test equipment) to a depth of 716 m. It is then assumed that all water standing in the borehole must pass the annular gap between the blocks and the rock surface. In order to compare the test results with a borehole with an inner diameter of 76 mm (standard SKB investigation boreholes) it was assumed that the water velocity in the annular gap should be the same. This means that the performed test simulates lowering of bentonite plugs to a depth of 794 m in 66 min. The figures used in the scoping calculations are presented in Table 7-1.

Tests have been performed using both tap water and a 1 % saline solution of 50/50 mix sodium and calcium chloride (by weight). Since it was not efficient to prepare 4 m^3 of saline solution to each of the tests with saline water, a recirculation system with sediment traps was used. The water circulated through a set of containers by means of centrifugal pumps. The containers were intended to sediment the bentonite from the water. For tap water this was not efficient. The test setup included 800 liters of water.

After having finished the test, the remaining clay was measured, dried and compared to the start values. In addition, samples of the water was taken every 3 minute and analyzed by weighing and drying to measure the amount of eroded material. For each 3 min period the eroded mass in water was calculated and multiplied with the flow volume, these masses were then summed up and compared to the initial dry mass. Since the water was recirculated this measurement can only be used to monitor the water and is not a value of eroded material.

Table 7-1. Conditions used for the scoping calculations. In the calculations the water velocity were set to the same value in the two boreholes.

	Test equipment	SKB borehole
Locked test parameters (bold)		
Diameter borehole, m	0.08	0.076
Simulated installation time, min	60	63
Flow rate, l/sec	1.0	0.9
Flow rate, m^3/sec	0.0010	0.00095
Calculated borehole data		
Volume borehole, m^3	3.60	3.60
Depth borehole, m	716	794
Bentonite blocks		
Diameter bentonite block, m	0.074	0.07
Length bentonite block, m	0.25	0.25
Exposed bentonite surface		
Area of annular gap, m^2	0.00073	0.00069
Velocity in annular gap, m/s	1.378	1.378

Figure 7-1. *Photo of blocks ready for installation. The blocks on the photo are coated with shellac.*

Figure 7-2. *Photo and sketch of the test rig.*

7.3.3 Test matrix

Test were made with bentonite blocks with an initial water content of 13 %. The blocks were either untreated (Normal) or painted with Shellac (Coated). The complete test matrix is provided in Table 7-2 together with the initial average dry density of each test setup. There was a slightly difference in the average density between the tests but this is considered to only marginally affect the test results.

Table 7-2. Initial dry density.

	Normal	Coated
Tap water	1787 kg/m³	1795 kg/m³
Saline water	1784 kg/m³	1796 kg/m³

7.3.4 Test results

In the two tests performed with uncoated blocks, see photos provided in Figure 7-3, the erosion was localized to the interface cone/block at the bottom of the test setup i.e. at the water inlet side, where vortexes probably have been formed. The uncoated blocks were very sensitive for the water salinity. The amount of eroded material increased from 10.3 % of the installed mass (tap water), to 43.5 % (1 % salinity).

In the tests with coated blocks, the mass loss seemed to mainly be localized to where the coating has been cracked or damaged. These blocks did not show any sensitivity for the water salinity. In fact the determined mass loss was lower for the test with saline water. This is, however, judged to depend on the randomly cracking of the shellac, see photos in Figure 7-3.

The mass loss for all tests is summarized in Table 7-3. Another way to evaluate the results is to calculate the resulting dry density from the remaining dry mass after each test and the volume of the simulated borehole volume, see Table 7-4.

Table 7-3. Test results. Mass loss from mass measurements recalculated to a flow of 1 l/s.

	Normal	Coated
Tap water	10.3 %	2.7 %
Saline water	43.5 %	0.3 %

Table 7-4. Resulting dry density calculated from the dry mass at the end of the tests and the final diameter of the borehole d = 80 mm. The original density of the bentonite blocks was between 1784–1796 kg/m³, see Table 7.2.

	Normal	Coated
Tap water	1371 kg/m³	1494 kg/m³
Saline water	862 kg/m³	1532 kg/m³

The water sampling procedure included that a water sample of about 0.9 l was taken every third minute from the outflowing water during the test time. The sample was weighed and dried and the amount of bentonite in the water was determined. The determined bentonite mass was compensated for the salt content of the water that was evaporated. The results from the tests performed with tap water were logical, see Figure 7-4, showing an increase of the erosion rate with time for the uncoated specimen, but the tests performed with saline water were judged to not be reliable, probably depending on that the same water was used for both tests. It was believed that the bentonite should settle in the large vessels, see photo provided in Figure 7-2, but this settlement was obviously not enough and the results were judged to be unreliable.

Figure 7-3. *Photos of the four specimens after test termination. Upper left: Uncoated blocks exposed to tap water. Upper right: Uncoated blocks exposed to saline water. Lower left: Coated blocks exposed to tap water. Lower right: Coated blocks exposed to saline water.*

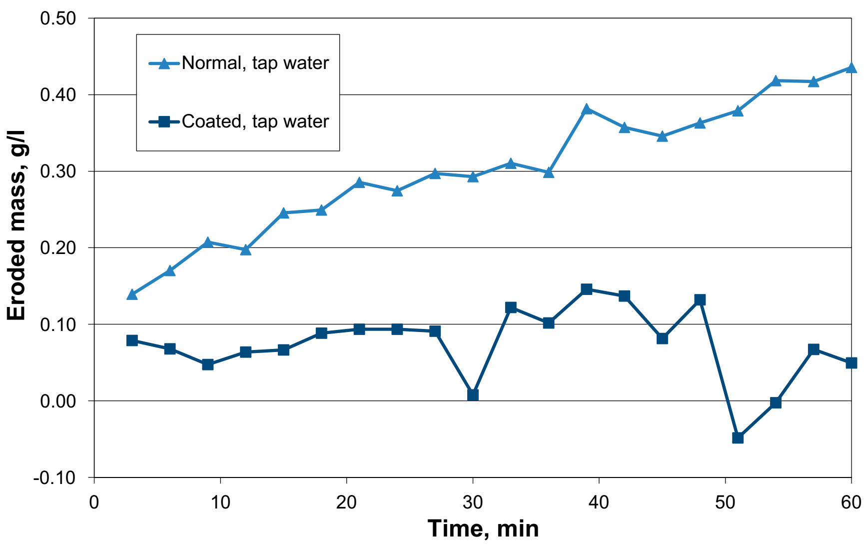


Figure 7-4. *Determined bentonite mass measured in the water as a function of test time for the two tests performed with tap water.*

7.3.5 Discussion

The erosion of the bentonite blocks during installation is an important property if the installation is made by lowering the bentonite packages down in a water filled borehole. From the performed tests the following conclusions can be drawn:

- Installation of uncoated bentonite blocks to great depth, several hundred meters, will result in high erosion. This will result in lower installed bentonite density than intended. This loss of material has to be considered at the planning and design of a sealing.
- The use of coating on the exposed bentonite surfaces will considerably decrease the bentonite erosion. The tests showed that it is possible to install bentonite to a depth of 800 meters in a water filled borehole with only small losses of bentonite by erosion.
- If installing uncoated bentonite blocks in a borehole it will be favorable to change the water to tap water. This action will strongly decrease the erosion rate of the bentonite.
- The influence of shellac on the long term properties of the bentonite is still unclear. The coated bentonite blocks in the performed tests had a shellac content of about 0.2 %. This is in the same range as the natural organic content of MX-80 and about half of the content in several other commercial bentonites e.g. in Asha bentonite.

7.4 Swelling pressure and hydraulic conductivity

7.4.1 General

The use of shellac (coating) to protect the bentonite from large erosion during installation means that a thin layer of organic material will remain on the surface of the bentonite plug after installation. The coating material, shellac, is not supposed to influence the swelling and sealing properties of the bentonite but tests on this was necessary. By comparing results from specimens with and without initial layers of shellac any influence could be studied. For comparison, the results could also be compared to other studies on swelling pressure and hydraulic conductivity of MX-80 bentonite e.g. the models presented by Börgesson et al. (1995) and Åkesson et al. (2010).

7.4.2 Test equipment and test procedure

The equipment used for the tests is shown in Figure 7-5. The height and diameter of the cylindrical specimens were 10–20 mm and 35–50 mm, respectively.

The specimens were compacted from powder to the predetermined density in a compaction device. Before the specimens were placed into the test cell, layers with shellac were applied to all surfaces of the specimens by a brush. Sintered steel filters were put under and on top of the specimens.

A solution with a salinity of 1 % by weight (according to Section 7.2.2) was applied to the specimens during saturation and the swelling pressure was measured continuously. After saturation, i.e. when the swelling pressure was considered constant with time, a water pressure of 250–300 kPa was applied from the bottom of the specimens to determine the hydraulic conductivity. The water pressure was applied with a pressure/volume controller (GDS). The water content and density were determined after the dismantling and the dry density and degree of saturation were calculated according to Section 3.3.

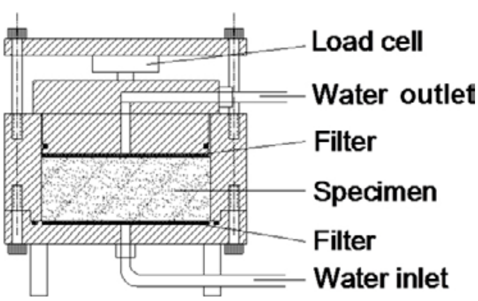


Figure 7-5. A sketch of the test cell used for the determination of swelling pressure and hydraulic conductivity.

7.4.3 Test plan and evaluation of data

Swelling pressure and hydraulic conductivity were determined mainly at low densities corresponding to the conditions after swelling of a block installed in a borehole and also at densities after erosion.

The evaluation of hydraulic conductivity was made when the outflow of water was considered constant with time and the evaluation was made with an accumulated flow and by Darcy's law according to Equation 4-2.

7.4.4 Test results

The test results are shown in Figure 7-6 and Table 7-5. Two different test series were run. In the first series (PK1–PK4) specimens with the diameter and height 35 mm and 10 mm, respectively, were used. Some problems were seen on one of the specimens with shellac, PK3, already at start but was still completed. At dismantling of this specimen shellac was found on the filters and since it was assumed to have clogged the filters the results from this specific specimen are not regarded as representative and are thus not further plotted and interpreted. An improved device was used for the second series where it was possible to flush the filters above and under the specimens during the tests. In the improved device larger specimens were tested having the diameter and height 50 mm and 20 mm, respectively. The swelling pressure was measured before the application of water pressure and the hydraulic conductivity was calculated from an accumulated flow during the testing time.

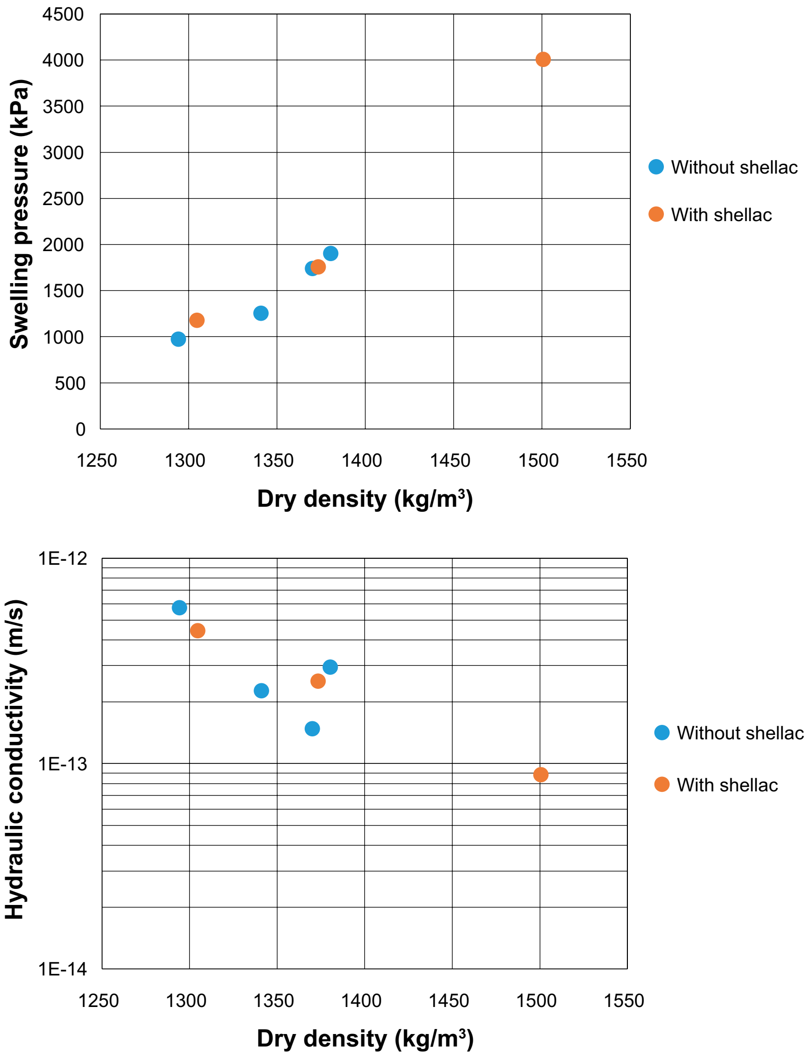


Figure 7-6. *Swelling pressure (upper) and hydraulic conductivity (lower) as a function of dry density.*

Table 7-5. Test results from swelling pressure and hydraulic conductivity tests of bentonite specimens with and without shellac. The gradient was 2 500 m/m for PK1–PK4 and 1 530 for PK5–PK8.

Sample ID	Material	Shellac	Water content %	Dry density kg/m³	Degree of saturation %	Swelling pressure kPa	Hydraulic conductivity m/s
PK1	MX-80		39.0	1 341	101	1 253	2.3×10^{-13}
PK2	MX-80		37.7	1 370	102	1 741	1.5×10^{-13}
PK3[1]	MX-80	Yes	36.7	1 387	101	475	0.20×10^{-13}
PK4	MX-80	Yes	29.7	1 501	97	4 006	0.88×10^{-13}
PK5	MX-80		40.1	1 294	97	976	5.8×10^{-13}
PK6	MX-80		36.3	1 380	100	1 903	3.0×10^{-13}
PK7	MX-80	Yes	39.7	1 305	97	1 179	4.4×10^{-13}
PK8	MX-80	Yes	36.8	1 373	100	1 756	2.5×10^{-13}

[1] Some problems with this specimen were seen.

7.4.5 Discussion

The use of coating on the exposed bentonite surfaces was found to decrease the erosion of bentonite blocks exposed to water flow. The use of shellac as coating material surrounding the bentonite was suggested in Section 7.3 but the influence of this on the swelling pressure and hydraulic conductivity of the bentonite remained to be tested.

Swelling pressure and hydraulic conductivity were determined on specimens with initial layers of shellac and good agreement between the results from the specimens with shellac and without shellac was observed, see Figure 7-6.

The average density of the bentonite after installation and with its final volume are planned to be approximately 1 500 kg/m³ and the swelling pressure and hydraulic conductivity at this density are thus the most interesting. In the test series the main part of the tests were run on specimens with lower density but in Figure 7-7 the results are shown with models of MX-80 presented by Börgesson et al. (1995) and Åkesson et al. (2010) from which swelling pressure and hydraulic conductivities at the actual density can be estimated.

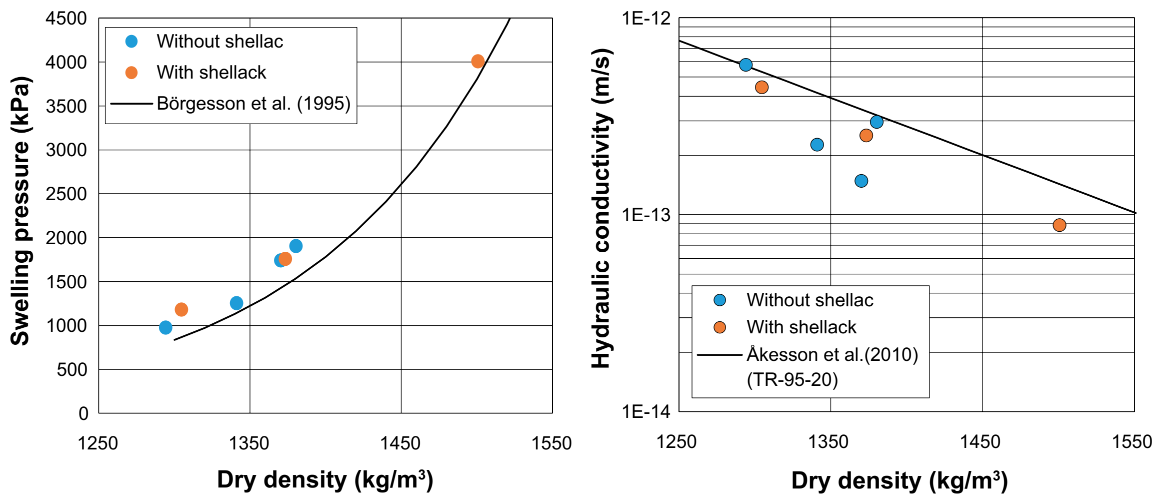


Figure 7-7. Test results from Figure 7-6 with models of MX-80 presented by Börgesson et al. (1995) and Åkesson et al. (2010).

7.5 Homogenization – demonstration

7.5.1 General

The homogenization of a sealing section has been demonstrated in a laboratory test. The main objectives with the test have been to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite installed in a rock section.

The test was started in October 2016. At the time for this report, the bentonite has not homogenized completely and the test is therefore still running. The results from the test is planned to be reported in the final project report.

7.5.2 Test equipment

In conjunction with earlier investigations regarding borehole sealing a special designed test equipment was designed and manufactured (Pusch and Ramqvist 2006). In this equipment the present reference design including a perforated copper tube was tested. The new test represents bentonite installed as packages that have been lowered down in water filled borehole according to the Sandwich-concept described in Chapter 2.

The test equipment simulates a borehole section with a length of 250 mm and an inner diameter of 80 mm, Figure 7-8. On the borehole periphery two filter mats, each with a height of 115 mm, are positioned. A length of 30 mm at the mid-height of the simulated borehole is thus without filter. This section simulates a rock section without any cracks and is planned to be used to determine the hydraulic conductivity of the homogenized bentonite. This can be made by applying different pressures in the filter mats above and below and by that achieve a pressure gradient over the 30 mm long bentonite section.

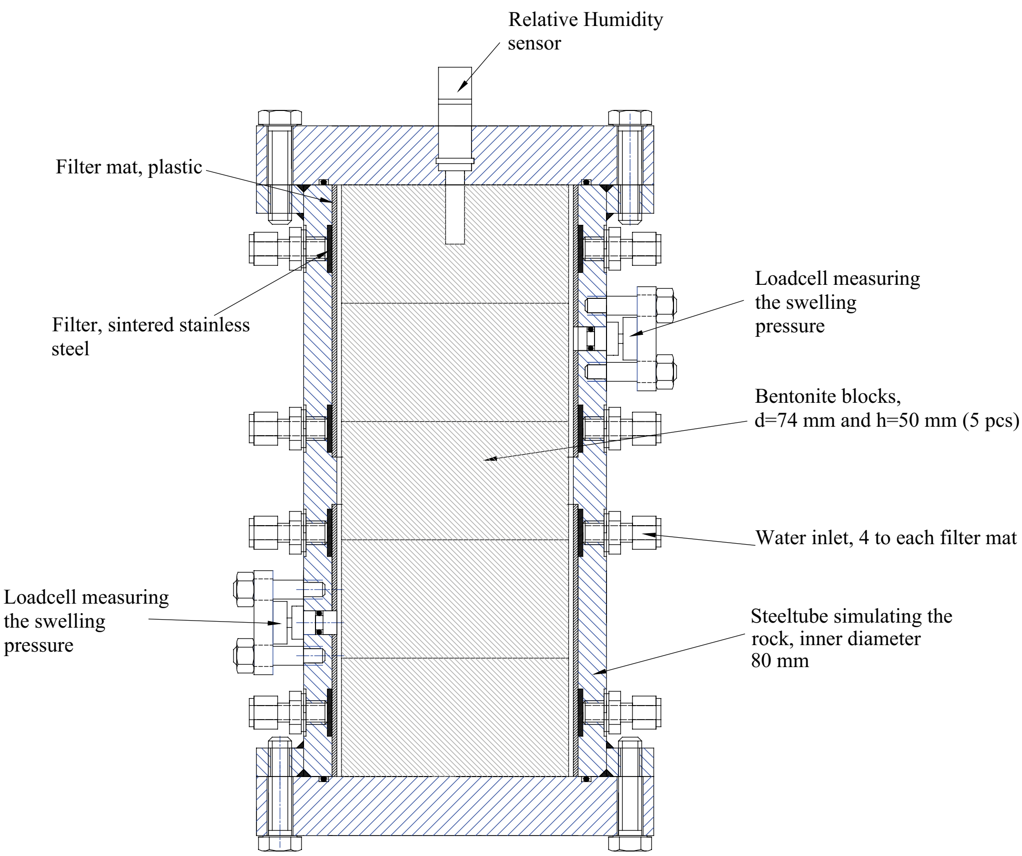


Figure 7-8. *Schematic drawing showing the test equipment simulating a section of a borehole that has been filled with dense bentonite plugs.*

Two radial pistons are used to register the swelling pressure built up. At the middle of the upper lid, a sensor measuring the relative humidity in the midpoint of the uppermost bentonite plug is installed. The sensor in placed in a vessel with a filter at the top (part of the upper lid). This sensor is used as an indicator regarding the status of the water saturation of the bentonite.

7.5.3 Test procedure

Bentonite plugs were compacted to a bulk density of 2 100 kg/m^3 and with a water content of 12.5 %. The plugs had a diameter of 74 mm and a height of 50 mm. The dry density after installation is calculated to approximately 1 560 kg/m^3 which is a little bit higher than the density achieved in the erosion tests (1 494–1 532 kg/m^3 for the coated specimens). A central hole was carefully drilled in the uppermost plug for the vessel containing the relative humidity sensor. The five bentonite plugs were thereafter piled on top of each other in the center of the simulated borehole.

The borehole section was filled up with water via the lower inlets while the uppermost were used for de-airing. The water used had a salinity of 1 % by weight (50/50 Na/Ca). After five days, when it was estimated that the swelling bentonite had sealed possible leakage ways to the relative humidity sensor (free water hitting the sensor will destroy it), the sensor was pushed into the vessel and a water pressure of 100 kPa was applied in the filter mats. The water uptake is continuously measured during the test period.

7.5.4 Test results

When writing this report, the homogenization test is still running. The registered pressure and relative humidity as a function of time is provided in the graph in Figure 7-9.

The registered swelling pressure after 66 days test is between 2 and 4.2 MPa i.e. the registered total pressure minus the applied pore pressure (100 kPa). There is thus a rather large difference between the upper sensor (2 MPa) and the lower (4.2 MPa). This difference is judged to decrease with time and as shown in the graph the pressure registered by the upper sensor (black line) is still clearly increasing. The registered relative humidity at time for installation was just above 50 % but increased fast to 90 % and has then increased slowly with time.

The injected water volume since test start is continuously measured, Figure 7-10. Approximately 0.2 liters were injected at test start to fill up all empty voids and filter mats. The water uptake by the bentonite has then continued during the test time but seems to have more or less stopped after about 60 days. The total water volume needed to saturate the bentonite in the locked volume was before test calculated to 0.215 l. The difference in injected volume and the calculated depends on the volumes of tubes and filter mats.

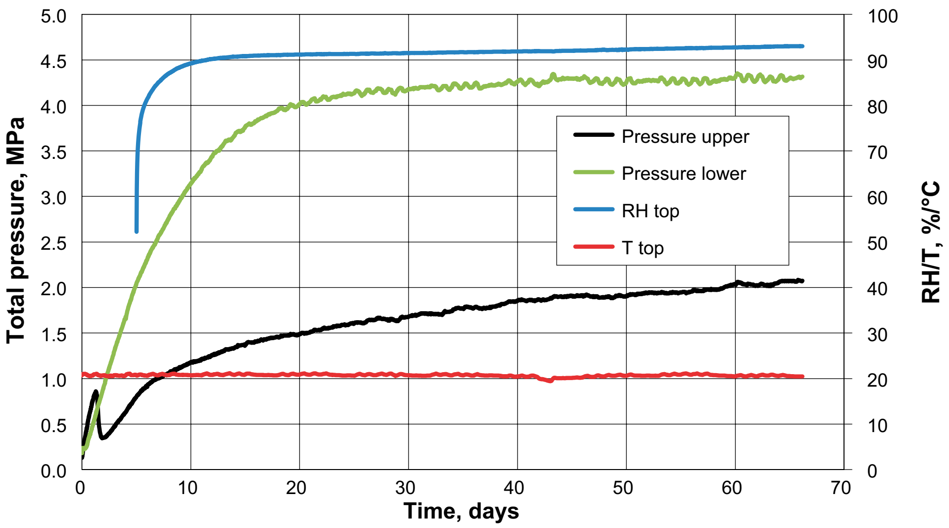


Figure 7-9. *Graph showing the pressure built up and the relative humidity plotted versus time for the homogenization test.*

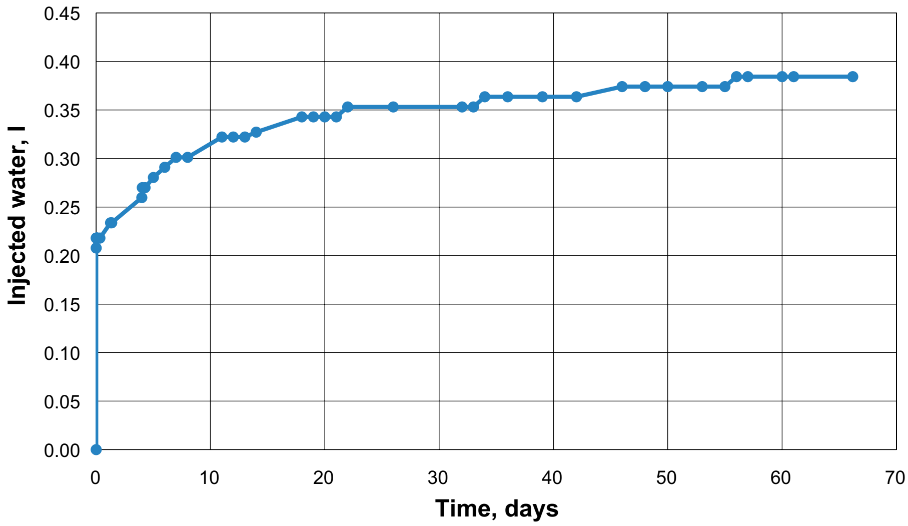


Figure 7-10. *Injected water volume plotted versus time.*

7.5.5 Discussion

The main objectives with the test have been to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite installed in a rock section. The registered swelling pressure after 66 days test is between 2 and 4.2 MPa which is a little bit lower than the expected (3–7 MPa). The homogenization is, however, still proceeding and the registered swelling pressures increasing.

This test and the Mockup test described in Chapter 8 are considered to give important information regarding the properties of an installed bentonite section in a borehole.

7.6 Comments and discussion

The bentonite plugs are an essential part of the "Sandwich-concept". Three types of test, directly related to the Sandwich-concept have been performed within this project:

- Erosion tests. The bentonite plugs are planned to be installed as packages that are lowered down in a water filled borehole. The standing water in the borehole will have to pass the annular gap between rock and bentonite which means that there will be an erosion of material.
- Swelling pressure and hydraulic conductivity tests. If coating (shellac) is used as an erosion protection there will be remaining impurities also after installation. The effect of these impurities on the swelling pressure and on the hydraulic conductivity have been investigated.
- Homogenization test. The homogenization of the bentonite after installation is important. A small scale test simulating a section of a borehole, L = 0.25 m, have been installed. The radial swelling pressure built up as function of the test time is continuously registered. The results will be reported later.

From the results the following conclusions can be drawn:

- Installation of uncoated bentonite blocks to large depth, several hundred meters, will result in high erosion. This will result in lower installed bentonite density than intended which will affect the hydraulic conductivity of the sealing.
- The use of coating on the exposed bentonite surfaces will considerably decrease the bentonite erosion. The tests showed that it is possible to install bentonite to a depth of 800 meters in a water filled borehole with only small losses of bentonite by erosion.
- If installing uncoated bentonite blocks in a borehole it will be favorable to change the water to tap water. This action will strongly decrease the erosion rate of the bentonite.

- The influence of shellac on the long term properties of the bentonite is still unclear. The coated bentonite blocks in the performed tests had a shellac content of about 0.2 %. This is in the same range as the natural organic content of MX-80 and about half of the content in several other commercial bentonites e.g. in Asha bentonite.
- Swelling pressure and hydraulic conductivity were determined on four specimens with initial layers of shellac. Good agreement between the results from the specimens with shellac and the results from specimens without shellac was observed.
- Additional tests on bentonite with shellac are suggested to increase the statistics.

8 Mockup test

8.1 General

After having tested and designed all components included in the Sandwich design it was decided to perform a so called Mockup test in large scale. The main objectives with the test are:

- To verify and to demonstrate the function of all components and also of the concept itself.
- To study the homogenization of the bentonite sealing part of the concept.
- To study the interaction between the different components after installation.

The test was installed in the beginning of December 2016 and is still running. The final results of the test are planned to be presented in the final report for the project.

8.2 Test equipment

The simulated borehole section has a total length of 4 000 mm. The inner diameter of the steel tubes is 83.7 mm. The section with bentonite installed is covered with a filter in the periphery with a thickness of 2 mm which means that the inner diameter in this section is 79.7 mm. The filters are necessary to ensure saturation of the bentonite. Each of the filters are connected to separate water inlets and outlets which make it possible to feed the borehole with water and also to circulate water in order to get rid of trapped air. In the sections without filter, it is possible to apply a point inflow in order to fill also these sections with water. The Plexiglas tubes have an inner diameter of 80 mm. There are thus small variations in the simulated borehole diameter but they are all close to 76 mm which is the most common size of the SKB investigation boreholes. The schematic drawing provided in Figure 8-1, shows the principle test layout and the position of the different components.

The four Plexiglas sections have a height of 100 mm. These sections are positioned at the two sections with gravel fillings and at the two sections with concrete filling. There are thus no Plexiglas tube at the bentonite section since it was judged that there was a risk that the swelling pressure could destroy them. The homogenization of the bentonite sealing section is monitored with three radial pressure sensors. In addition one pressure sensor is positioned at the top of the simulated borehole, measuring the axial pressure in the borehole filling.

8.3 Seal and closure components

8.3.1 Sand filling

It was decided to use "Fogsand < 2 mm" as the sand component. This material has the lowest compressibility and can be installed in deep borehole to relatively high densities.

8.3.2 Bentonite plugs

Bentonite plugs were compacted to a bulk density of 2 100 kg/m^3 and with a water content of 10 %. The plugs had a diameter of 70 mm (turned down to the desired diameter) and a height of 50 mm. The bentonite plugs have a central hole with a diameter of 7 mm. By threading the plugs on a central rod with a diameter of 6 mm, two packages, each with a length of 0.6 meter were put together, Figure 8-2. Nuts were positioned in recesses machined out from the end surfaces of the outermost plugs.

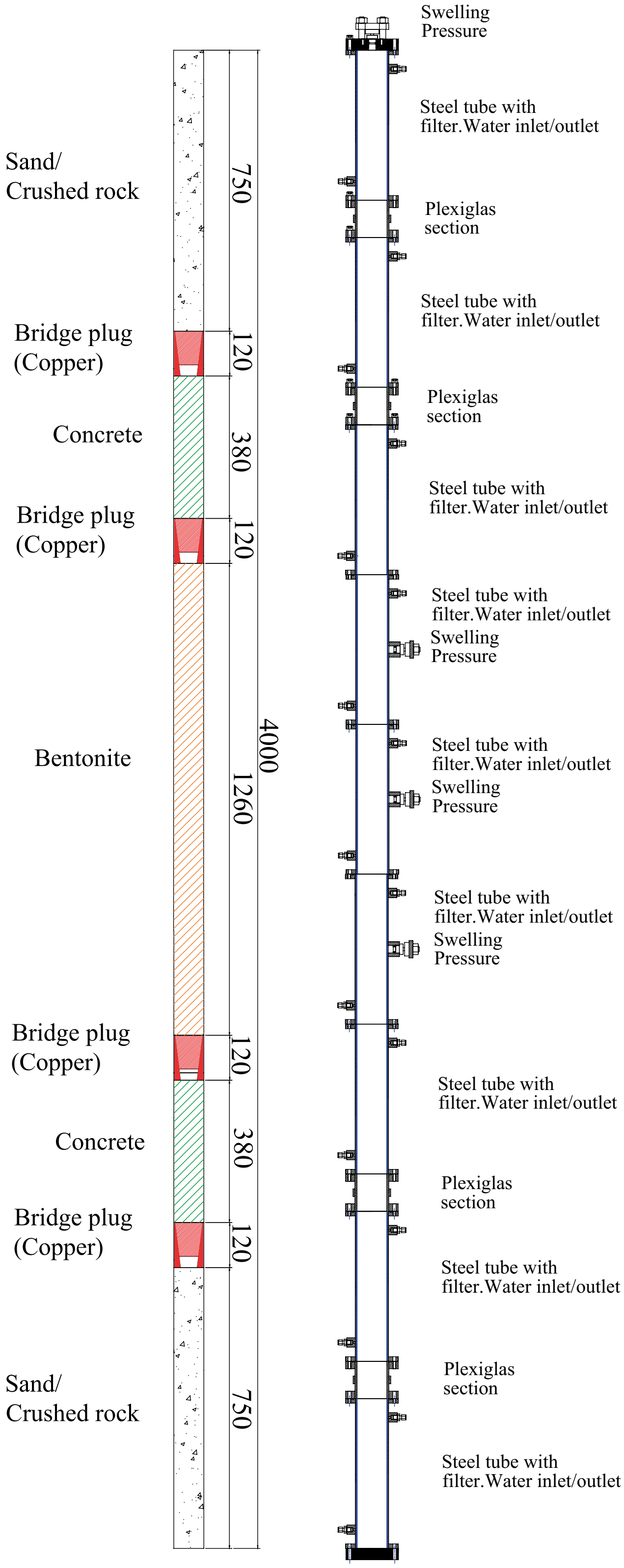


Figure 8-1. *Schematic drawing showing the test equipment simulating a section of a borehole. The different components included in the Sandwich-concept are all included in the test, see description on the left side of the drawing.*

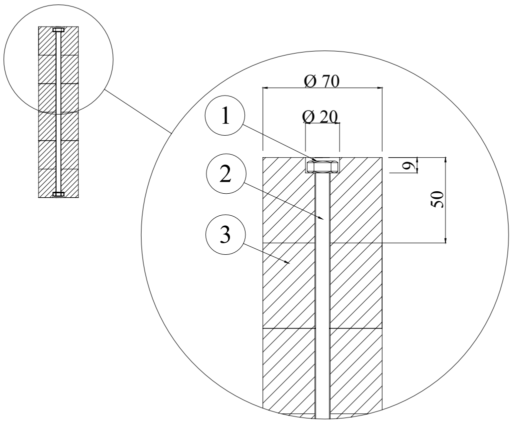


Figure 8-2. *Schematic drawing showing a bentonite plug package. 1 = Nut, 2 = Rod, 3 = Bentonite blocks.*

8.3.3 Quartz based concrete

The quartz based concrete was installed using the recipe provided in Table 5-1. The installation was made manually during the mounting of the equipment i.e. no dump bailer was used.

8.3.4 Bridge plug made of copper

The copper expanders of the latest version, type III in Figure 6-1, were installed in the Mockup test.

8.4 Installation and test start

The simulated borehole was built up step by step by adding new tubes. The different sealing components were also installed subsequently i.e. the installation was not made as it is planned to be done in the full scale. All installations were made without any water present in the borehole.

8.4.1 Sand filling

Two sections were filled with sand, one at the top and one at the bottom. The sand was poured into the tube and was then vibrated by shaking and knocking on the tube. As mentioned earlier, this sand is very sensitive for a small vibration but after this initial settling, the compressibility is very low.

Figure 8-3 shows a photo of the upmost surface of the sand section installed at the top (left photo) and also a close-up taken through one of the Plexiglas sections (right photo). The close-up was taken after having filled up the simulated borehole with water.

Figure 8-3. *Left: The top of the uppermost sand section. Right: Close-up of the lower sand filled section. The photo is taken through one of the Plexiglas sections.*

The achieved bulk density of the sand filling was calculated to 1 484 kg/m^3 for the lower section and to 1 433 kg/m^3 for the upper section. The density achieved for the lower section is in the same range as expected while the density at the upper section is somewhat lower, probably depending on the fact that it was more difficult to manually vibrate this section during the installation. The water content of the installed sand was 2.2 %.

8.4.2 Bridge plug made of copper

In total four copper expanders were installed in the Mockup test i.e. one expander in every transition zone between two different materials, see Figure 8-1. The expanders were installed by lowering them into the borehole, standing on the material installed below, Figure 8-4. A hydraulic piston was used to compress the expanders, Figure 8-5. The flanges on the steel tubes were used to mount a temporary anvil, see Figure 8-5, which after compression of the expander could be removed again.

Figure 8-4. *Installation of a copper expander in the simulated borehole.*

Figure 8-5. *A hydraulic piston was used to compress the copper expander.*

The copper expanders have an outer diameter of 80 mm. They were installed in steel tube sections with an inner diameter of 83.7 mm. The results from the laboratory test made on this design of an expander (III), showed that an axial force of below 10 kN should be needed to compress and expand the copper so that it would seal against the simulated borehole wall, see results from the test in Section 6.4.3. An axial force of 15 kN was used for the installations of the four expanders. After having reached 10 kN no further compression could be seen. The axial compression/displacement were for all expanders determined to between 14 and 16 mm cf. the results from the laboratory tests provided in Figure 6-7.

8.4.3 Quartz based concrete

The quartz based concrete was mixed just before installation in the simulated borehole. The concrete was installed by hand in the borehole. The concrete is not fluent and it was not possible to pour it into the borehole. After installation, the concrete was left for curing for about 16 hours before the next sealing component was installed. After this time the concrete surface was hard and stable.

The achieved bulk density of the concrete was calculated to 1 960 kg/m^3 for the lower section and to 1 954 kg/m^3 for the upper section. These figures are very close to the density determined in the laboratory tests, see Section 5.3.

Figure 8-6 shows the upper surface of one of the concrete sections after curing (left) and also a close-up of the concrete seen through a Plexiglas section (right).

8.4.4 Bentonite plugs

The bentonite plugs were installed as two packages, see Figure 8-2. The packages have a length of 600 and 650 mm respectively. The packages were lowered down in the simulated borehole one at a time, Figure 8-7 (left photo). The outer diameter of the bentonite plugs was 70 mm and the simulated borehole has in this section a diameter of 79.7 mm (the steel tube has a diameter of 83.7 mm but is covered on the periphery with a filter with a thickness of 2 mm).

The resulting saturated density of the bentonite is calculated to be 1 936 kg/m^3 (dry density 1 455 kg/m^3). This is somewhat lower than intended. It is estimated that the bentonite plugs can have the same diameter (70 mm) also if they are installed in a borehole with a diameter of 76 mm and this would result in a saturated density of 2 035 kg/m^3 (dry density 1 635 kg/m^3). The bentonite installed in the simulated borehole is expected to result in a swelling pressure of about 2.5 MPa and a hydraulic conductivity of 2×10^{-13} m/s.

The radial swelling pressure is continuously registered at three positions, see photo in Figure 8-7. In addition one sensor is measuring the axial pressure at the top of the test equipment.

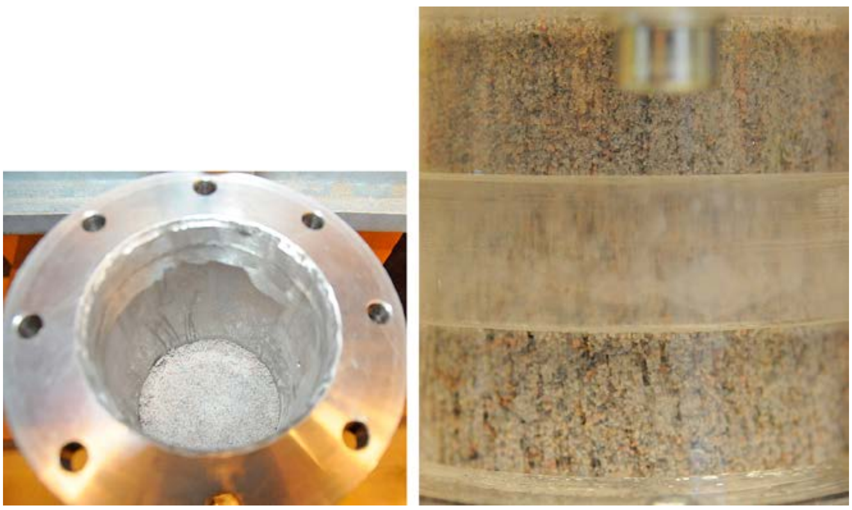


Figure 8-6. *Left: Top of the quartz based concrete section after about one day curing. Right: Close-up of the quartz based concrete through one of the Plexiglas sections.*

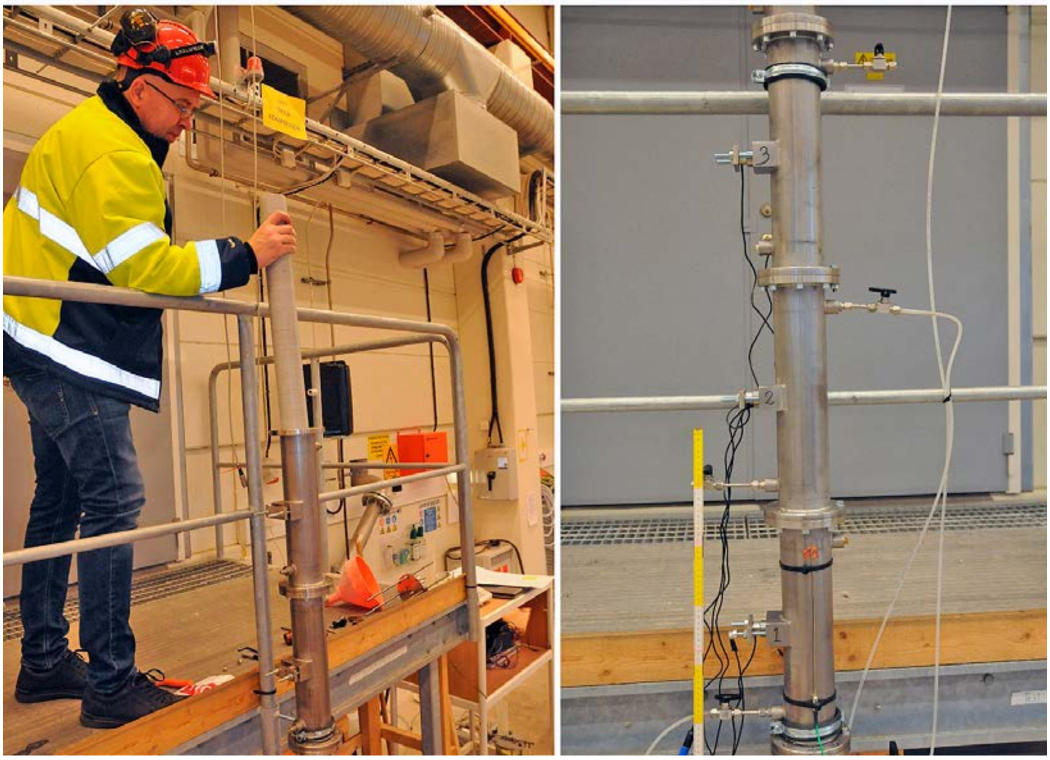


Figure 8-7. *Left: Installation of one of the bentonite packages. Right: Three sensors (left side of the tube) are registering the radial swelling pressure from the bentonite section.*

Figure 8-8. *Overview of the test setup after having finished the installation. The vessel on the floor to the right contains the pressurized water.*

Water filling and test start

After having finished the installation and started the registration of data, the borehole was filled up with water from the bottom and upwards. In total about 5.3 liters of water was injected. After having completed the water filling, a water pressure of 100 kPa was applied. The water consumption will continuously be measure during the test time.

An overview of the test setup is shown on the photo in Figure 8-8. The total height is 4 meters. The vessel standing on the floor on the right side of the test equipment is used to pressurize the water.

8.5 Results

The Mockup test was installed and started between the fifth and seventh December 2016. No registered data was available at the time for the writing of this report. The test is planned to be terminated during the spring 2017 and the results reported in the final report of this project.

9 Analysis of the friction between components and the borehole

9.1 General

The sealing of boreholes will essentially entail the emplacement of compacted bentonite in limited sections of the borehole which are enclosed by intact rock. Remaining sections will be filled with some granular soil, from here on denoted sand. The swelling properties of the bentonite, the compressibility of sand and very long sections filled with sand could potentially imply that the dry density of the bentonite decreases with time during and after the saturation phase. The interfaces between the bentonite and the sand will be filled with concrete, but these sections can be ignored since they are assumed to be dissolved in the long perspective. The swelling and the compression will be counteracted by frictional forces along the rock wall and this will limit the displacements in the borehole.

The objective of this work was to develop a tool for calculation of mechanical equilibration of borehole sealing materials due to swelling. This tool was used to assess the risk of reaching unacceptably low dry density of the bentonite.

9.2 Model description

The model essentially consists of expressions for the bentonite and the sand, respectively. These are derived separately from stress distributions, which are defined as functions of the axial position (defined in opposite directions, see Figure 9-1), and the boundary stress (which is common for the two materials). These distributions are subsequently converted to dry density distributions, which also are defined as functions of the position and the boundary stress. The integrals of these distributions should be equal to the initial products of the dry density and the length for each material, in order to fulfill the conservation of mass. These conditions can be used to define the final lengths as functions of the boundary stress, although there are no analytic explicit expressions for this. Finally, the sum of these two length should be equal to the sum of the initial lengths. Together with the conditions of a common boundary stress, this means that an equilibrium stress can be calculated.

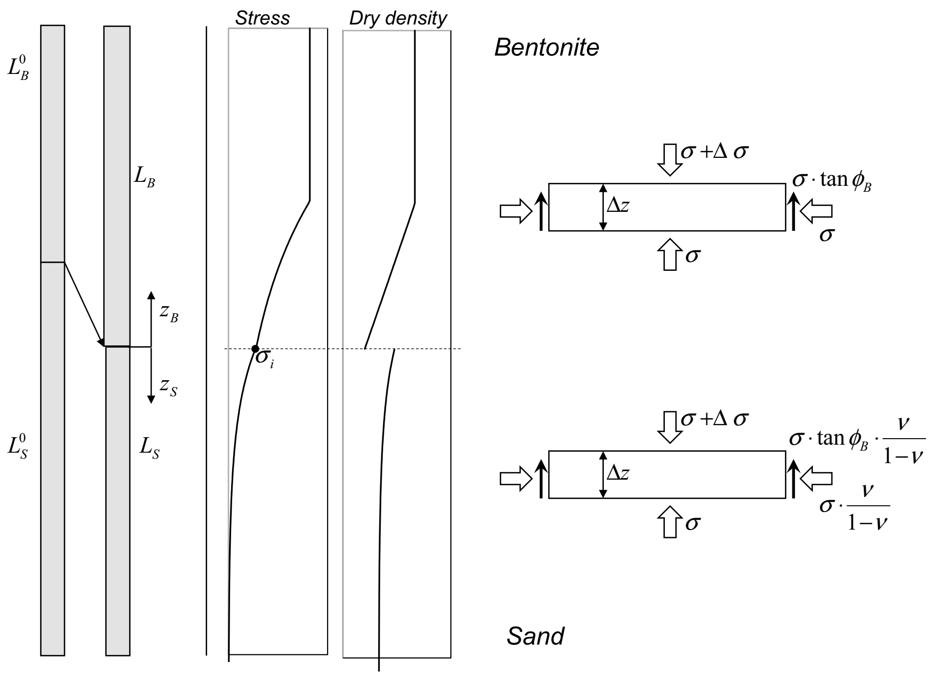


Figure 9-1. *Borehole filling materials, bentonite and sand: initial and final lengths (left), distributions of axial stress and dry density (center) and stress balance of thin elements (right).*

The swelling pressure (p_{swell}) is a crucial property of the bentonite which can be defined as a function of the dry density (ρ_d). Such a function was adopted from retention data by Åkesson et al. (2010) on the following form:

$$\log^{10}(p_{swell}) = c_2 \cdot \rho_d{}^2 + c_1 \cdot \rho_d + c_0 \qquad \text{(Eq 9-1)}$$

with the following coefficients (p_{swell} in kPa): $c_0 = -1.74$; $c_1 = 4.12 \times 10^{-3}$; $c_2 = -3.94 \times 10^{-7}$.

The compressive property of the sand is also of major importance. A function for the strain was adopted on the following form:

$$\varepsilon(\sigma) = m_2 \cdot \sigma + \frac{m_1 - m_2}{m_3}\left[1 - \exp(-m_3 \cdot \sigma)\right] \qquad \text{(Eq 9-2)}$$

with the following coefficients (σ in kPa): $m_1 = 4 \times 10^{-5}$; $m_2 = 8 \times 10^{-6}$; $m_3 = 3 \times 10^{-3}$ (see also next section).

The stress distributions were derived from force balances of thin elements of the borehole fillings. These were based on the assumption that the frictional force on the circumference is proportional to the axial stress, and also that this is related to the gradient of the axial stress. This implies a differential equation which yield an exponential stress distribution with a defined boundary value (see for instance Åkesson et al. 2010). For the bentonite, this should however not exceed the swelling pressure for the initial dry density (ρ_B^0), and this was therefore defined as a minimum in the following way:

$$\sigma_B(z_B, \sigma_i) = \min\left[\sigma_i \cdot \exp\left(\frac{2 \cdot \tan\phi_B \cdot z_B}{r}\right), p_{swell}(\rho_B^0)\right] \qquad \text{(Eq 9-3)}$$

were σ_B is the axial stress in the bentonite at the z_B coordinate; σ_i is the boundary stress, r is the radius of the borehole and ϕ_B is the friction angle for the bentonite-rock contact. It can be noted that this is based on the assumption that the swelling pressure is isotropic.

The corresponding distribution for the sand was based on the assumption that the sand can be characterized with a Poisson's ratio (ν):

$$\sigma_S(z_S, \sigma_i) = \sigma_i \cdot \exp\left(-\frac{2 \cdot \tan\phi_S \cdot z_S}{r} \cdot \frac{\nu}{1-\nu}\right) \qquad \text{(Eq 9-4)}$$

were σ_S is the axial stress in the sand at the z_S coordinate; and ϕ_S is the friction angle for the sand-rock contact.

The conversion of the stress distribution to a density distribution was based on an inverse function to the swelling pressure curve (Equation 9-1):

$$\rho_B(z_B, \sigma_i) = \rho_d(\sigma_B(z_B, \sigma_i)) \qquad \text{(Eq 9-5)}$$

For the sand, the corresponding conversion was based on the strain function (9-2), and the initial sand dry density (ρ_S^0):

$$\rho_S(z_S, \sigma_i) = \frac{\rho_S^0}{1 - \varepsilon\left[\sigma_S(z_S, \sigma_i)\right]} \qquad \text{(Eq 9-6)}$$

The conservation of mass for each material was fulfilled with the following equations:

$$L_B^0 \cdot \rho_B^0 = \int_0^{L_B} \rho_B(z_B, \sigma_i)\, dz_B \qquad \text{(Eq 9-7)}$$

$$L_S^0 \cdot \rho_S^0 = \int_0^{L_S} \rho_S(z_S, \sigma_i)\, dz_S \qquad \text{(Eq 9-8)}$$

where $L_B{}^0$ and $L_S{}^0$ are the initial length of the bentonite and the sand, respectively, and L_B and L_S are the corresponding final lengths. These conditions were used to define the final lengths as functions of the boundary stress: $L_B(\sigma i)$ and $L_S(\sigma i)$. These lengths were finally used to calculate an equilibrium stress (σ_{Eq}) for the system:

$$L_B(\sigma_{Eq}) + L_S(\sigma_{Eq}) = L_B^0 + L_S^0 \qquad \text{(Eq 9-9)}$$

The σ_{Eq}-quantity can be used for a first assessment of the influence of the mechanical equilibration. A more crucial quantity is the axial stress at the outer boundary of the bentonite, denoted $\sigma_F = \sigma_B[L_B(\sigma_{Eq}), \sigma_{Eq}]$.

9.3 Friction effects in sand fillings

The equations for the sand (i.e. Equations 9-2, 9-4, 9-6 and 9-8), were analyzed separately and compared with experimental results, in order to adopt parameter values and to tentatively validate the description of frictions effects for this material.

The total strain was calculated as:

$$\varepsilon_F(\sigma_i) = \frac{L_S^0 - L_S(\sigma_i)}{L_S^0} \qquad \text{(Eq 9-10)}$$

This was used to mimic the compression tests performed on “fog sand” in the current project. The diameter of the oedometers used in these test was 50 mm, and two different sample heights (40 and 200 mm) was investigated. The strain function (Equation 9-2) was adopted from these experimental results and the friction angle was fitted to a value of 25°. A value of 0.25 was used for the Poisson’s ratio, which was supported by ranges presented by Das (1997). The agreement between experimental and model results is shown in Figure 9-2.

The fraction of the counteracting stress which is caused by the frictional forces was calculated as:

$$r_F(\sigma_i) = \frac{\sigma_i - \sigma_S[L_S(\sigma_i)]}{\sigma_i} \qquad \text{(Eq 9-11)}$$

This was used to mimic a compilation of experimental data for different height-diameter ratios found in the literature (Sällfors and Andréasson 1986). The diameter was set to 83 mm. A fairly good agreement could be obtained for a friction angle of 25° and a Poisson’s ratio of 0.25 (Figure 9-3).

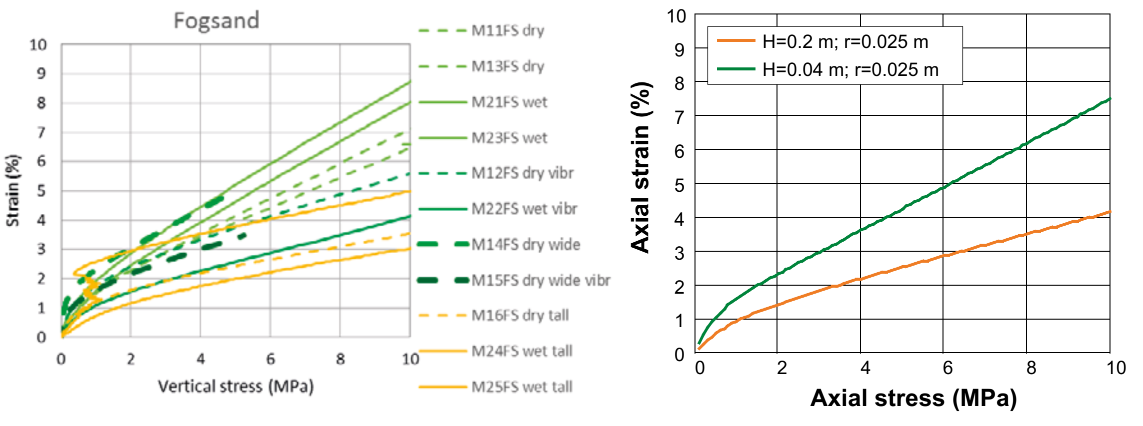


Figure 9-2. *Strain vs axial stress for different geometries. Experimental data (left) and model results (right).*

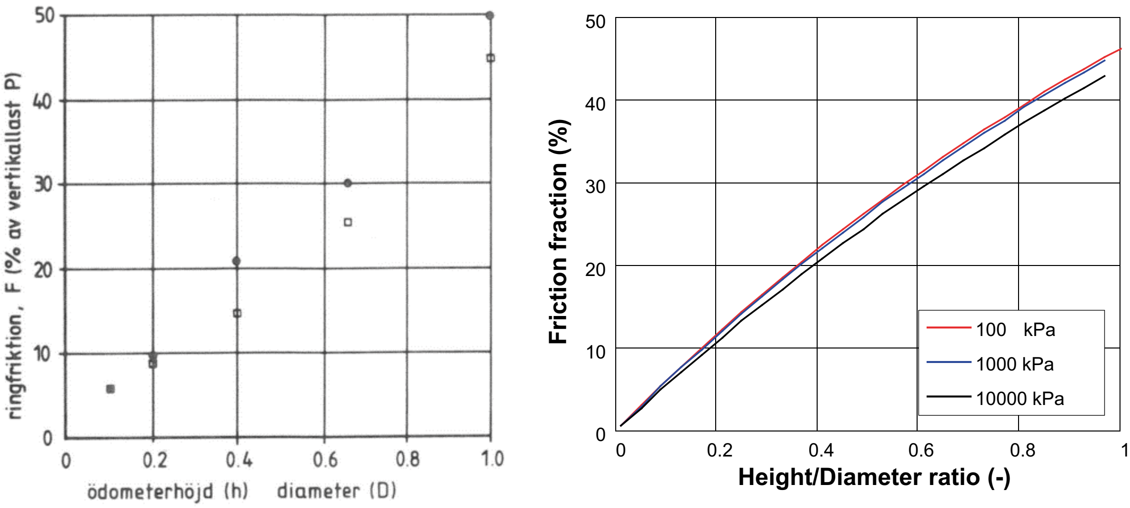


***Figure 9-3.** Ring friction vs H/d-ratio. Experimental data, (from Sällfors and Andréasson 1986; left) and model results (right).*

9.4 Parameter analysis

The model was used to analyze the influence of the friction angles on the profiles of axial stresses and dry density. The radius of the borehole was set to 38 mm. A compilation of parameter values is given in Table 9-1. The initial length of the bentonite was chosen deliberately low for numerical reasons, although this can be considered as conservative. The initial dry density of the bentonite was set to slightly lower than buffer density. The initial dry density of the sand was based on lab tests on "fog sand" although this value has no influence of the results. The Poisson's ratio for the sand was set to 0.25. The friction angles for the bentonite and the sand were varied from 1 to 10°, and 1 to 30°, respectively.

Stress profiles for the extreme friction angle values are shown in Figure 9-4. It can be noted that the lower friction angle values result in relatively flat profiles with an influence on a significant length of the material, while the higher values yield quite steep profiles with only minor influence. An influence on the entire length of the bentonite filling was only found for the case with 1° for both materials. The highest equilibrium stress was found for the case with ϕ_B = 1° and ϕ_S = 30°, while the lowest was found for the case with ϕ_B = 10° and ϕ_S = 1°. Corresponding dry density profiles are shown in Figure 9-5.

Contour plots of the equilibrium stress at the interface and at the bentonite boundary are shown as a function of the two friction angles in Figure 9-6. The left plot illustrates that the highest interface stresses are found for low ϕ_B values, while the lowest stresses are found for low ϕ_S values. The right plot illustrates that a reduction of stresses at the bentonite boundary is only found for very low friction angles in both materials.

Table 9-1. Parameter values.

Parameter	Bentonite	Sand
Initial length (m)	1	100
Initial dry density (kg/m^3)	1 550	1 500
Friction angle (°)	1 → 10	1 → 30
Swelling pressure	c0 = −1.74	m1 = 4×10^{-5}
coefficients and elastic parameters	c1 = 4.12×10^{-3}	m2 = 8×10^{-6}
(see Eq 9-1 and Eq 9-2)	c2 = -3.94×10^{-7}	m3 = 3×10^{-3}
		v = 0.25

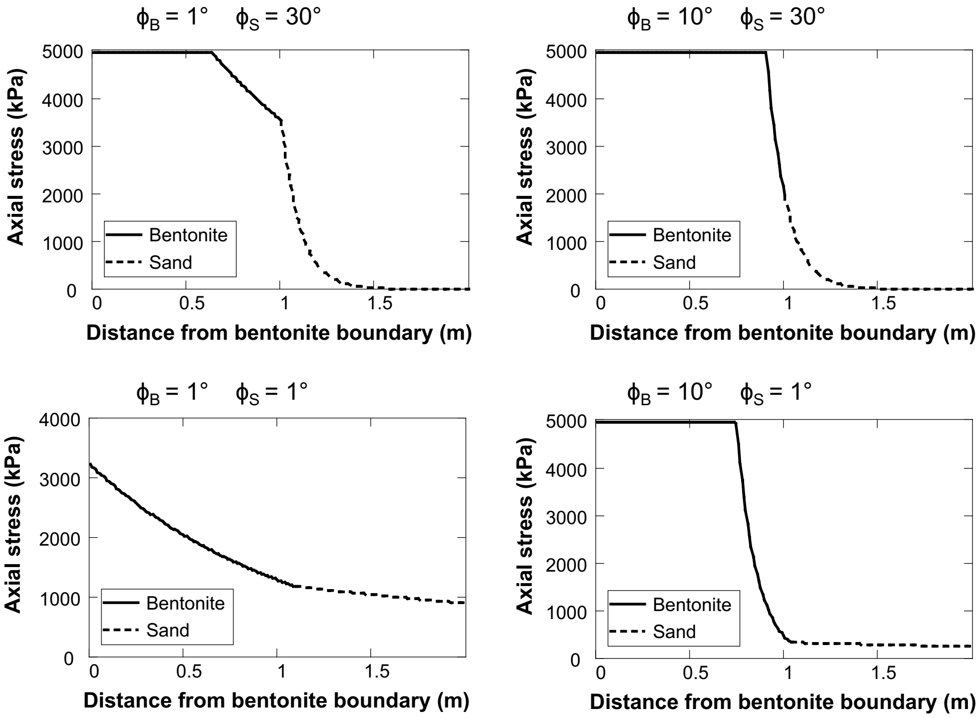


Figure 9-4. Stress profiles for different combinations of friction angles.

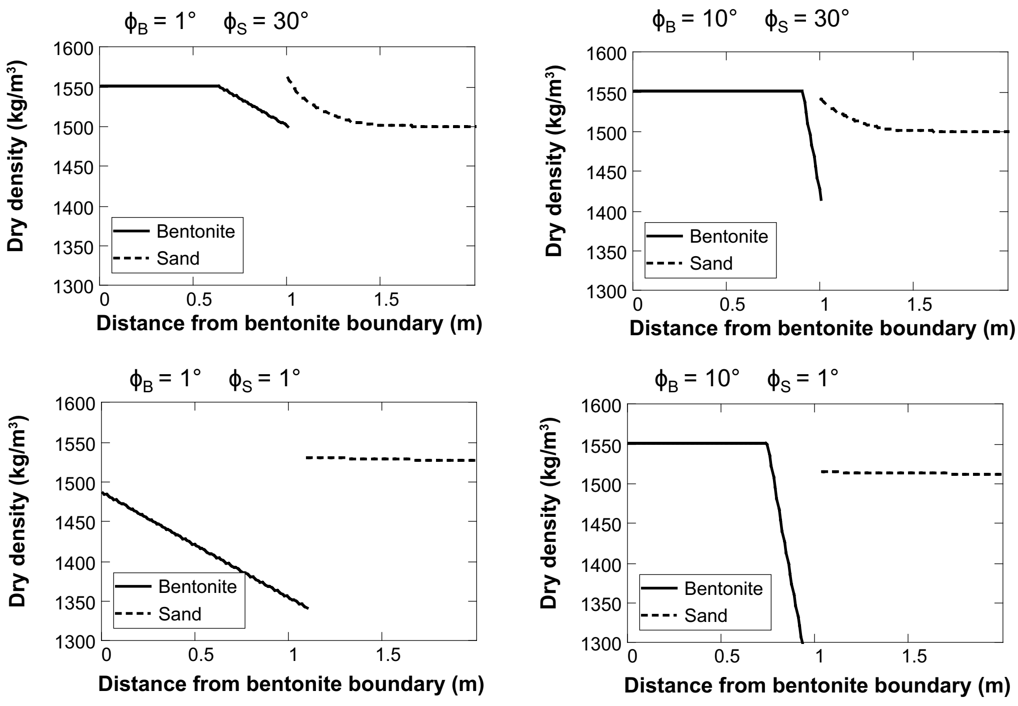


Figure 9-5. Dry density profiles for different combinations of friction angles.

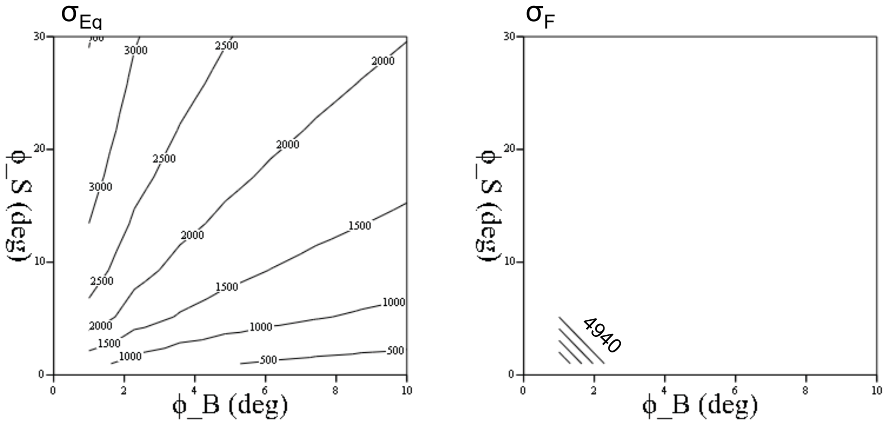


Figure 9-6. Equilibrium stress at interface (left) and at bentonite boundary (right) as a function of the two friction angles.

9.5 Concluding remarks

A general observation in this analysis was that the bentonite will only be influenced along its entire length for cases with very low friction angles for both materials. Since such values are unrealistic, at least in short terms, there appears to be no risk of any major displacements in the current design of borehole seals. However, there is currently only very little data that supports the presented description of counteracting frictional forces in the sand-filled section. Moreover, and more importantly, there is with the author's knowledge no data that supports the notion that the frictional forces will display a long term stability.

Due to these uncertainties, it would be valuable to perform tests which could further validate the description of the frictional effects. A fairly simple test would be to perform oedometer tests, similar to the ones presented in Figure 9-2, in which the force acting on the bottom face of the oedometer is measured. The difference between the forces applied at the top and the measured force at the bottom, would thereby be caused by friction. For a geometry with a high H/d-ratio (~ 10), this would mean that the bottom force would be negligible. In order to test the long term stability of the sand filling, more complex tests could be performed to try to provoke a reduction of the frictional force, for instance through vibration or through cyclic loading.

10 Alternative sealing materials

10.1 General

In addition to the investigations made on material components included in the Sandwich-concept, minor investigations have been made on two other possible sealing materials, Sandaband and Barite.

10.2 Sandaband

10.2.1 General

Sandaband is a patented material produced by Sandaband Well Plugging AS, Stavanger, Norway. The name Sandaband is a contraction of "SAND for ABANDonment". The material is mainly used for sealing of wells, temporary or permanently.

The information presented in this report is mainly obtained from the web site of Sandaband Well Plugging AS and also from e-mail communication with Vidar Rygg at Sandaband AS. In addition, laboratory tests have been performed in order to study material properties that are assessed to be of high interest when using Sandaband as a sealing material for deep investigation boreholes in granitic rock. The results from these laboratory tests are presented below.

10.2.2 Material description

Sandaband consists of 70–80 % by volume of solids together with about 20–30 % of water and other fluid additives. The solids are quartz grains of different dimensions, from 2.5 mm to less than 0.0005 mm. A brochure describing the Sandaband material is provided in Appendix 4.

The rheology of Sandaband can be characterized as Bingham plastic i.e. the Sandaband mixture may be described as a solid inside a liquidized annulus of itself when in motion, otherwise it's a deformable solid. The material is not shrinking or fracturing after installation, and it is not sensitive for water salinity.

10.2.3 Installation in boreholes

The Sandaband material is emplaced by using standard cement pumps, bullheading or circulating. The material will fill up any irregularities which means that the borehole rugosity will not be a problem. It will also be possible to install Sandaband in both vertical and almost horizontal boreholes by pumping the material through a tube to the bottom of the borehole. If the borehole diameter is small, the pumping pressure may get too high, depending on depth.

10.2.4 Chemistry, aspects on post closure safety

By weight, Sandaband consists of 50 to 70 % quartz sand in the size fraction 0 to 2.5 mm, also 0 to 25 % microsilica (also known as Silica fume), and less than 1 % ethane-1,2-diol (ethylene glycol).

Quartz may be considered inert at the relevant boundary conditions in a borehole. Microsilica on the other hand is an ultrafine powder of amorphous (non-crystalline) polymorph of silicon dioxide. The individual particles are spherical with a diameter of less than 1 µm. Microsilica reacts with water according to:

$2H_2O + SiO_2 = H_4SiO_4$, and has a solubility limit of approximately 2 mM, which may be compared to 0.1 mM for quartz. Quartz is abundant in granitic rock and the groundwater is usually saturated with respect to quartz. The higher solubility of microsilica may lead to significant material loss in the long term perspective in permeable zones with fast groundwater turnover. In contact with e.g. calcium hydroxide solutions from cement, the microsilica may be cemented by the reaction:

$$Ca(OH)_2 + H_4SiO_4 \rightarrow CaH_2SiO_4 \cdot 2\,H_2O$$

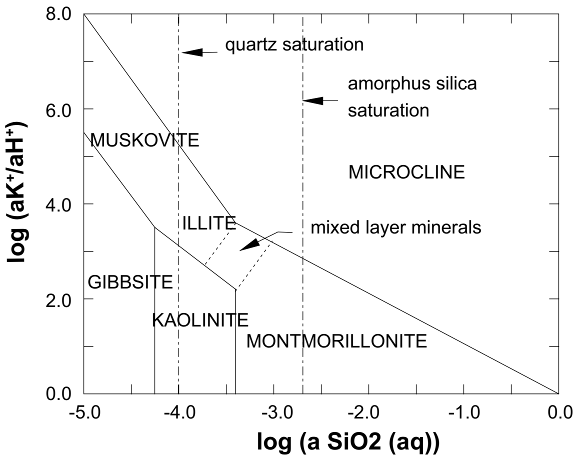


Figure 10-1. *Phase diagram for silica activity indicating the saturation lines for quartz and silica.*

The magnitude of loss or conversion of the microsilica is consequently site specific and has to be calculated for actual boundary conditions.

The ethane-1,2-diol is miscible in water and will consequently flow or diffuse away in a short term perspective in open systems. The effect is not expected to affect the sealing properties of the installed material in a significant way.

10.2.5 Laboratory tests on Sandaband

Two buckets, 2 × 10 kg, with Sandaband material were delivered to Clay Technology for the laboratory tests. The material is rather stiff in rest, and before installation in any test cell it was necessary to apply a torque which will remobilize the Sandaband as a liquid and after that it could be poured into the current test cell.

The test program has included the following measurements:

1. Water content of the delivered material
2. Bulk density of the delivered material
3. Strength as function of time after installation
4. Hydraulic conductivity
5. Compressibility
6. Piping and erosion

10.2.6 Water content and bulk density

The determinations of water content and dry density were made according to Section 3.3. Details of the determinations of water content included that the sample was placed in aluminum tin and the bulk mass of the sample was determined before and after placing the sample in an oven for 24 h at a temperature of 105 °C. The water content was then calculated from the mass of water and the dry mass of the sample. The determination of bulk density was made by use of a 250 ml measuring cylinder. The cylinder was weighed with and without Sandaband and from the known volume of the cylinder the density of Sandaband was be determined.

Results

The water content was determined to 20.7 %. The bulk density was determined to 1 950 kg/m^3 and the dry density to 1 615 kg/m^3. In the material data given in the brochure available on the homepage the specific gravity is specified to 2 150–2 200 kg/m^3. This density is, however, measured when the material is pressurized to 1 000 psi (6.9 MPa) confining pressure i.e. the entrained air is compressed.

10.2.7 Strength

The sand slurry has a very low strength when it is kept in motion. As soon as the movement stops, the slurry starts to stiffen and after a few days the Sandaband has reached a rather high strength. The strength is assessed to influence the other properties and therefore a simple measurement of the strength growth has been made.

Method

The shear strength was determined with the fall cone method (ISO/TS 17892-6:2004). The method is based on the measurement of the penetration into the slurry of a standard cone of specific mass. Three different cones were used in the test series:

0–24 h: Cone with a weight of 10 g and inclination of 60°

96 and 144 h: Cone with a weight of 60 g and inclination of 60°

240 h: Cone with a weight of 100 g and inclination of 30°

Test matrix

Two test series were performed:

1. The as-delivered material. Six vessels (100 ml) were prepared with the sand slurry and tested at different times after preparation.
2. Material that was dried and then re-saturated to the same water content. Six vessels (100 ml) were prepared with the sand slurry and tested at different times after preparation.

Results

The graph provided in Figure 10-2 shows the results from the investigation. The graph shows that there was a very clear increase in shear strength with time. No significant differences were find between the two performed test series.

10.2.8 Hydraulic conductivity

The hydraulic conductivity is one of the most important properties of the borehole sealing material.

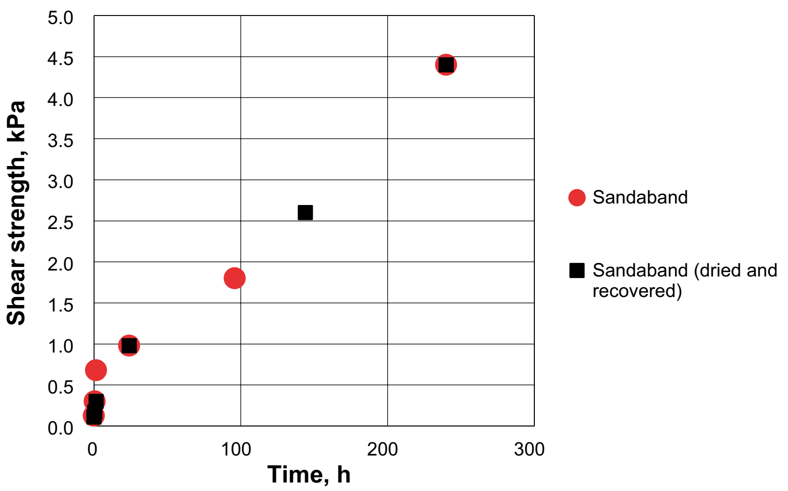


Figure 10-2. *The measured shear strength plotted versus time for the two test series performed with the Sandaband material.*

Method

In order to determine the hydraulic conductivity of the Sandaband, special test cells were used, Figure 10-3, see also Figure 7-5 . The sample holder had a diameter of 50 mm and a height of 20 mm. The sand slurry was poured into the test cell and thereafter the piston was mounted.

The filters and pipes were filled with water by use of a thin tube and an injection needle. A first test was made using a vacuum pump but it was obvious that fluid containing fine material was sucked out from the sample. A water pressure of 1 meter water column was applied in the bottom filter by use of a burette. The volume of the water coming out through the upper filter was measured by measuring the level of the meniscus in a transparent tube with an inner diameter of 4 mm. The hydraulic conductivity (m/s) is evaluated by using Darcy's law according to Equation 4-2.

Test matrix

In total three tests were made on the Sandaband material. The tests were made at different times after installation in the test cell, immediately after installation, after 1 day and after 4 days.

Results

A compilation of the test results is provided in Table 10-1. The measured hydraulic conductivity is similar for all three measurements i.e. there does not seem to be any dependence on the time after preparation.

Table 10-1. Compilation of results from the measurements on hydraulic conductivity on Sandaband.

Time after preparation days	Hydraulic conductivity m/s
0	1.3×10^{-9}
1	3.5×10^{-9}
4	1.2×10^{-9}

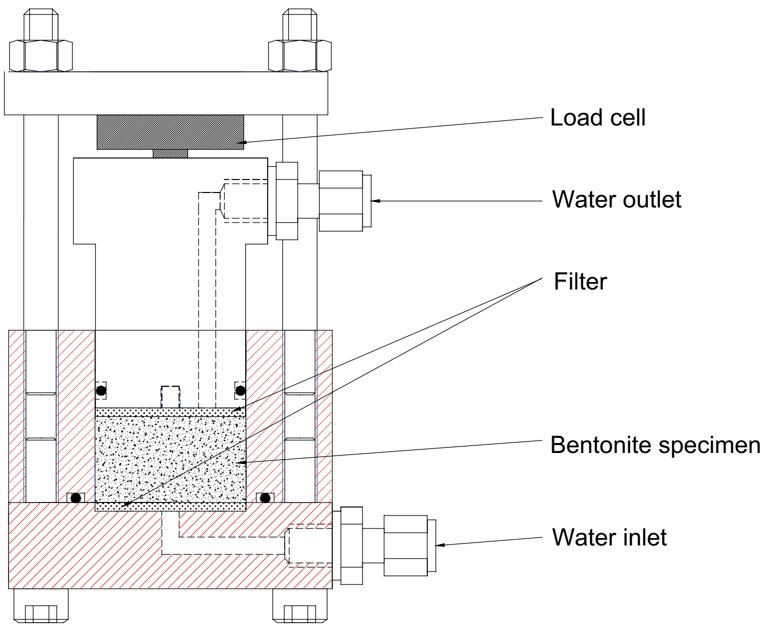


Figure 10-3. *Schematic drawing of the test cell used for the measurements of hydraulic conductivity.*

10.2.9 Compressibility

Determination of compressibility was included in the test program to characterize the Sandaband material.

Method

The method used for the tests on compressibility of Sandaband is the same as described in Section 4.5. The equipment used for the tests were previously shown in Figure 4-10. As shown in the sketch filters were used on both sides of the specimen and the height of the specimen was H = 40 mm and the diameter D = 50 mm.

Test matrix

Three tests were run where two tests were run directly after the installation of the material into the test device and one test was run 96 h after the installation. The two tests run directly after the installation were run at different deformation rates: 0.5 mm/min and 0.05 mm/min.

Results

The results of the three tests are shown in Table 10-2 and Figure 10-4. The initial density of the specimens used for the compressibility tests was approximately the same as the originally determined density from Section 10.2.5. From the compressibility tests no large difference was seen between the tested specimens, irrespective of the deformation rate and if the test was run directly or 4 days after the installation.

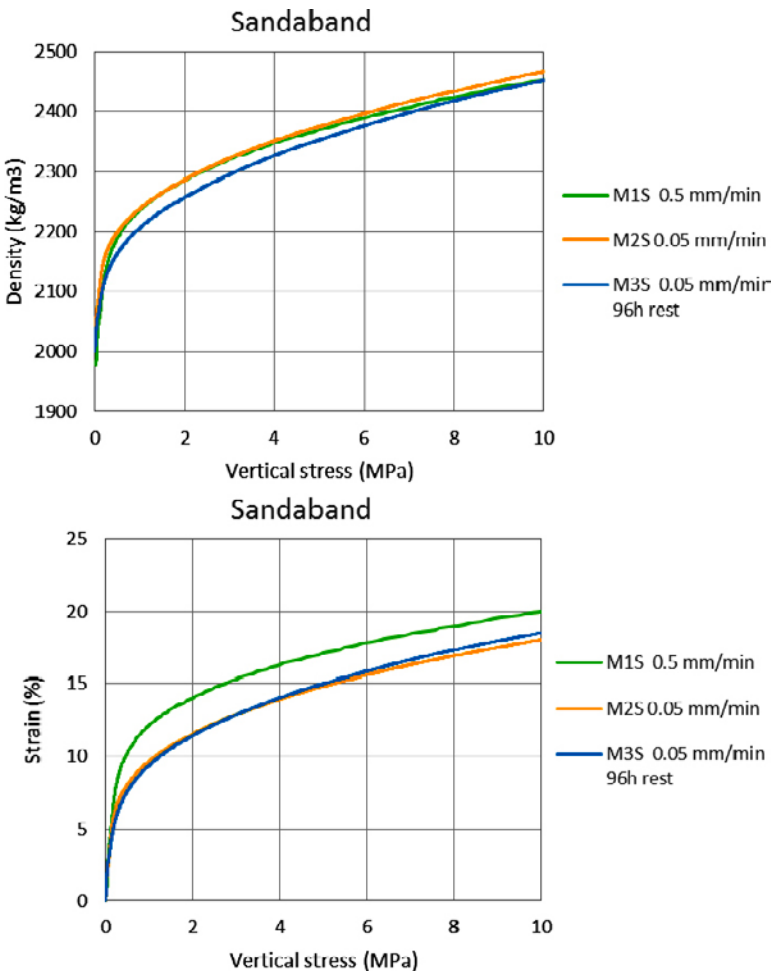


Figure 10-4. *Density (upper) and strain (lower) as a function of vertical stress from the compressibility tests on Sandaband.*

Table 10-2. Test results from the compressibility tests on Sandaband.

Sample ID	Rate mm/min	Time after preparation, days	Initial density kg/m^3	Final stress MPa	Strain at final stress, %	Final density kg/m^3
M1S	0.50	0	1964	10.2	20.1	2457
M2S	0.05	0	2023	10.0	18.0	2467
M3S	0.05	4	1999	10.0	18.5	2454

Comments

The compressibility was relatively high in Sandaband compared to the other tested materials shown in Section 4.5. To some extent this could be explained by the fluid which was clearly squeezed out of the Sandaband specimens during the tests.

Since the material easily separated at compression it would be of interest to do further tests on the properties of both the outflowing fluid and on the material remaining in the test device after such test.

10.2.10 Piping and erosion

Determination of piping and erosion properties were included in the test program to characterize the Sandaband material. In addition, these properties are important if the material are going to be used as a sealing material. Three tests were run.

Method

The tests on piping and erosion of Sandaband were run in the device shown in Figure 10-5. The specimens had the diameter 60 mm and height 120 mm. After fixing the bottom plate to the confining ring the material was poured into the test cell to accurately fill out the volume and finally the top plate was mounted.

After filling and closing the device a water pressure was connected radially to the test device, according to the arrows in Figure 10-5. During an initial phase of the test a water pressure of approximately 10 kPa was applied to the inflowing water until water was visible at the opposite side of the device. After the initial phase the actual test started by increasing the water pressure manually by 100 kPa/h. The methodology used was a result of some pretests made in slightly different ways regarding dimensions, drainage conditions and direction of flow.

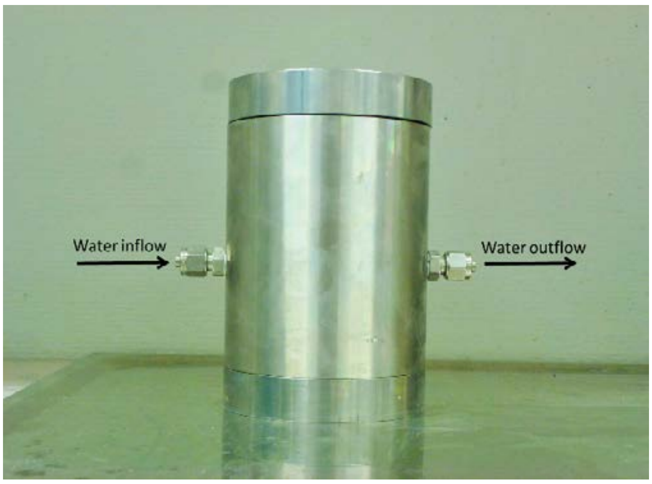


Figure 10-5. *Photo of the device used for the piping (erosion) tests with D = 60 mm and H = 120 mm. The arrows show the water in- and out-flow.*

Test matrix

Three tests were run in the test device shown in Figure 10-5. Two of the tests were started directly after installation, i.e. the initial phase started immediately and some minutes later the actual test started by increasing the water pressure. The third test was not started until 4 days after the installation.

Results

The test results are shown in Table 10-3, Figure 10-6, Figure 10-7, Figure 10-8 and Figure 10-9. The densities of the specimens were in the same range but slightly higher than the originally determined density from Section 10.2.6.

In the first two tests, P1S and P2S, which both started directly after installation, piping was observed at a water pressure of 47 kPa and 81 kPa, respectively. In the third test, P3S, which started 4 days after the installation, clear piping was still not observed at a water pressure of 165 kPa when the test was paused. However, during the test, P3S, the water pressure increase levelled out at a water pressure of approximately 80 kPa and subsequently the water inflow rate increased 45 times (from $q \approx 300\ mm^3/min$ to $q \approx 13\,500\ mm^3/min$). After the piping-like condition the previous water pressure increase and the lower flow rate re-established after approximately 45 minutes.

Test P3S was paused during 17 hours and after the pause the water pressure was again increased from zero and the results are shown in Figure 10-9. This second part of P3S was finished after 4 hours and despite the final water pressure of 400 kPa no piping or piping-like conditions was observed.

Table 10-3. Test matrix for the tests on piping and erosion of Sandaband.

Test ID	Initial bulk density kg/m^3	Time after installation days	Initial state Pw kPa	Initial state kept min	Piping kPa
P1S	2010	0	15	12	47
P2S	2060	0	20	8	81
P3S	2027	4	25	45	No clear piping

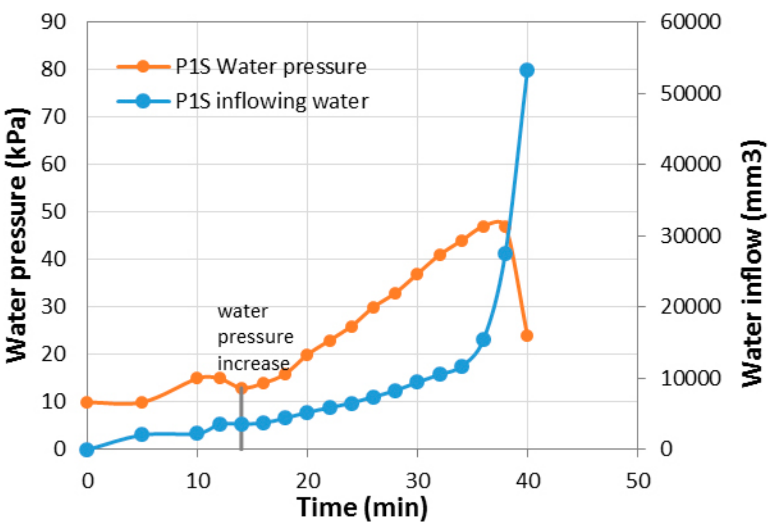


***Figure 10-6.** Water pressure and water inflow from test P1S. The time when the water pressure was manually increased is marked with a grey line.*

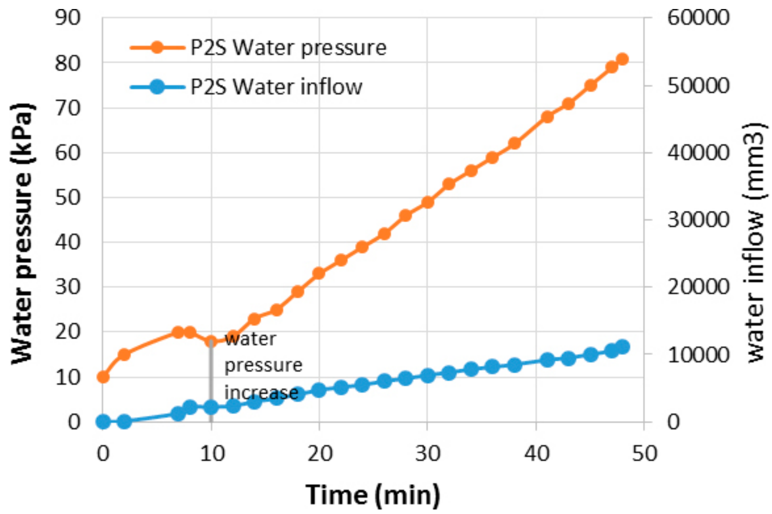


__Figure 10-7.__ Water pressure and water inflow from test P2S. The time when the water pressure was manually increased is marked with a grey line.

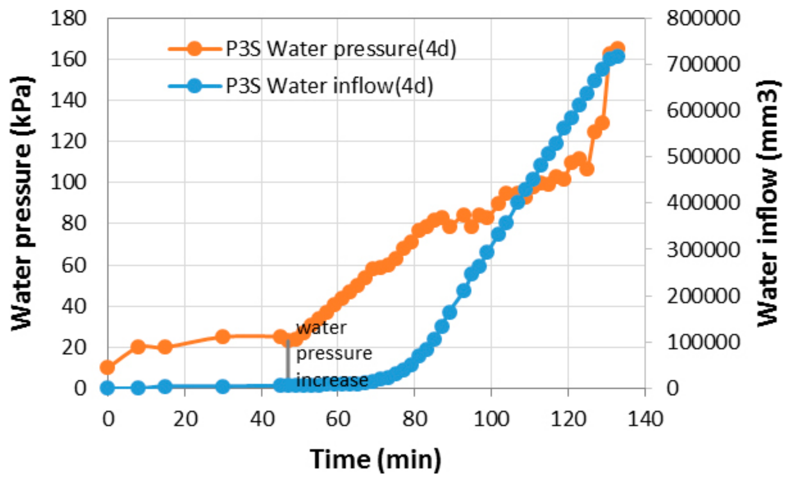


__Figure 10-8.__ Water pressure and water inflow from test P3S. The time when the water pressure was manually increased is marked with a grey line.

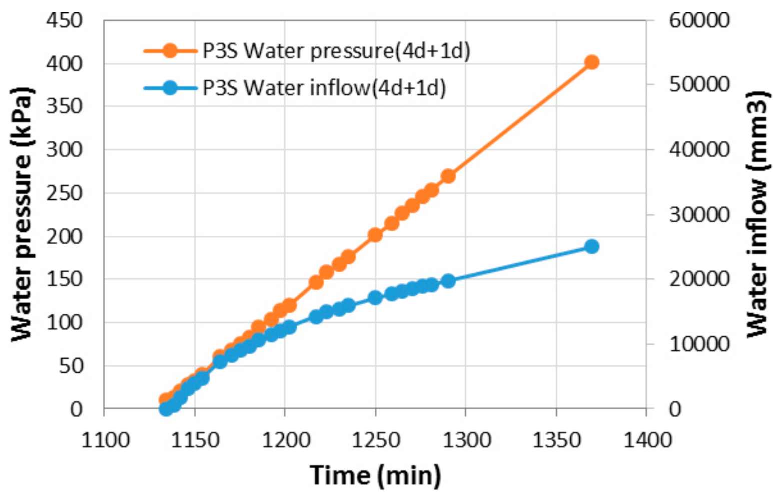


__Figure 10-9.__ Water pressure and water inflow from the second part of test P3S. The time refers to the start of test P3S and in addition a pause during 17 hours was made between the first and second part of the test.

Comments

Consistency of the behavior during the initial part of tests P1S, P2S and P3S was seen in that the flow rate, $q \approx 300$ mm³/min, was approximately the same. Approximately the same flow rates were also seen initially in the second part of P3S, however in that case the material sealed with time and less flow was seen as the water pressure increased.

After the observed piping in test P1S and P2S the eroded mass was registered as a function of the water outflow during approximately 30 minutes and the results are shown in Figure 10-10 together with a model presented by Sandén and Börgesson (2010).

The erosion data in Figure 10-10 was only determined during half an hour and it would be interesting to apply a constant water flow through the material during a longer time period however, following after a time period of water pressure increase up to approximately 80 kPa.

10.2.11 Discussion

Laboratory test results

The properties determined so far are summarized in Table 10-4.

No large difference was seen in the properties determined directly after installation and after 4 days. However, it is suggested to further study the material in a second laboratory test series.

Table 10-4. Properties determined on Sandaband in the limited laboratory test series

Property	Directly after installation	4 days after installation
Original water content	20.7 %	
Original dry density	1615 kg/m^3	
Shear strength (cone)	0.15 kPa	4.4 kPa
Hydraulic conductivity	1×10^{-9} m/s	1×10^{-9} m/s
Compressibility	19 % at 10 MPa	19 % at 10 MPa
Piping at water pressure	47–81 kPa	

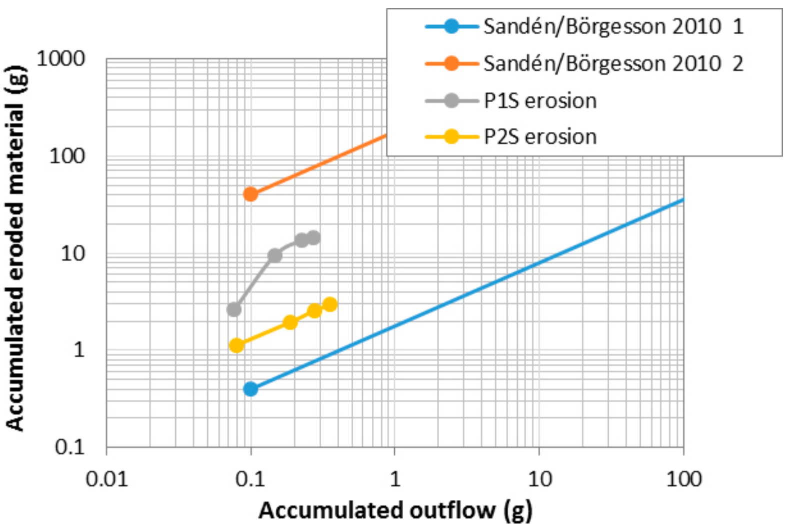


Figure 10-10. Test results from P1S and P2S.

Suggested further laboratory tests

If Sandaband is considered to be of interest for sealing boreholes, further tests are needed to broaden and deepen the knowledge of this material. Since some properties seem to be dependent on the time after installation this must be taken into account.

Shear strength

The determination of shear strength was in the first series made by the cone method. To further understand the strength of the material the angle of friction should be determined e.g. by triaxial tests or direct shear tests.

Hydraulic conductivity

It is of interest to determine hydraulic conductivity according to the previous method in Section 10.2.8 slightly modified by use of higher pressure and larger gradient.

Compressibility

Since water was squeezed out of the material during the previous tests on compressibility it is suggested to do further tests on the compressibility either CRS-test, with continuous increased load and measurement of pore pressure, or Oedometer test, with incremental loading. It could also be valuable to use the previous method in Section 10.2.9 and to further study the fluid being squeezed out and the material remaining in the test device.

Piping and erosion

A piping pressure of 80 kPa was indicated with the previous method described in Section 10.2.10. Further tests should focus on the erosion after piping, i.e. the total outflow and the eroded mass when a constant flow is applied after piping. Further information can also be gained if piping and erosion are studied in another geometry, i.e. with another test device.

10.3 Barite

Barite or baryte, has been considered as a possible sealing material in deep investigation boreholes, see e.g. Blümling and Adams (2008). One of the main advantages with the material is the high density which facilitates installation (sedimentation through standing water) and also makes the filling self-compacting with time. Another advantage is that it is almost chemically inert.

10.3.1 Material description

The information presented in this section is mainly obtained from the Wikipedia web site. Barite or barite is a mineral consisting of barium sulfate ($BaSO_4$). The barite group consists of barite, celestine, anglesite and anhydrite. The mineral has a density of 4 480 kg/m^3. Most barite is ground to a small, uniform size before it is used as a filler or extender, an addition to industrial products, in the production of barium chemicals or a weighting agent in petroleum well drilling mud.

World barite production for 2014 was 9.7 million tons. The major producers of barite are China, India, Morocco and United States. 77 % of barite worldwide is used as a weighting agent for drilling fluids in oil and gas exploration to suppress high formation pressures and prevent blowouts. As a well is drilled, the bit passes through various formations, each with different characteristics. The deeper the hole, the more barite is needed as a percentage of the total mud mix. An additional benefit of barite is that it is non-magnetic and thus does not interfere with magnetic measurements taken in the borehole, either during logging while drilling or in separate drill hole logging. Barite used for drilling petroleum wells can be black, blue, brown or gray depending on the ore body.

10.3.2 Installation in boreholes

Depending on the requirements on the borehole sealing, barite can be used either on its own or as a support element filling up the main part of a borehole. Barite has been used to form plugs to control active gas zones in wells (Messenger 1969). The plugs were composed of barite, water and a thinner. The material is installed as a slurry with a density of between 2 157–2 875 kg/m^3, using cementing equipment and spotted through the drill pipe.

10.3.3 Chemistry, aspects on post closure safety

The solubility of barite is very low (< 10^{-4} moles/L) for all realistic cases, and no chemical alteration is expected also in the long term perspective. The main concern for sealing with barite is the potential settlement due to the high density in comparison to other involved materials.

11 Conclusions

11.1 General

The Sandwich-concept, has been suggested for sealing of boreholes. The main components included in this design are the sand/gravel filling, the bentonite plugs, and the quartz based concrete and the copper expanders. The results from performed investigations and tests on these components are provided in this report and the conclusions are compiled below.

The swelling bentonite will compress the sand but this will be counteracted by frictional forces along the rock wall and this will limit the displacements in the borehole. A theoretical analysis of the friction between the components installed in the borehole and the wall of the borehole has been made and some concluding remarks from this analyses are also included below.

In addition, a mockup test, simulating a borehole section with a length of 4 meters have been started.

Also included in this report is an investigation of an alternative commercial sealing material, Sandaband. The investigation includes both laboratory tests and a literature study. A minor literature study has also been made on another candidate material for borehole sealing, Barite, which is a natural mineral with very high density.

11.2 Test of components – granular material

In the Sandwich-concept, the main part of the borehole length will be filled with granular materials. The most important behavior of the granular material is to secure that the bentonite plugs stay in position also when a swelling pressure from the bentonite is developed towards the granular material. To optimize the properties of the installed granular material the requirements of the material and the installation can be further specified according to the following:

- The chosen material should be possible to install at a relatively high density compared to the maximum achievable density for the actual material.
- The material should be as homogeneous as possible after installation, i.e. the risk of separation and bridge structures should be minimized.
- The material should have low compressibility.

11.2.1 Installation tests, settlement at water saturation, compressibility and hydraulic conductivity

From the tests the following advice can be given regarding of the choice of the granular material. Since the boreholes most likely are filled with water and installation in a water filled borehole is plausible the comments below are concentrated on water-filled conditions.

- Densities after installation in a borehole were shown to be of a magnitude comparable to the lowest densities achieved in the small scale tests and some efforts to increase the density at installation will be valuable. This is valid for installation in a water filled as well as a dry borehole.
- Sensitivity of vibrations was observed in some of the materials and to increase the final density it could be valuable to use vibrations or similar already during the installation. This seems to be especially important for Fogsand, which was observed as extra sensitive but vibration will be useful also for MakPak and Ballast 2–4. The technique to vibrate the sand filling after installation has, however, not been investigated within this project.
- The effects of vibrations on Fogsand on the achieved density seems to be of the same magnitude or greater than compression at high pressure.
- How the vibration of the sand after installation in a borehole should be done in practice has not been investigated within this project.

- Tendencies of separation during installation in a water filled borehole were seen in tests on MakPak and at dry conditions separation was observed in tests on both MakPak and Fogsand.
- After installation, low compressibility will be an important property and the lowest compressibility was seen in tests on Fogsand and on MakPak.
- Tendencies to form bridge structures might be minimized by lowering the installation rate of the material into the borehole. Especially during installation of Fogsand and MakPak into a water filled borehole it seems to be important to use a low installation rate, below 10 kg/min. The fastest installation into a water filled borehole could be achieved with Ballast 4–8 which in addition seems not to be sensitive to vibrations but, however, has a rather high compressibility.
- For all materials, the hydraulic conductivity after installation will be between 1×10^{-5} and 9×10^{-5} m/s. This means that since the hydraulic conductivity of the bentonite sealing is much lower, between 10^{-12} and 10^{-13} m/s, the effect on the sealing of the borehole from the sand is almost negligible.

11.3 Test of components – quartz based concrete plug

The main function of the concrete plugs is to prevent the bentonite from swelling into the sand filling in long term. The adhesion or friction between concrete and rock was studied in order to prevent movements of the sealing in the early phase. Laboratory tests have been performed to determine the compressibility and hydraulic conductivity of a core consisting of the quartz material that is assumed to be left of the concrete after leaching of the cement.

11.3.1 Friction between concrete and rock

- The tests show that as long as the concrete is in good condition i.e. no cement has leached, it will function as a very good delimiter between different materials.
- Based on the peak values from the test results a concrete filled borehole section with a length of 1 meter can, after about one week, withstand an overload of 72 kN. This load corresponds to an axial swelling pressure from a bentonite section of more than 15 MPa.
- After having reached the maximum strength, a residual strength will be present, resulting in that still after additional deformation the concrete filled borehole section can withstand an overload which, however, is only half of the value calculated from the peak values.

11.3.2 Compressibility and hydraulic conductivity

A conservative assessment is that the cement component in the concrete plugs will leach with time, leaving a core of coarse and fine grained quartz based material left in the borehole. The material of such core was used for determinations of compressibility and hydraulic conductivity in order to get a conservative estimation of the properties of what will be left of the concrete after long time.

The compressibility and hydraulic conductivity of the core of coarse and fine grained material are in the same range as that of Fogsand which, is logical since the main part of the tested material consisted of this ballast material. As mentioned earlier, the compressibility of Fogsand was considerably lower than that of the other tested granular materials.

11.3.3 Bentonite swelling into ballast material

The function of the remaining core of coarse and fine quartz grains after that the cement has leached, see Chapter 5, is that it should serve as a filter preventing bentonite from swelling directly into the sand filling. The Fuller-type gradation of the ballast material minimizes penetration and migration through the structure.

The max loss of bentonite by swelling into the remaining ballast is probably negligible. The process has not been investigated in this project.

11.4 Test of components – copper plug

In order to facilitate the installation and also to limit the interaction between different sealing materials (during the post-closure phase), special copper expanders are suggested to be positioned in the transitions between the different materials. The first two designs of a copper expander that were tested required a high load to expand and the radial expansion was also judged to be too small to be practical i.e. the initial dimensions of the expander would have to be rather close to the borehole diameter (about 3 mm less than the borehole diameter).

The third design tested required much less force to expand and the radial expansion was much higher. It is judged that a copper expander with the tested dimensions can be installed in the Mockup test and be expanded to reach the simulated borehole walls at a force of about 10 kN. Complementary laboratory tests are required in order to study the expansion when the expander is installed in a borehole i.e. there will be an anvil when the copper reach the borehole wall. It is also judged that the design can be further improved so that a longer section can expand e.g. the design can be made so that there will be radial expansion on both ends of the copper expander.

It is recommended that expanders made of copper should be used as a component at borehole sealing although the stability of copper during the post-closure phase may be questioned due to sulfide (S^{2-}) corrosion, unless it is protected by bentonite. Also under stagnant water conditions bacteria may produce sulfide from sulfate (SO_4^{2-}), which typically is present in relatively high concentrations. Alternative metals, especially titanium, may be considered for long term use.

11.5 Test of components – bentonite plug

The bentonite plugs are an essential part of the "Sandwich-concept". Three types of test, directly related to the Sandwich-concept have been performed within this project; erosion tests and tests on swelling pressure and hydraulic conductivity. In addition, a homogenization test has been installed and started. This test will, however, be running for some time and the results will be presented later in a report.

11.5.1 Erosion

The erosion of the bentonite blocks during installation is important to know if the installation is made by lowering the bentonite packages down in a water filled borehole. From the performed tests the following conclusions can be drawn:

- Installation of uncoated bentonite blocks to great depth, several hundred meters, will result in significant erosion. This will result in lower installed bentonite density than intended which will affect the hydraulic conductivity of the sealing.
- The use of coating on the exposed bentonite surfaces will considerably decrease the bentonite erosion. The tests showed that it is possible to install bentonite to a depth of 800 meters in a water filled borehole with only small losses of bentonite by erosion.
- If installing uncoated bentonite blocks in a borehole it will be favorable to change the water to tap water. This action will strongly decrease the erosion rate of the bentonite.
- The influence of shellac on the long term properties of the bentonite is still unclear. The coated bentonite blocks in the performed tests had a shellac content of about 0.2 %. This is in the same range as the natural organic content of MX-80 and about half of the content in several other commercial bentonites e.g. in Asha bentonite.

11.5.2 Swelling pressure and hydraulic conductivity

If coating (shellac) is used as an erosion protection there will be remaining impurities also after installation. The effect of these impurities on the swelling pressure and on the hydraulic conductivity has been investigated. The swelling pressure and hydraulic conductivity were determined on four specimens with initial layers of shellac. Good agreement between the results from the specimens with shellac and the specimens without shellac was observed.

11.6 Alternative materials

11.6.1 Sandaband

Sandaband is a patented material produced by Sandaband Well Plugging AS, Stavanger, Norway. The material is mainly used for sealing of wells, temporary or permanently. The material consists of 70–80 % by volume of solids together with about 20–30 % of water and other fluid additives. The solids are quartz grains of different dimensions, from 2.5 mm to less than 0.0005 mm.

The rheology of Sandaband can be characterized as Bingham plastic. Sandaband mixture is a solid inside a liquidized annulus of itself when in motion, otherwise it's a deformable solid. The material is not shrinking or fracturing after installation. Another advantage is that the material is not sensitive for the water salinity.

In the first laboratory test series mainly made to characterize the material the following were found: a water content (as-delivered) of 20.7 %, an originally dry density of 1 615 kg/m^3 and the strength determined with the cone method after four days was 4.4 kPa. The hydraulic conductivity 1×10^{-9} m/s and the compressibility 50 MPa were values measured both directly and four days after the installation.

Microsilica (also known as Silica fume) makes up a significant part of the solids in Sandaband. Both the small particle size and the relatively high solubility may be a problem in the long term perspective. It is assumed that the small particles will erode into rock fractures and loss of material due to leaching will decrease the density of the filling.

11.6.2 Barite

The literature study shows that barite has a potential to be used as a sealing component in deep investigation boreholes. The mineral is chemically almost inert and has a high density which will result in self compaction with time. The installation can be made as a slurry with high density, consisting of barite, water and a thinner. This will facilitate the installation considerably.

The minimum attainable hydraulic conductivity is 10^{-9} to 10^{-10} m/s according to Blümling and Adams (2008), but these figures are recommended to be checked by performing some laboratory experiments.

Barite is chemically very stable, and the main concern for long term stability is potential settling of the material due to the relatively high density.

11.7 Mockup test

The Mockup test simulates a borehole section with a length of 4 meters. All material components included in the Sandwich-concept have been installed in the test. The test was installed and started in the beginning of December 2016 and no data was available at the time for the writing of this report. The test is planned to be terminated during the spring 2017 and the results reported in the final report of this project.

11.8 Analysis of the friction between components and the borehole wall

The objective of this work was to develop a tool for calculation of mechanical equilibration of borehole sealing materials due to swelling. This tool was used to assess the risk of reaching unacceptably low dry density of the bentonite.

A general observation in this analysis was that the bentonite will only be influenced along its entire length for cases with very low friction angles for both materials. Since such values are unrealistic, at least in short terms, there appears to be low risk of any major displacements in the current design of borehole seals. However, there is currently only very limited data that supports the presented description of counteracting frictional forces in the sand-filled section. Moreover, and more importantly, there is according to the authors` knowledge no data that supports the notion that the frictional forces will display a long term stability.

Due to these uncertainties, it would be valuable to perform tests which could further validate the description of the frictional effects.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

Abarca E, Idiart A, de Vries L, Silva O, Molinero J, von Schenk H, 2013. Flow modeling on the repository scale for the safety assessment SR-PSU. SKB TR-13-08, Svensk Kärnbränslehantering AB.

Blümling P, Adams J, 2008. Grimsel Test Site Investigation Phase IV. Borehole sealing. Nagra Technical Report 07-01, Nagra, Switzerland.

Börgesson L, Johannesson L-E, Sandén T, Hernelind J, 1995. Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element application. SKB TR 95-20, Svensk Kärnbränslehantering AB.

Das B M, 1997. Advanced soil mechanics. 2nd ed. Washington, DC: Taylor & Francis.

Howatson A M, Lund P G, Todd J D, 1972. Engineering tables and data. London: Chapman & Hall.

ISO/TS 17892-6:2004. Geotechnical investigation and testing – Laboratory testing of soil – Part 6: Fall cone test. Geneva: International Organization for Standardization.

Luterkort D, Gylling B, Johansson R, 2012. Closure of the Spent Fuel Repository in Forsmark. Studies of alternative concepts for sealing of ramp, shafts and investigation boreholes. SKB TR-12-08, Svensk Kärnbränslehantering AB.

Messenger J U, 1969. Barite plugs effectively seal active gas zones. In Drilling and production practice. American Petroleum Institute, Paper API-69-160.

Pusch R, Ramqvist G, 2006. Cleaning and sealing of Borehole. Report on Sub-project 3 on plugging of borehole OL-KR24 at Olkiluoto and reference boreholes at Äspö. SKB IPR-06-30, Svensk Kärnbränslehantering AB.

Rao T S, Kora A J, Anupkumar B, Narasimhan S V, Feser R, 2005. Pitting corrosion of titanium by a freshwater strain of sulphate reducing bacteria (*Desulfovibrio vulgaris*). Corrosion Science 47, 1071–1084.

Sandén T, Börgesson L, 2010. Early effects of water inflow into a deposition hole. Laboratory test results. SKB R-10-70, Svensk Kärnbränslehantering AB.

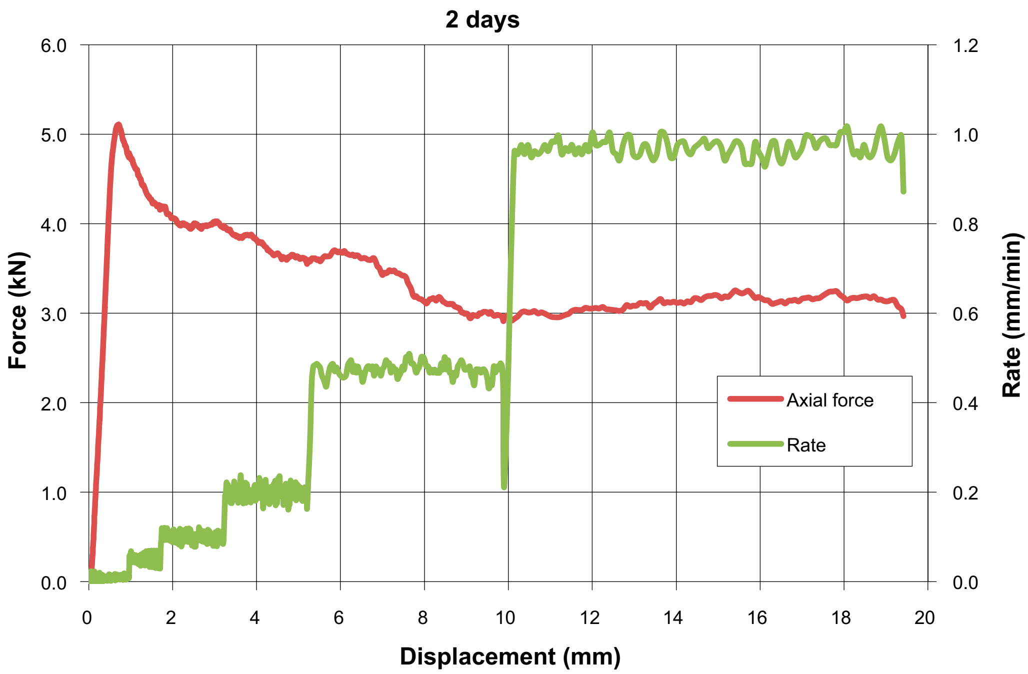
SKB, 2010. Design, production and initial state of the closure. SKB TR-10-17, Svensk Kärnbränslehantering AB.

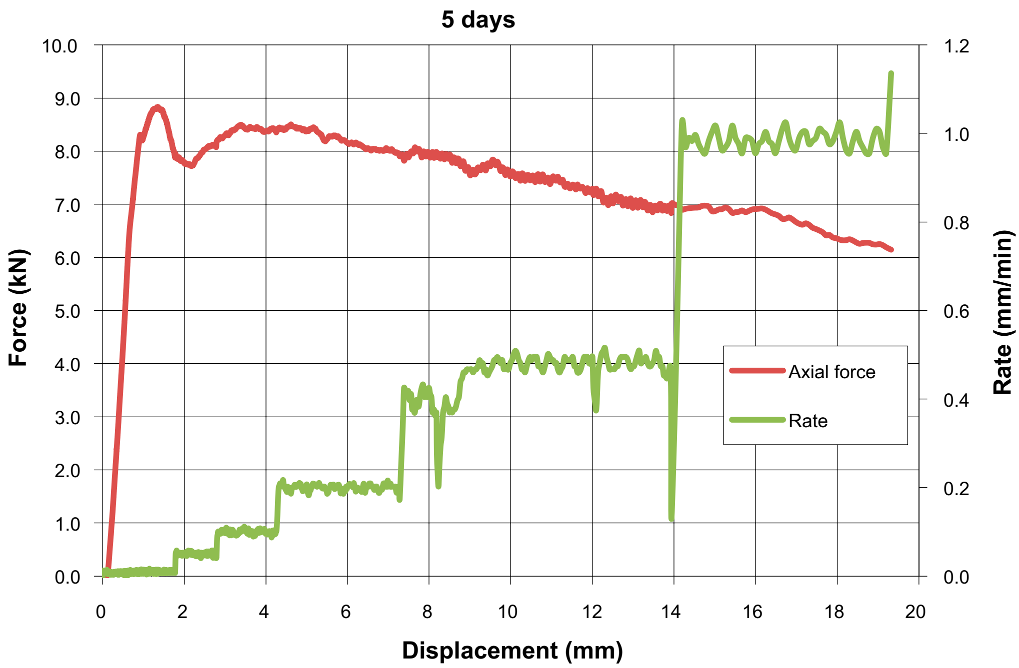
SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Sällfors G, Andréasson L, 1986. Geotekniska laboratorieanvisningar. D. 10, Kompressionsegenskaper. Stockholm: Statens råd för byggnadsforskning. (Statens råd för byggnadsforskning T 1986:23) (In Swedish.)

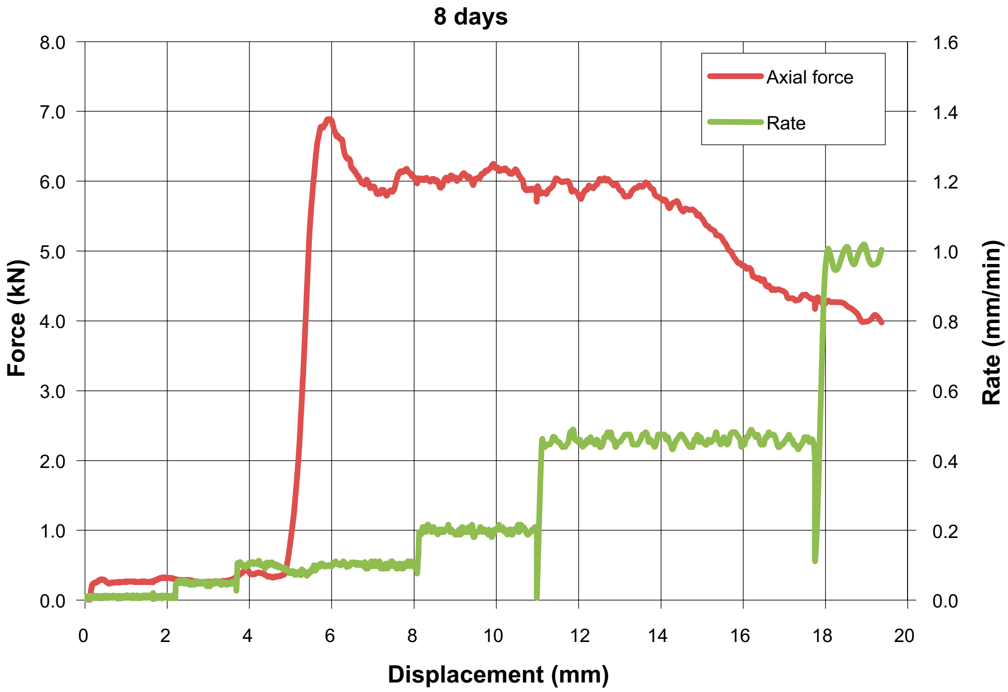
Åkesson M, Kristensson O, Börgesson L, Dueck A, Hernelind J, 2010. THM modelling of buffer, backfill and other system components. Critical processes and scenarios. SKB TR-10-11, Svensk Kärnbränslehantering AB.

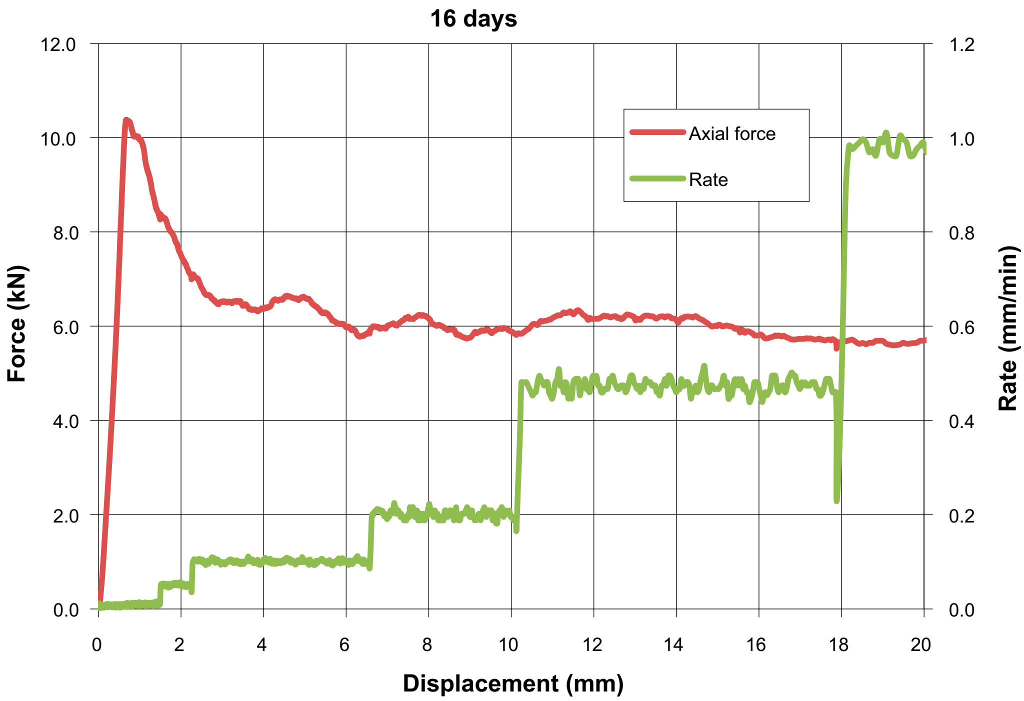
Friction between concrete and rock, 2 days and 5 days test



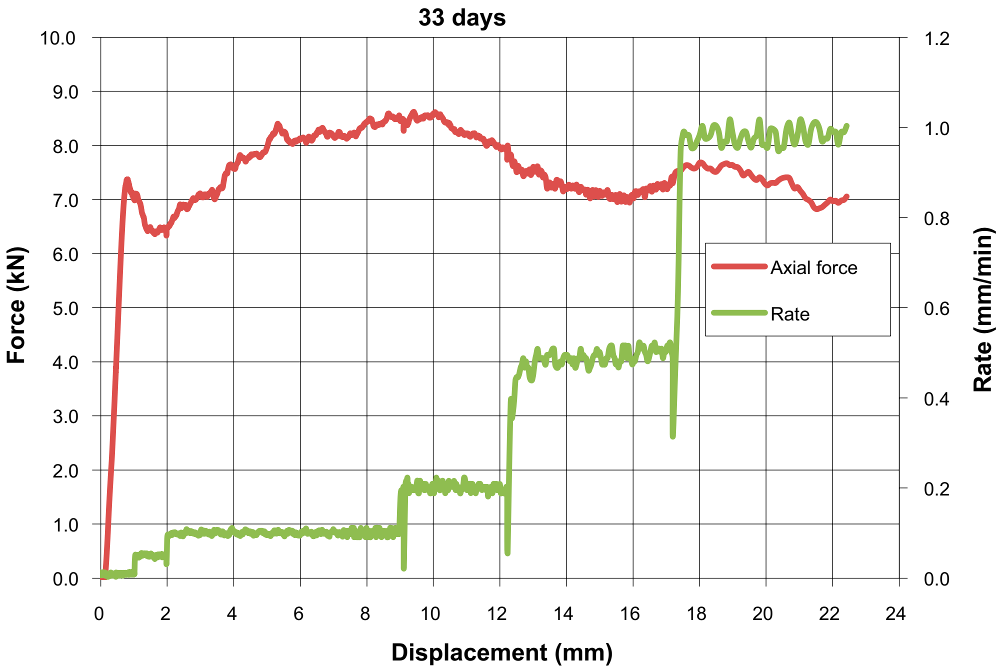


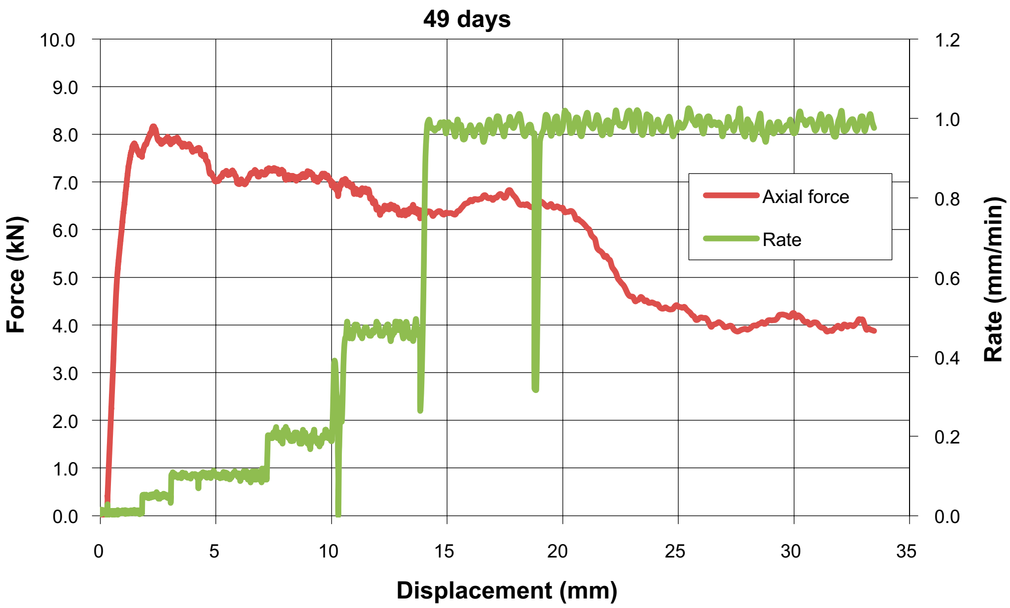
Friction between concrete and rock, 8 days and 16 days test





Friction between concrete and rock, 33 days and 49 days test





Sandaband Material

Sandaband Material

A cost saving technical revolution!

Applications for oil & gas wells:

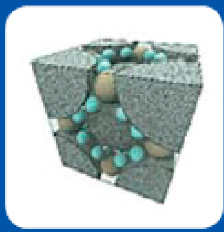
Sandaband: Permanent & Temporary Plugging Material

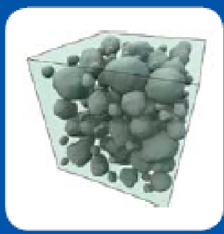
Sandaband: Fill behind Casing

Sandaband: LCM

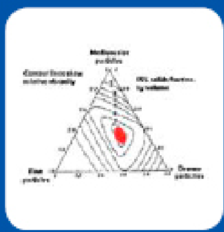
Sandaband products are developed in Norway and patented worldwide.

Sandaband consists of about 70-80% by volume of solids, together with about 20-30% of water and other fluidising additives. Its rheology can be characterised as Bingham plastic. Sandaband mixture is a solid inside a liquidized annulus of itself when it is in motion, otherwise it's a deformable solid.





- Sandaband is a green/non polluting product.
- Sandaband installation is safe and saves rig time (no waiting on hardening, etc).
- Sandaband is easy to place / replace.
- Sandaband is pre-mixed onshore; no mixing offshore.
- Sandaband is chemically inactive.
- Sandaband mixture does not harden, but remains fluidisable (self healing).
- Sandaband leaves no micro annulus.
- Sandaband maintains its fluid flow prevention effect.
- Sandaband complies with NORSOK requirements for P&A.
- Sandaband has been approved by the environmental authorities, both in UK and Norway.
- Sandaband reduces Life Cycle Well Cost.



Sandaband

Permanent & Temporary Plugging Material

Occasionally it is necessary to plug back wells temporarily, mostly because the well is drilled by use of one rig and the completion operation with a different rig. Historically, the common method to plug back wells in the time period while waiting for the completion rig, has been to partially cement back the wells. The reservoir section formation has been cemented back totally, leaving the completion rig the option of re-drilling this section. A selection of packers and short cement plugs in the bottom of the last casing has been used to obtain total well control.

Sandaband as plugging material is an application that allows a temporary plug back of a reservoir section without the need to re-drill. This system consists of a concentrated sand made into a slurry with water and brines. The sand slurry has a particle fraction in excess of 70% by volume. The particle size distribution controls the rheology, permeability and porosity of the slurry.

This method has been performed with success in a 5000 m deep HPHT well in Norway. Use of Sandaband as plugging material is evaluated to have caused little, if any formation damage. The use of the concentrated sand slurry gives a potential time saving of approximately one week per well compared to using cement and removing it from the reservoir section. The sand slurry consists of particles in the range from larger than 2 mm sand to smaller than 0.1µm. The insignificant permeability of the sand slurry is in a range of several orders of magnitude less than 1 millidarcy.

In the HPHT well, the sand slurry was placed in the well from 4917 mMD to 5150 mMD, at an angle between 30° to 35°. The sand slurry, with a 2.2 s.g. density, was placed using the balanced plug method. Two years later the temporary plug was washed out easily. The hole was in perfect shape and the permeability was intact.

A permanent barrier shall and Sandaband does:

- Hold tight for eternity although the well changes over time (pressure, corrosion, shearing of casing).
- Separate the layers in the overburden and protect the fresh ground water ("inner environment").
- Protect the environment ("outer environment"

Why Sandaband remains impermeable:

- A suspension wherein the distances between the particles stay fixed while in the solid state, i.e. the grain distribution remains fixed and with the low porosity (i.e. the volume fraction of liquid ~30% volume) and the non-sorted p article distribution results in permeabilities in the <<0.1mD range.

The natural properties of the Sandaband grains help maintain the plug:

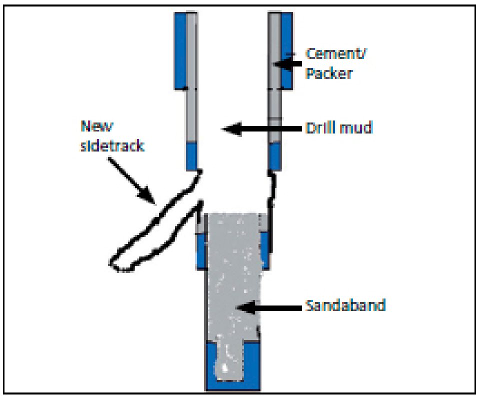
- The electrostatic binding (Zeta potential) between the water molecule and the surface of the smallest micro-silica grains hinders flow in the pore space.
- Sandaband behaves as a Bingham plastic material that becomes a solid unless subjected to its Yield Point limit.

Resistance to fracturing:

- Due to the Yield Point, Sandaband material cannot fracture, because the material in the yielded zone becomes liquid.
- There is no chemical reaction between the solid particles and the liquid phase and therefore no volume shrinkage.

Liquid to solid to liquid:

- Any overburden movement causes the Sandaband plug to move into the liquid state and reshape to the new hole conditions before returning to the solid state.



Sandaband

LCM

The pressure required to move a Bingham Plastic must exceed the product YP*A, where YP=Yield Point and A=Area. When a volume of the material is squeezed into a fracture, the Area (between the fracture surface and the Sandaband material) increases very fast. When the squeeze pressure becomes balanced by the increasing YP*A, further movement into the fracture stops and the material transforms to solid. The subsequent circulation in the well bore can wash out only an insignificant amount next to the well, but the fracture is left permanently sealed, by Sandaband.

A lost circulation situation can be fixed effectively and permanently by using Sandaband LCM both if the loss took place into high permeability or through fractures without permeability into the matrix. No liquid leak off from Sandaband LCM is required.

The material will not filter through itself nor into the formation, due to the low permeability and the large particles that cannot move through the lattice. The entire volume is like a screen out from common types of particle/liquid materials.

The pressure closer to the fracture tip falls below the fracture propagation pressure and fracture radius growth stops. When the pressure applied to propagate/bullhead Sandaband material into the fracture is subsequently bled off, the formation closes and traps the material inside the fracture where it acts as a permanent seal.

Sandaband material cannot flow into the porosity around the fracture. The way to get more material into a fracture that does not propagate radially from the well is by widening the aperture of the fracture. This creates additional counteracting, circumferentially acting stresses from the formation and increased restriction against new fracture opening, so called hoop stress.

The hoop stressed ring around the well bore will act as a reinforcement element of the near-well rock volume; therefore improved well bore stability. This phenomenon has been observed in building of arches. The phenomenon has been modelled.

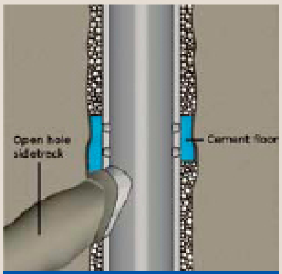
Pink area is stressed, and provides hole stabilization

Because of the presence of all grain sizes, from 2.5 mm to less than 0.000,5 mm, the permeability of the Sandaband material is much smaller than 0,01 mD. This has been confirmed by testing.

Sandaband

Fill behind Casing

Annulus shear strength is necessary only for transfer of load to the formation, therefore only for the structural casing is cementing necessary (and in cased production interval).

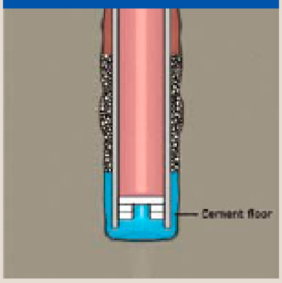


Get rid of the common "cementing problems".

- Sandaband does not shrink and does not set up.
- With Sandaband pressure testing of casing does not create micro annulus or radial cracks.
- With Sandaband mechanical activity inside the casing does not fracture the annulus fill.
- With Sandaband thermal expansion is minimized.
- Use of Sandaband gives less stress on casing.
- Sandaband acts as if the hole is under reamed and facilitates lateral movements in the overburden.
- Casing with Sandaband as the annular pressure integrity medium can easily be recovered, by applying torque and pull on top portion above a casing cut, which will remobilize the Sandaband as a liquid.
- Sandaband gives sufficient stability to the casing.
- Sandaband is placed quicker than cement into the well; no waiting on cement hardening and no pressure testing.
- Sandaband provides annulus seal with everlasting properties.
- Sandaband remains forever as a liquefiable material that deforms as required but without fracturing.
  Sandaband does not develop micro annulus.
- Sandaband does not lose its hydrostatic head.
- Sandaband is not effected by minor casing leaks.
- Sandaband is the perfect "preparation" for the inevitable final well abandonment, for which the superior Sandaband abandonment method should be applied.
- External forces cause less deformation of the casing and no development of annulus or cracks.
- No migration to result in annulus pressure or cross flow between formations.
- Reduced deformation of casing.
- External forces on the casing will not effect the sealing properties in the Sandaband filled annulus.
- Reduced load transfer results in less buckling tendency, corrosion etc..
- Cement fractures and shrinks. Sandaband will become liquid in order to undergo shape change, and is then incapable of fracturing.

The most evident benefits:

- Environmentally superior.
- Protection of ground water.
- Prevents cross flow all along the well.
- Reduces thermal expansion effects by 70% or more.
- Same material has been used in HP/HT well, up to 175°C.
- Perfect for "cementing" of expandable casings.
- Drastically reduced life cycle cost.



SANDABAND®

U.S Patent # 6,715,543
U.S. Patent # 7,258,174

www.sandaband.com

Sandaband Well Plugging AS
Hammaren 15
N-4056 Tananger
Phone +47 47 67 91 28
e-mail: tf@sandaband.com

Arkitektkopia AB, Bromma, 2017

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

skb.se