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Full scale field test and large-scale laboratory tests

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Abstract

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 to the planned start of the construction of aboveground buildings for the Spent Fuel Repository (a few investigation boreholes start 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 have to be developed and tested.

This report describes tests performed in laboratory, implementation of several large-scale installation tests, and finally a field test where a 255-meter-deep borehole has been sealed. The tests were made to demonstrate the recently proposed so-called Sandwich-concept. This concept is based on that the main part of a borehole is filled with granular material (sand, crushed rock), while sealing sections consisting of highly compacted bentonite, are positioned in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. Concrete is positioned on both sides of the bentonite. In addition, copper expanders are positioned to separate different materials.

Requirements

The functional requirements on the borehole sealing for boreholes with hydraulic connections to the repository, regarding nuclear safety and radiation protection is that the hydraulic conductivity of the sealing should not significantly change the natural ground water flow. The design premises stipulate that the hydraulic conductivity of the sealing material should be 10^{-6} m/s or lower. In addition, the project has assumed, in analogy with other barriers within the KBS-3 system, that the borehole closure should fulfill the requirements during the lifetime of the repository (100 000 years). This place demands on the different sealing components included in the suggested Sandwich concept.

For all boreholes close to the repository, the local regulations from the municipality must also be considered.

Borehole characterization

The purpose with the characterization is to classify the boreholes and after that perform a detailed design of the closure for every individual borehole. The work with classification is ongoing and is therefore only briefly described in this report.

Preparatory tests in laboratory and full-scale test in field

Laboratory tests were performed to test and demonstrate the installation of the different sealing components but also to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite. Installation tests in large scale were performed in the Multi Purpose Facilities at Äspö. The tests included installation of both bentonite pellets and sand in an artificial borehole with a length of ten meters. The tests were made at both dry and wet (water filled simulated borehole) conditions. Furthermore, tests were made to install concrete in a simulated borehole with the use of standard drill tubes.

After finalizing the preparatory tests, a full-scale installation test demonstrating the Sandwich concept, was performed. The borehole used for the test had a length of 255 meters and is situated at Äspö. The main objectives with this test were to demonstrate the installation technique of different sealing components in full scale and to test the suggested quality control system regarding e.g. achieved density and position of the different components in the borehole.

The work described in this report were performed within the projects KBP1013 and PSU17.

Sammanfattning

Ett stort antal undersökningsborrhål har borrats dels i det område där det planerade slutförvaret för utbränt kärnbränsle planeras att byggas men även där slutförvaret för kortlivat radioaktivt avfall (SFR) finns. Båda anläggningarna är lokaliserade till Forsmark i Östhammars kommun. Beroende på den planerade byggstarten av ovanjordsanläggningar för Slutförvaret för utbränt kärnbränsle (ett antal borrhål finns här) samt för utbyggnaden av SFR förvaret (sex befintliga borrhål bedöms korsa utbyggnaden), och eftersom det har bedömts att dessa borrhål bör förslutas innan byggstart, har det varit nödvändigt att utveckla och testa tekniker och metoder för förslutning av borrhål.

Denna rapport beskriver genomförandet av ett antal installationstester i stor skala, kompletterande laboratorieförsök samt slutligen förslutningen av ett 250 meter djupt borrhål. Ett av huvudsyftena med testerna har varit att demonstrera det så kallade Sandwich-konceptet. Detta koncept baseras på att borrhålet till stora delar fylls med granulärt material (sand, krossat berg etc.) medan tätningssektioner bestående av högkompakterad bentonit placeras strategiskt i sektioner med bra berg, det vill säga där det inte finns några vattenförande sprickor. Betongsektioner är placerade på båda sidor om bentonitsektionerna och i alla övergångszoner mellan olika material finns kopparexpandrar placerade.

Krav

Funktionskraven på en borrhålsförslutning, för borrhål som är hydrauliskt förbundna med slutförvaret, när det gäller kärnsäkerhet och strålskydd är att den hydrauliska konduktiviteten hos tätningen inte markant skall ändra det naturliga grundvattenflödet. Konstruktionsförutsättningarna säger att den hydrauliska konduktiviteten hos tätningsmaterialet skall vara 10^{-6} m/s eller lägre. Förutom dessa krav har projektet antagit, i analogi med andra barriärer inom KBS-3 systemet, att borrhålsförslutningen skall uppfylla kraven under förvarets livstid (100 000 år). Detta ställer krav på de olika förslutningskomponenterna som ingår i det föreslagna Sandwich-konceptet.

För alla borrhål i närområdet gäller att lokala föreskrifter från samhället också måste inkluderas.

Borrhålsklassificering

Syftet med att karakterisera borrhålen är att kunna klassificera dom och därefter göra en detaljerad design av förslutningen för varje individuellt borrhål. Detta arbete pågår fortfarande och är därför endast kortfattat beskrivet i denna rapport.

Förberedande tester i laboratorium och förslutning i full skala

Laboratorieförsök har genomförts för att demonstrera installationen av alla olika förslutningskomponenter men också för att mäta och demonstrera svällltrycksuppbyggnaden samt tätningseffekten av bentonit med hög densitet. Storskaliga installationstester genomfördes i bentonitlaboratoriet på Äspö. Testerna innefattade installation av både bentonitpellets och sand i simulerade borrhål med ett djup av tio meter. Testerna simulerade både torra och våta (vattenfyllda borrhål) förhållanden. Försök gjordes också med att installera betong i ett simulerat borrhål med hjälp av standard borrör.

Efter det att de förberedande försöken hade avslutats, gjordes en förslutning av ett borrhål i full skala. Borrhålet som använts för det fullskaliga försöket har en längd på 255 meter och finns på Äspö. Målen med detta försök var att demonstrera installationstekniken av de olika förslutningskomponenterna i full skala och att testa det föreslagna kvalitetskontrollsystemet när det gäller till exempel uppnådd densitet samt i vilka sektioner i borrhålet som de olika komponenterna har installerats.

Det arbete som finns beskrivet i denna rapport utfördes inom projekt KBP1013 och PSU17.

Contents

1 Introduction

1.1 General

Many 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 to the planned start of the construction of aboveground 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 to seal borehole 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 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).
- 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. 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.
- 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.

Because of the ongoing development work, a new design for sealing of deep boreholes has been suggested, referred to as the” Sandwich concept”.

The work presented in this report has been performed within the SKB projects PSU-17 and KBP1013.

1.2 Objectives

The main objectives with the project were:

1. To investigate the properties of the different sealing components included in the Sandwich concept by performing small scale laboratory tests.
2. To develop and demonstrate the installation technique for different sealing components. Pretests were performed in both laboratory and in field.
3. To perform a sealing of a full-scale borehole using the Sandwich concept. The main objectives with this test were to demonstrate the installation technique of different sealing components in full scale and to test the suggested quality control system regarding e.g. achieved density and position of the different components in the borehole.

Except for the objectives mentioned above, it has also been a goal to perform an inventory of all boreholes together with a classification. This work is, however, still ongoing and is only briefly described in this report.

1.3 Outline of the report

The different components included in the Sandwich concept and their function have been investigated earlier in the project, see results presented in Sandén et al. (2017). The work presented in this report can be divided according to the following:

1. Requirements
2. Borehole classification
3. Development of the Sandwich concept
4. Laboratory tests
5. Large scale tests
6. Field test

1.3.1 Requirments

The requirements for the borehole sealing are provided in Chapter 2.

1.3.2 Borehole classification

It has been judged that a characterization of all boreholes is needed to classify them and after that perform a detailed design of the closure for every individual borehole. The work with classification is ongoing and is therefore only briefly described in this report but the preliminary outcome is that all boreholes will be divided into three different classes. The classification will be made based on borehole depth, distance to the repository and on the presence of hydraulic connections between the borehole and the repository area. The present suggestion for classification is provided in Chapter 3.

1.3.3 Development of the Sandwich concept

The work with the development of the new Sandwich concept has been ongoing in parallel to the performed tests. The Sandwich concept is described in detail in Chapter 4.

1.3.4 Laboratory tests

Since no measurements after installation were planned after the full-scale installation, completing tests have been performed in laboratory:

1. A Mockup test where all the suggested components were included. After installation, the bentonite, and the other components, had access to water via filter mats on the borehole periphery. The swelling pressure development was registered and after homogenization the hydraulic conductivity of a bentonite section was measured.
2. A homogenization test simulating a 300 mm long section of a borehole sealed with bentonite. 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 laboratory tests are described in Chapter 5 and 6.

1.3.5 Large scale tests

Large scale tests have been performed in the Multi Purpose Facilities at Äspö to develop and demonstrate installation of the different sealing components. The tests can be divided according to the following:

1. Large scale bentonite pellet installation tests. Many short boreholes, and also the uppermost part of deep boreholes, are planned to be filled with bentonite pellets. The main reason for this is to prevent surface water to flow, via the borehole, down to water bearing layers.
2. Large scale sand installation tests. Installation of sand in long sections of a borehole is an important part of the Sandwich concept.
3. Large scale installation tests of concrete where both the technique and the equipment were developed.
4. Test of installation techniques of both copper expander and bentonite package.

The large-scale tests are described in Chapter 7 to 11.

1.3.6 Field test

The Sandwich concept has been tested and demonstrated in a full-scale sealing of a borehole. The borehole used is situated at Äspö and is denominated KAS13. The test has been performed as an installation test and focus of the work has been on the quality control regarding the installed components in different borehole sections.

The field test is described in Chapter 12.

2 Requirements

2.1 Nuclear safety and radiation protection

The functional requirements on the borehole sealing regarding nuclear safety and radiation protection is that the hydraulic conductivity of the sealing should not significantly change the natural ground water flow.

The design premises stipulate that the hydraulic conductivity of the sealing material should be 10^{-6} m/s or lower. This requirement is, however, only valid for the boreholes which are in hydraulic connection with the repository.

2.2 Other requirements

The project has assumed, in analogy with other barriers in the KBS-3 system, that the borehole closure should be mechanical stable during the lifetime of the repository, 100 000 years (valid for the boreholes which are in hydraulic connection with the repository). This place demands on the different sealing components included in the suggested concept. The following has therefore been considered in the design work:

- Degradation of material.
- Erosion of bentonite.
- Redistribution (mixing) of material installed in the borehole.

In addition to the requirements above, local regulations from the municipality must be considered (SGU 2016):

- Surface water should be prevented from flowing down in the borehole and contaminate the groundwater.
- Different water bearing regolith layers shall not have contact with each other via the sealed borehole.

These requirements are valid for all boreholes close to the repository.

3 Borehole classification

3.1 General

Many 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). The variation of borehole types is high, from short boreholes which mainly are drilled through the regolith layers to deep investigation boreholes passing through or close to the planned repository. Due to the large variation of borehole types, it has been decided to perform a classification of all boreholes based on borehole depth, distance to the repository area and on the presence of hydraulic connections between the borehole and the repository area. The work with inventory and classification is ongoing and is therefore only briefly presented in this report. One preliminary outcome is that all boreholes will be divided into three different classes. A preliminary description of the classification and a suggestion for how to seal the boreholes in each class is provided in this chapter.

3.2 Borehole characterization

The purpose with the characterization is to classify the boreholes and after that perform a detailed design of the closure for every individual borehole. The detailed design includes e.g. which sealing components/materials that should be used and where in the borehole they should be positioned. The characterization includes the following activities:

- Review of existing data (SICADA data base, technical reports etc.)
- Geohydrological assessment i.e. how the boreholes are connected to other boreholes or to the repository via different water bearing fractures.
- Preliminary investigation of the borehole on site (ocular inspection, dimensions, instrumentation, casing tubes etc.)
- Decide if the borehole should be cleaned from precipitates and if it must be reamed.

3.3 Borehole classes

The boreholes are suggested to be divided into three classes:

- **BHC1**. Shallow boreholes, 0–75 m, which are assessed to have no hydraulic influence on a repository. This group includes both boreholes going through regolith and through rock and that are not crossing any water bearing fracture zones with hydraulic connections to the repository.
- **BHC2**. Deep boreholes, 75 to > 1 000 m, located rather far from the repository area, > 400 m. The boreholes are not crossing water bearing fracture zones with hydraulic connections to the repository.
- **BHC3**. Deep boreholes, 75 to > 1 000 m, located close to the repository area, < 400 m. Also, other boreholes that are hydraulically connected to the repository area should be in this class.

3.4 Borehole sealing

3.4.1 General

Preliminary descriptions of the borehole classification, the requirements for the closure of the different borehole classes (see description in Chapter 2) and recommendations regarding sealing method for boreholes in each class are provided in this chapter.

3.4.2 Borehole Class BHC1

General description

Shallow boreholes which are assessed to have no hydraulic influence on a repository. The boreholes in this class are divided into two subgroups:

1. Type A: Shallow boreholes in regolith.
2. Type B: Shallow boreholes going in both regolith and rock.

Borehole depth: < 75 m

Hydraulic influence: The boreholes should not cross any water bearing fracture zones with hydraulic connections to the repository area. If they do, they should be upgraded to BHC3.

Distance from repository: Concerns all boreholes that have been drilled in the disposal area.

Requirements on the closure

The requirements for the borehole closure are provided in Chapter 2. The requirements relevant for borehole Class BHC1 are:

- **Tightness (hydraulic conductivity)**. Surface water should not be able to flow via the borehole down to water bearing layers. Different water bearing regolith layers shall not have contact with each other via the sealed borehole. This should be guaranteed by having installed a seal material that is much tighter than the surrounding regolith layers.
- **Mechanical**. The material should constitute a mechanical support for the borehole walls.
- **Post closure safety**. No requirements.

Recommended method for closure of BHC1 boreholes

To fulfill the requirements these boreholes should be filled with bentonite pellets. The bentonite pellet filling will have a hydraulic conductivity that is much lower than the surrounding regolith layers and it will also constitute a mechanical support for the borehole walls.

The boreholes in this class are divided according to the following, Figure 3-1:

- Borehole Type A. Boreholes that only are going through the regolith layer will be filled with bentonite pellets.
- Borehole Type B. If the borehole also is going into the bedrock (borehole Type B), a concrete plug is installed in the upper part of the rock, before reaching the regolith layer. The plug consists of a quarts-based concrete that is in-situ cast in a borehole section with a diameter larger than the nominal.

A top closure (the uppermost meter of the borehole) will consist of either compacted regolith (same as the surroundings) or with conventional concrete.

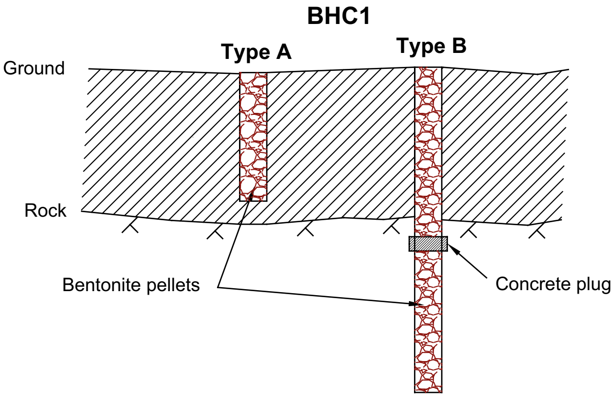


Figure 3-1. Schematic showing how shallow boreholes are sealed with pellets of bentonite.

3.4.3 Borehole Class BHC2

General description

Boreholes with different depths, 75 to > 1 000 m, located relatively far from the disposal area. Boreholes in this class are assessed to have marginal or no hydraulic impact on the repository. It is recommended to seal these boreholes with a rather simple method.

Borehole depth: 75 to > 1 000 m

Hydraulic influence: The boreholes should not cross any water bearing fracture zones with hydraulic connections to the repository area. If they do, they should be upgraded to BHC3.

Distance from repository: > 400 m

Requirements on the closure

The requirements for the borehole closure are provided in Chapter 2. The requirements that are relevant for borehole Class BHC2 are:

- **Tightness (hydraulic conductivity)**.
    1. Regolith layer: See Section 3.4.2.
    2. Rock: No requirements on hydraulic tightness for the parts of the borehole that is going through the rock.
- **Mechanical**. The material should constitute a mechanical support for the borehole walls.
- **Post closure safety**. No requirements.

Recommended method for closure of BHC2 boreholes

The closure of boreholes in this class can be divided in three parts, Figure 3-2:

1. **The regolith layers**. To fulfill the requirements this section of the borehole should be filled with bentonite pellets. The bentonite pellet filling will have a hydraulic conductivity that is much lower than the surrounding regolith layers and it will also constitute a mechanical support for the borehole walls.
2. **Upper part of the borehole section going in rock**. A concrete plug is installed in the upper part of the rock, before reaching the regolith layer. The plug consists of a quarts-based concrete that is in-situ cast in a reamed section with larger diameter.
3. **Borehole going through rock**. Since there are no requirements on the hydraulic tightness for these parts of the boreholes in this class, sand will be used to fill up the volume and give a mechanical support to the borehole walls.

A top closure (the uppermost meter of the borehole) will consist of either compacted regolith (same as the surroundings) or with conventional concrete.

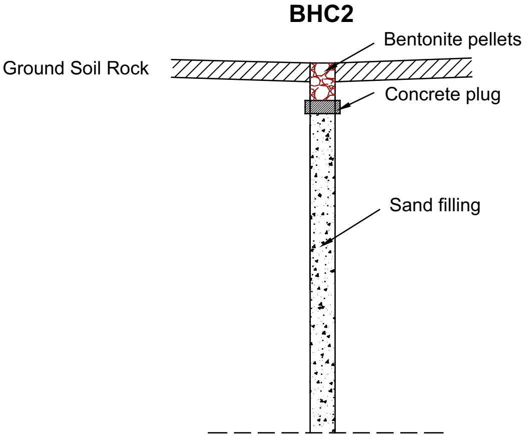


Figure 3-2. *Schematic showing how deep boreholes which are not hydraulic connected to the repository area are sealed.*

3.4.4 Borehole Class BHC3

General description

Medium deep and deep boreholes close to the repository area. These boreholes are assessed to have a certain influence on the hydraulic situation on repository depth. Boreholes in this class are recommended to be sealed in an efficient way to prevent axial water flow.

Borehole depth: 75 to > 1 000 m

Hydraulic influence: All boreholes in the nearfield, < 400 m, with a depth > 75 meters are included in this class.

Distance from repository: < 400 m

Requirements on the closure

The requirements for the borehole closure are provided in Chapter 2. The requirements that are relevant for borehole Class BHC3 are:

- **Tightness (hydraulic conductivity)**.
    1. Regolith layer: See Section 3.4.2.
    2. Rock: The hydraulic conductivity of the sealing should be 10^{-6} m/s or lower.
- **Mechanical**. The material should constitute a mechanical support for the borehole walls and for the sealing sections that are planned to be installed.
- **Post closure safety**. The requirements on mechanical stability and hydraulic conductivity should be fulfilled on the life span of the repository.

Recommended method for closure of BHC3 boreholes

Boreholes in this class should be sealed with the so-called Sandwich method, see detailed description in Chapter 4. The closure of boreholes in this class consists of following components:

1. **Bentonite pellets**. To fulfill the requirements on the part of the borehole that is going through regolith layers, this part should be filled with bentonite pellets. The bentonite pellet filling will have a hydraulic conductivity that is much lower than the surrounding regolith layers and it will also constitute a mechanical support for the borehole walls.
2. **Concrete plug (Upper top seal)**. A concrete plug is installed in the upper part of the rock, before reaching the regolith layer. The plug consists of a quarts-based concrete that is in-situ cast in a reamed borehole section a larger diameter.
3. **Sand**. The main part of the borehole is filled with sand. The sand is mechanically and chemically stable.
4. **Bentonite**. Highly compacted bentonite plugs are positioned in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. These sections will after saturation have a very low hydraulic conductivity.
5. **Concrete**. A special developed concrete with low cement content will be positioned in the transition zones between bentonite and sand.
6. **Copper expanders (bridge plugs)**. The copper expanders are installed to separate different materials. They facilitate the installation e.g. prevents concrete from flowing into the annular gap between bentonite plugs and rock walls and they will also prevent mixing between different materials in the long term.

A top sealing of a borehole i.e. the uppermost meter of the borehole, will consist of either compacted regolith (if the borehole entrance is in regolith) or of conventional concrete (if the borehole entrance is in rock).

4 The Sandwich-concept

4.1 General

New results from hydrogeological modeling are showing that the tightness of the sealed boreholes only marginally will affect the groundwater flow at the depth of a repository (see description in Chapter 1). This has resulted in suggestions for mitigated requirements on the closure of boreholes in class BHC3 (see description in Section 3.4.4).

The new borehole sealing 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, while strategically positioned bentonite seals are placed in selected borehole sections with good rock quality i.e. there are no water bearing fractures present, see the schematic drawing provided in Figure 4-1. 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, copper plugs are installed to separate different materials, to prevent concrete from flowing into the annular gap between bentonite plugs and rock, and to prevent mixing of different materials in the long term. The number of sealing sections (bentonite with concrete on both sides) in a borehole can be decided after characterization of the borehole. The sealing sections can be positioned so that interaction between different water bearing fracture zones at different depths can be minimized. 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 top seal is placed in the uppermost part of the rock. The top seal has a larger diameter than the borehole and will serve as a mechanical lock of the borehole.

The Sandwich concept is assumed to be possible to use in both cored boreholes and percussion boreholes with different diameters. However, except for the laboratory tests, only one full scale test has been made so far (see description in Chapter 12).

The development work of the Sandwich-concept has implied investigations and laboratory tests on the four main components included in the design (Sandén et al. 2017). A detailed description of all components is provided in Chapter 12.

4.2 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 in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. The hydraulic conductivity of the seals will be in the order of 10^{-13} m/s. This implies that a requirement of a certain hydraulic conductivity along the whole borehole length of 10^{-6} m/s will not be fulfilled, but locally the hydraulic conductivity will be much lower.

By using the hydraulic conductivity of the different sealing materials, the hydraulic resistance (R) for the entire sealed borehole can be calculated:

- Assume that the requirement of the hydraulic conductivity (h_w) 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: $R = L/(h_w) = 1\,000/(10^{-8})\ \text{s} = 10^{11}$ 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.

Based on that, the sealing can be substantially simplified and still fulfill the requirements on preventing water from flowing in axial direction of the borehole.

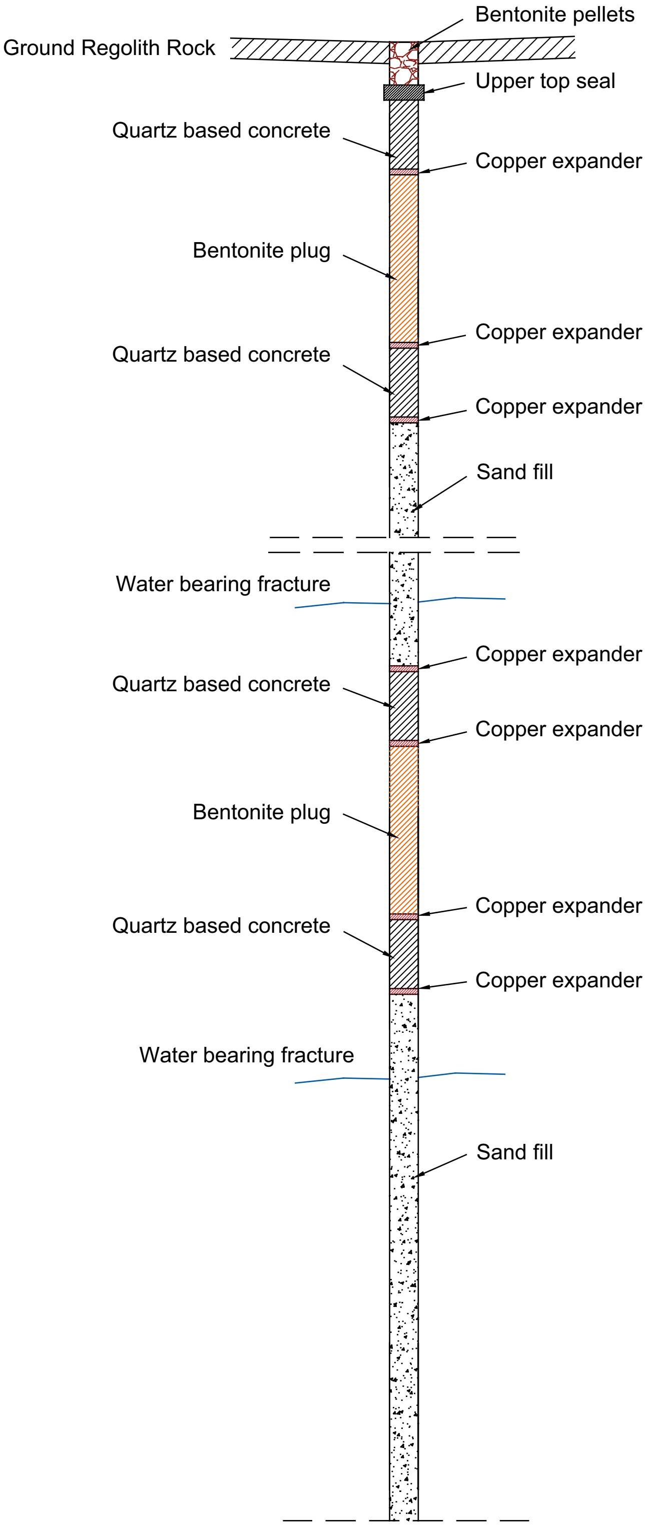


Figure 4-1. *Schematic showing the suggested principle for sealing of deep investigation boreholes, the so called "Sandwich-concept". The design includes dense bentonite plugs positioned in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. Permeable 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 installed to separate different materials.*

4.3 Selection of sealing materials

4.3.1 Sand

The reason for choosing natural quartz sand as a filling material in the transmissive part of the borehole is that it is assumed to be chemically and mechanically stable. The sand used in the tests is a natural quartz sand with a grain size of < 2 mm. Concrete has also been considered but because there are ambiguities regarding the long-term stability due to cement leaching it was decided to use sand.

Possible erosion of sand into open fractures should, however, be further investigated.

4.3.2 SKB concrete

A recipe for quartz-based concrete has been developed earlier within another SKB project (Pusch and Ramqvist 2006). 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 Sandwich-concept, this special concrete is positioned on both sides of the bentonite seal. The main function of the concrete plugs is to prevent the bentonite from swelling in axial direction into the larger voids of the sand 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.

4.3.3 Bentonite

In the Sandwich concept, bentonite seals are placed in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. The bentonite will gradually absorb water and swell to fill the space between the compacted plugs and the borehole walls. After saturation the bentonite is forming a tight seal in the borehole.

4.3.4 Copper expander

Copper expanders (bridge plugs) are installed to separate all materials. An expander consists of 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 is expanded, see further description in Section 12.4.3).

The copper expanders are intended to 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.

5 Homogenization test

5.1 General

Since no investigations and measurements were made after installation of the full-scale field test, see Chapter 12, completing tests were performed in laboratory, one smaller homogenization test which is described in this chapter and one larger Mockup test including installation of all components, see description in next chapter.

The main objectives with the homogenization test were to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite installed in a borehole section.

The test started in October 2016 and the installation and early results were reported in Sandén et al. (2017). The results after termination of the test are provided in this report.

5.2 Test equipment

In accordance to earlier investigations regarding borehole sealing, a special designed test equipment was designed and manufactured (Pusch and Ramqvist 2006). The reference design for borehole sealing presented at that time was tested with this equipment and was now also used for the current homogenization test. The test represented bentonite installed as packages that have been lowered down in water filled borehole according to the Sandwich concept, see description in Chapter 4.

The test equipment simulates a borehole section with a length of 250 mm and an inner diameter of 80 mm, Figure 5-1. On the periphery of the test cylinder two filter mats, each with a height of 115 mm, are positioned. A length of 20 mm at the middle of the simulated borehole section is thus without filter. This section simulates a rock section without any cracks and was used to determine the hydraulic conductivity of the homogenized bentonite. Different water pressures were applied in the filter mats above and below and by that a pressure gradient over the twenty mm long bentonite section was achieved.

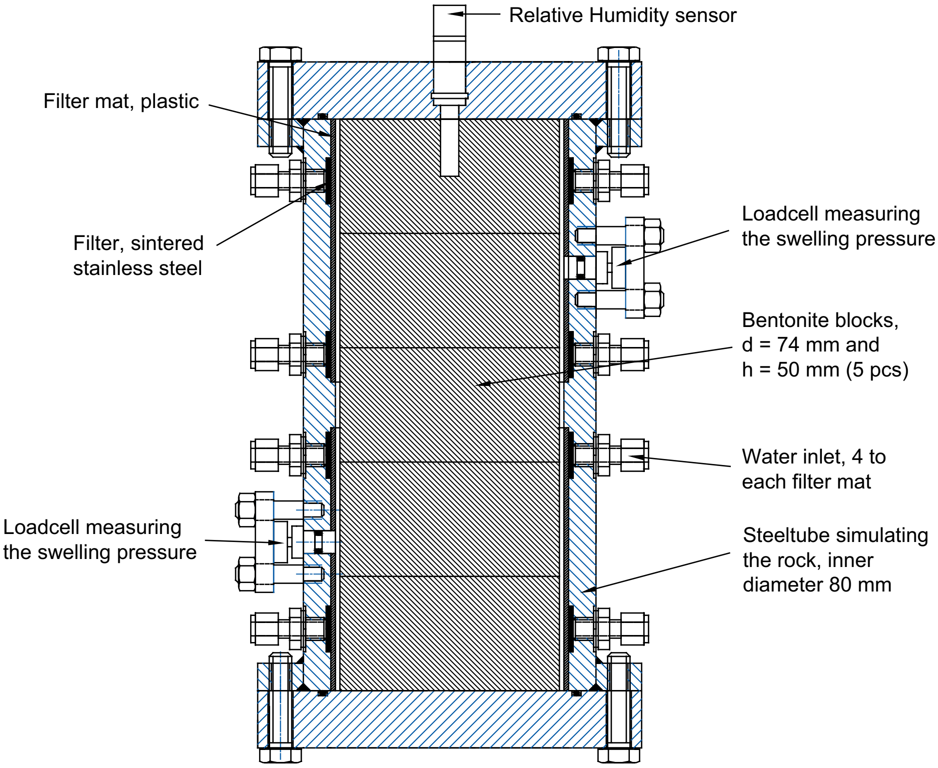


***Figure 5-1.** Schematic drawing of the test equipment simulating a section of a borehole that has been filled with dense bentonite plugs.*

Two radial pistons were used to register the built-up swelling pressure. In the midpoint of the uppermost bentonite plug, a relative humidity sensor was installed. This sensor was used to interpret the water saturation of the bentonite.

5.3 Material

5.3.1 Bentonite

The bentonite plugs were manufactured of MX-80 bentonite from American Colloid Company that 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 saturated density of the bentonite after swelling was calculated to approximately 2 011 kg/m^3 (corresponding to a dry density of 1 576 kg/m^3 . A central hole for the relative humidity sensor was carefully drilled in the uppermost bentonite block. The five bentonite plugs were thereafter piled on top of each other in the center of the simulated borehole. The expected swelling pressure after saturation was in the range of 5–6 MPa.

5.3.2 Water

The water used in the test had a salinity of 1 % by weight (50/50, Na/Ca).

5.4 Installation and test start

The test tube was filled up with water via the lower inlets while the uppermost were used for deairing. The bentonite had after that access to water via a burette (water pressure at the inlet point approximately one-meter water column). 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 would destroy it), the sensor was pushed into position and a water pressure of 100 kPa was applied in the filter mats.

5.5 Test results

5.5.1 General

The test was terminated after about six months test duration. In this section the results from the different measurements are provided, both those made when the test was running (water uptake, swelling pressure and hydraulic conductivity) but also the results from the measurements made after termination of the test i.e. water content and density distribution within the bentonite.

5.5.2 Water uptake

The injected water volume since test start was continuously measured, Figure 5-2. 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. After 140 days test duration, water was circulated in the filter mats and the water uptake continued after that. This affected also the registered swelling pressure, see Section 5.5.3. The total water volume needed to saturate the bentonite in the locked volume was before test calculated to 0.34 l. The difference in the actual injected and the calculated volume depends on the volumes of water in tubes and filter mats.

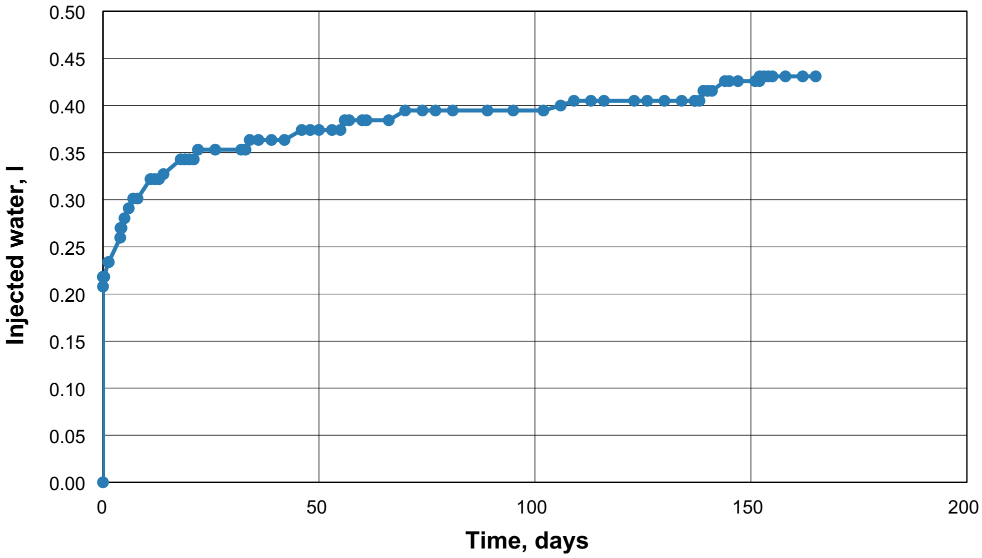


Figure 5-2. *Injected water volume plotted versus time.*

5.5.3 Swelling pressure

The registered pressure and relative humidity as a function of time is provided in the graph in Figure 5-3. There was during long time a large difference in swelling pressure between the two sensors. After about 140 days test it was decided to circulate water in the filter mats (see Section 5.5.2) and after that the swelling pressure measured by the upper sensor started to increase fast. It is believed that there was air trapped in the filter and this had locally prevented the water uptake of the bentonite. The registered swelling pressure after 165 days test was between 4.5 and 5.3 MPa. Day 166, the applied pore water pressure was increased to 500 kPa in the lower filter and decreased in the upper filter to 0 kPa, in order to measure the hydraulic conductivity.

The registered relative humidity at the installation was just above 50 % but increased fast to 90 % and has after that increased slowly with time.

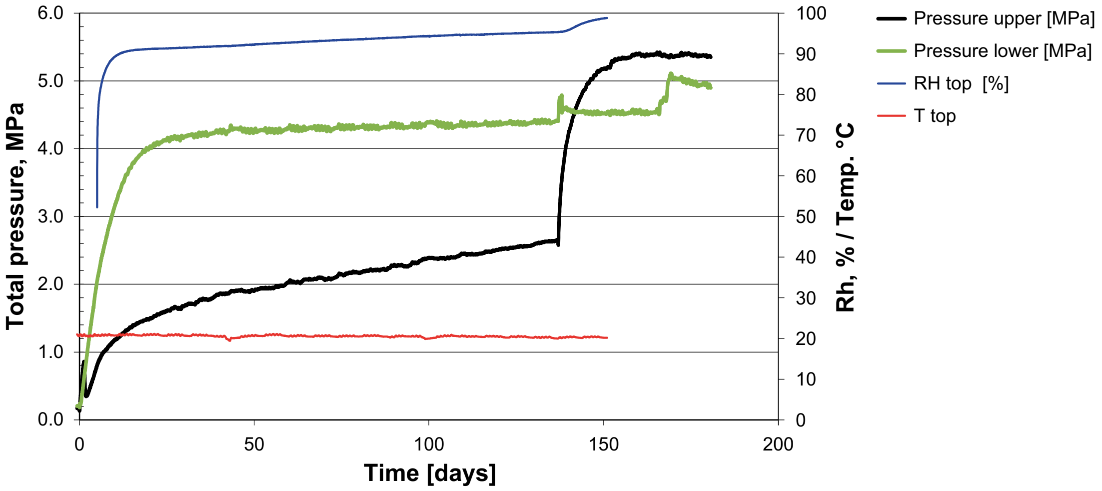


Figure 5-3. *Graph showing the pressure built up and the relative humidity plotted versus time for the homogenization test.*

5.5.4 Hydraulic conductivity

After completed saturation and homogenization, an estimation of the hydraulic conductivity was made. By applying a hydraulic gradient between the two filter mats equipped with water inlets and by measuring the water flow, the hydraulic conductivity along the section without filter was measured. The measurements were done by increasing the water pressure in the lower filter mat to 500 kPa and lower the pressure in the upper filter mat to 0 kPa.

Figure 5-4 shows the water volume injected by a GDS (advanced pressure/volume controller) and the measured outflow (the position of a meniscus in a tube with an inner diameter of 4 mm was measured) as function of time. The average flow rate when reaching steady state was estimated to 0.023 ml/h.

A preliminary and rough evaluation of the hydraulic conductivity was done. In the calculations the boundary conditions were simplified to one dimensional flow with the assumption that the flow goes from a filter applied perpendicular to the tube axis in the middle of the inflow filter to a filter applied perpendicular to the tube axis in the middle of the outflow filter. Figure 5-5 illustrates the simplified model.

The approximate value of the hydraulic conductivity can then be calculated as follows.

$$v = k \cdot i \qquad (5\text{-}1)$$

$$q = k \cdot i \cdot A = k \cdot A \cdot \Delta h / L \qquad (5\text{-}2)$$

where

v = rate of water flow in a porous media (m/s)

k = hydraulic conductivity (m/s)

i = hydraulic gradient

q = flow rate (m^3/s)

A = cross section area (m^2)

Δh = difference in hydraulic head (m)

L = flow length (m)

In the test, the hydraulic head difference was set to $\Delta h = 50$ meter water column.

$A = 0.00502\ \text{m}^2$

$L_f = 0.115$ m (length of filters on wall)

D = 0.02 m (distance between filters on wall)

$L = L_f/2 + L_f/2 + D = 0.135$ m

$q = 0.023\ \text{ml/h} = 6.4 \times 10^{-12}\ \text{m}^3/\text{s}$

$k = 3.4 \times 10^{-12}$ m/s

Since the flow situation in the experiment is rather complex and the analytical evaluation was too approximate, a more relevant evaluation by FEM-calculation should be done.

5.5.5 Water content and density distribution

General

In order to check the achieved density and the homogeneity of the bentonite sealing in the simulated borehole, the water content and the density were determined at several positions.

Sampling

After having pushed out the bentonite specimen from the test cell, slices were cut out at three levels; at the same level as the upper pressure measurement, at the mid height and at the same level as the lower pressure measurement, see Figure 5-1. From each of the slices, samples were sawed out according to the drawing provided in Figure 5-6. The bulk density and the water content were determined on every sample. With this data, the dry density, the void ratio and the degree of saturation were calculated, see description in next Section. Figure 5-7 shows a photo of the bentonite pieces after division.

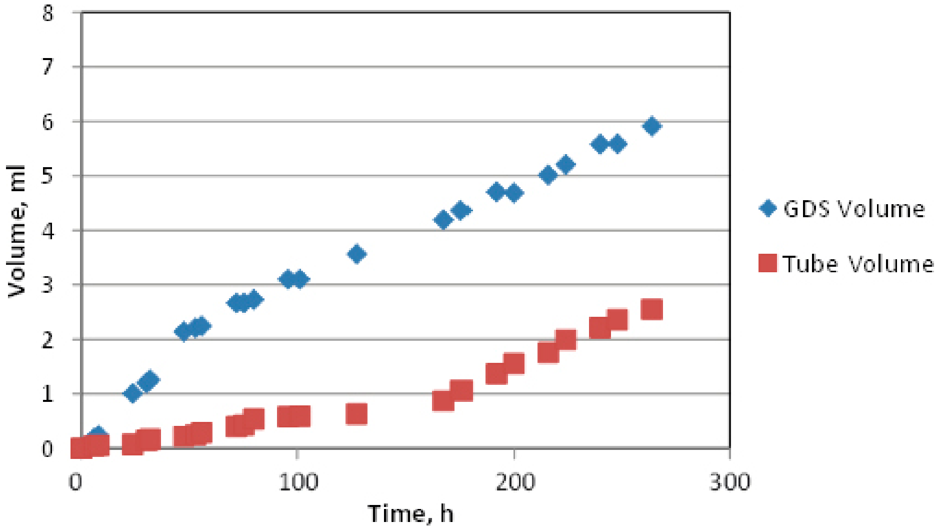


Figure 5-4. Injected water volume (GDS) and measured outflow (Tube) plotted versus time.

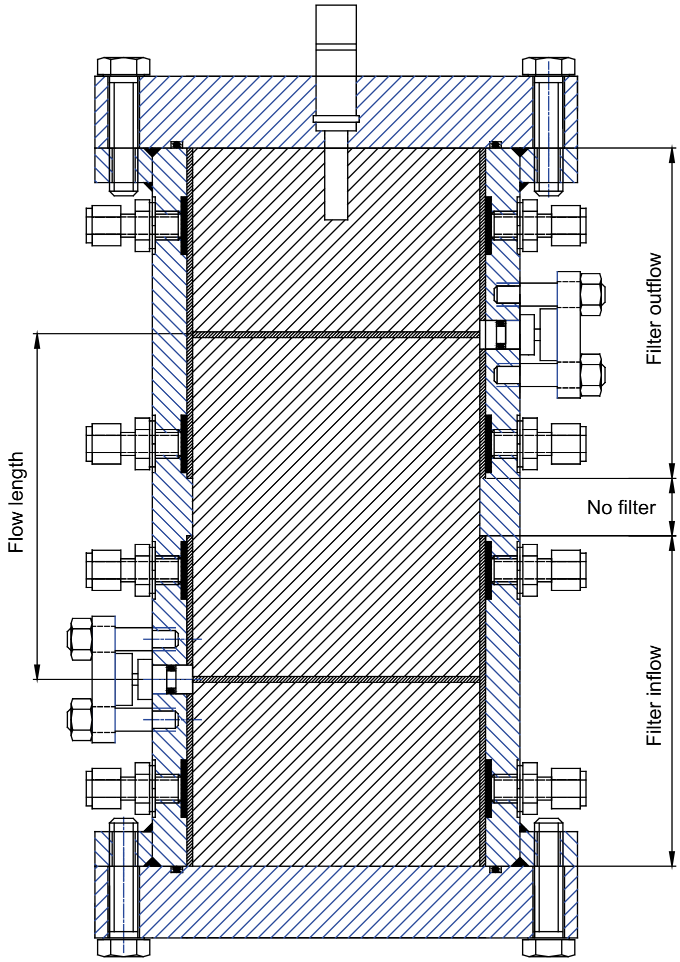


Figure 5-5. Illustration of the simplified flow model showing two imaginary filters perpendicular to the tube axis.

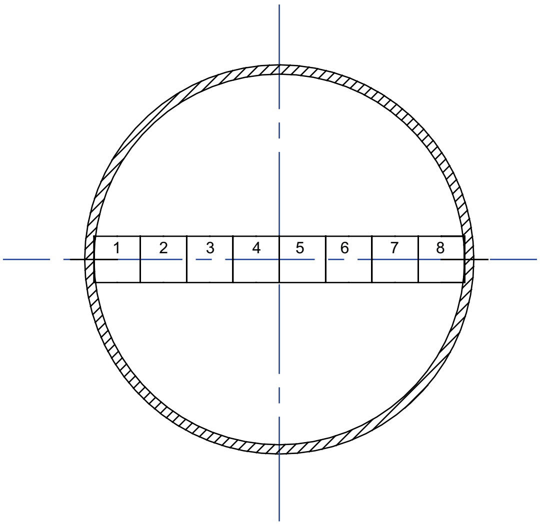


__Figure 5-6.__ Schematic drawing showing the sampling of a slice cut out from the bentonite specimen.

__Figure 5-7.__ Photo of the bentonite core. The different sampling sections have been cut out and then piled on each other.

Calculations

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 5-3–5-6.

$$w = 100 \cdot \frac{m_{tot} - m_s}{m_s} \tag{5-3}$$

$$\rho_d = \frac{\rho}{1 + w/100} \tag{5-4}$$

$$e = \frac{\rho_s}{\rho_d} - 1 \tag{5-5}$$

$$S_r = \frac{\rho_s \cdot w}{\rho_w \cdot e} \tag{5-6}$$

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

Presentation of results

The results from the determinations of water content and dry density distribution are presented in Figure 5-8 and Figure 5-9. The determined values are plotted versus the distance along the simulated borehole diameter i.e. 40 mm on the x-axis corresponds to the center of the specimen. All figures, including the calculated void ratio and degree of saturation for every sample are provided in Table 5-1.

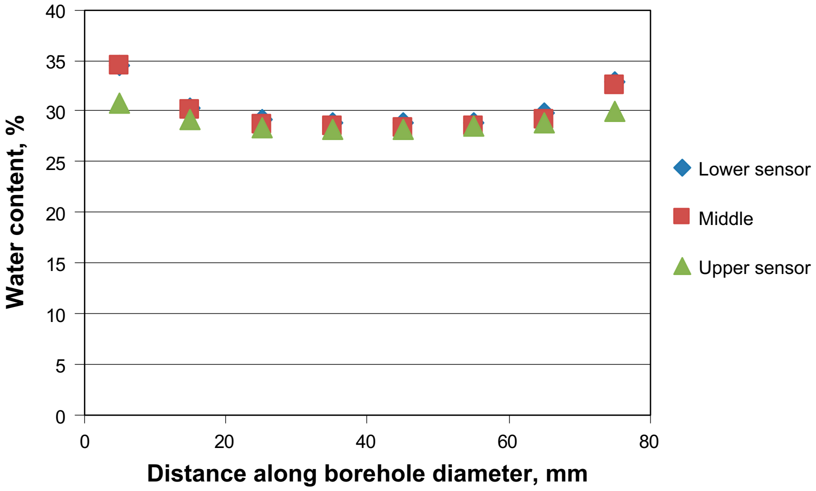


Figure 5-8. *Water content distribution determined at three levels of the bentonite.*

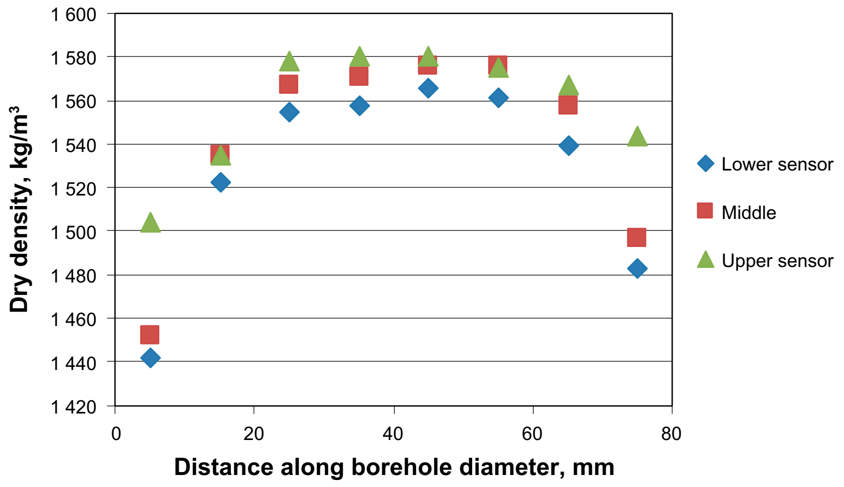


Figure 5-9. *Dry density distribution determined at three levels of the bentonite.*

Table 5-1. Compilation of results from the sampling of the bentonite.

	Water content %	Bulk density kg/m³	Dry density kg/m³	Void ratio	Degree of saturation %
Lower sensor 1	34.4	1937	1442	0.935	102.6
Lower sensor 2	30.2	1982	1523	0.832	101.2
Lower sensor 3	29.1	2007	1555	0.795	102.1
Lower sensor 4	28.8	2006	1558	0.791	101.4
Lower sensor 5	28.7	2015	1565	0.782	102.5
Lower sensor 6	28.8	2011	1561	0.787	102.2
Lower sensor 7	29.8	1998	1539	0.813	102.3
Lower sensor 8	32.8	1969	1483	0.881	103.7
Middle 1	34.4	1951	1452	0.922	104.1
Middle 2	30.1	1997	1535	0.818	102.6
Middle 3	28.7	2016	1567	0.781	102.4
Middle 4	28.5	2018	1571	0.776	102.3
Middle 5	28.3	2021	1575	0.771	102.3
Middle 6	28.5	2024	1576	0.771	103.0
Middle 7	29.0	2010	1558	0.791	102.4
Middle 8	32.4	1982	1497	0.864	104.8
Upper sensor 1	30.7	1967	1504	0.855	100.3
Upper sensor 2	29.2	1982	1535	0.818	99.5
Upper sensor 3	28.3	2024	1578	0.768	102.8
Upper sensor 4	28.1	2025	1580	0.765	102.5
Upper sensor 5	28.1	2024	1580	0.766	102.4
Upper sensor 6	28.4	2023	1575	0.772	102.8
Upper sensor 7	28.7	2017	1567	0.781	102.6
Upper sensor 8	29.9	2005	1544	0.807	103.3

The bentonite has swelled and filled up the initial gap between bentonite plugs and the wall of the test cylinder. There are, however, remaining differences in density between the center of the bentonite and in the former gap. The dry density in the center of the bentonite core was between 1 550 and 1 580 kg/m^3 and the density close to the simulated borehole walls was between 1 440 and 1 540 kg/m^3. The calculated degree of saturation varied in general between 99.5 and 104.8 %. The scatter is believed to partly depend on the fact that the water content and dry density used in the calculations were not made on the same clay sample, but on neighboring samples. It is, however, judged that all bentonite in the test was water saturated.

5.6 Comments and conclusions

The main objectives with the test were to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite installed in a rock section. The dry density of the bentonite installed in the simulated borehole section varied between 1 440 kg/m^3 (at the test tube walls) and 1 580 kg/m^3 (at the central parts).

The registered swelling pressure from the bentonite against the simulated rock wall was around 5 MPa which was well in agreement with the expected 4–6 MPa (Åkesson et al. 2010). The calculated hydraulic conductivity of the sealing, 3.4×10^{-12} m/s, is higher than expected for the density, 10^{-13} m/s (Åkesson et al. 2010). This depends on the rough method used for the calculation, see further discussion in Chapter 6.

6 Mock-up test

6.1 General

All components included in the Sandwich design have been tested separately in laboratory (Sandén et al. 2017). The main objectives with the Mockup test described in this chapter are

- to verify and demonstrate the function of all sealing components and 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 started at the beginning of December 2016 and the installation and early results were reported in Sandén et al. (2017). The results after termination of the test are provided in this report.

6.2 Test equipment

The simulated borehole section has a total length of 4 000 mm, Figure 6-1. The inner diameter of the steel tubes is 83.7 mm. The section with bentonite installed is covered with filters on the periphery, except for a short section at the center of the simulated borehole, 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 two filter mats are connected to separate water inlets and outlets which make it possible to both feed the bentonite with water but also to circulate water to get rid of trapped air. In the sand and concrete filled sections it is possible to apply point inflows to fill also these sections with water. The Plexiglas sections 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 6-1, 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 sand fillings and at the two sections with concrete filling. There was thus no Plexiglas tube at the bentonite section since it was judged that there was a risk that the swelling pressure from the bentonite could destroy it. The homogenization of the bentonite sealing section was monitored with three radial pressure sensors. In addition, one pressure sensor was positioned at the top of the simulated borehole, measuring the axial pressure in the filling.

6.3 Seal and closure components

6.3.1 Sand filling

As a result of the laboratory tests performed earlier (Sandén et al. 2017), it was decided to use "Fogsand < 2 mm" as the sand component. This material has the lowest compressibility and can be installed in deep boreholes to relatively high densities. The later performed tests in large scale, see Chapter 8, confirmed that this material should be suitable.

6.3.2 Bentonite plugs

The bentonite plugs were manufactured of MX-80 bentonite from American Colloid Company that was compacted to a bulk density of 2 100 kg/m^3 and with a water content of 10.0 %. The plugs had a diameter of 70 mm and a height of 50 mm. The saturated density of the bentonite after swelling is calculated to approximately 1 936 kg/m^3 (corresponding to a dry density of 1 455 kg/m^3, see further discussion in Section 6.4.4. 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 6-2. Nuts were positioned in recesses machined out from the end surfaces of the outermost plugs.

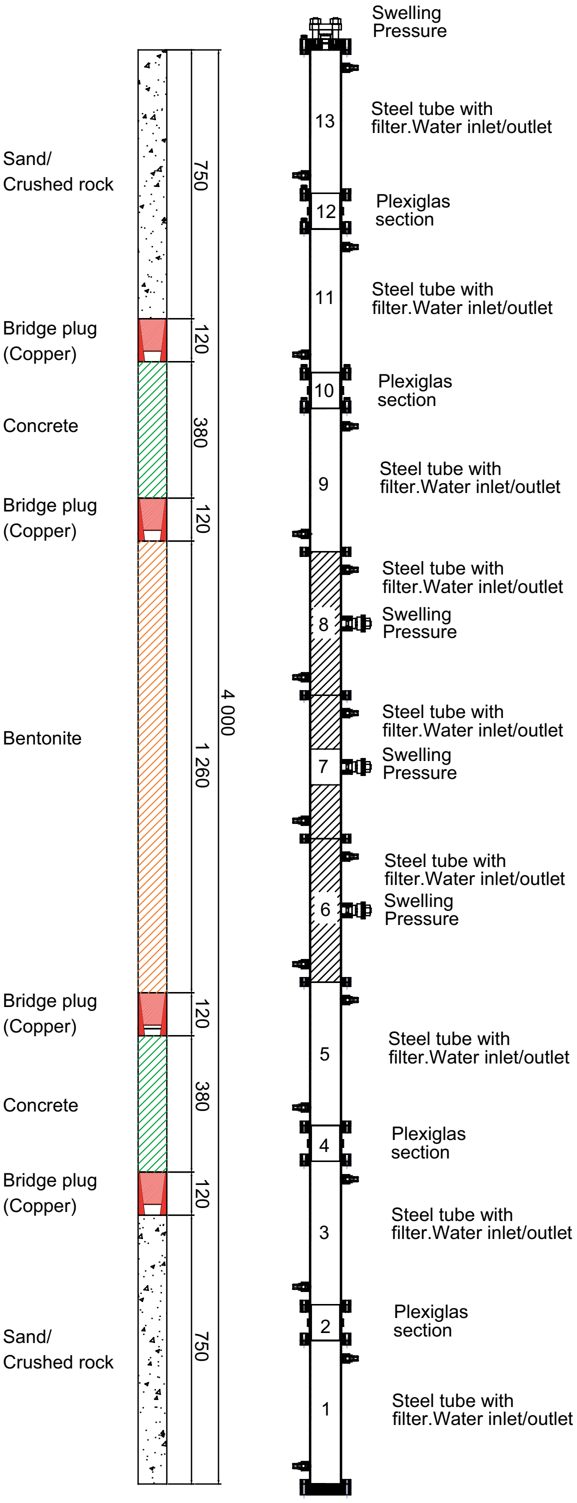


Figure 6-1. *Schematic drawing showing the test equipment simulating a section of a borehole. The different components in the Sandwich-concept are all included in the test, see description on the left side of the drawing.*

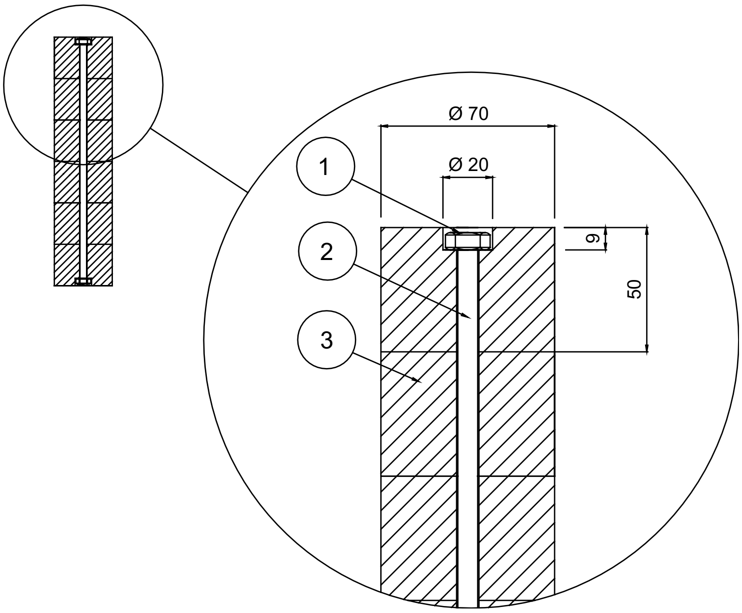


Figure 6-2. Schematic drawing showing a bentonite plug package.

6.3.3 Quartz based concrete

A recipe for quartz based concrete plugs was suggested in Pusch and Ramqvist (2006), see Table 6-1. 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 concrete was installed manually during the mounting of the equipment i.e. no dump bailer was used.

Table 6-1. 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 α 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

6.3.4 Copper expander (bridge plug)

The copper expanders used in the Mockup were developed and tested within an earlier phase of the project (Sandén et al. 2017), Figure 6-3. In total four copper expanders were installed in the mockup test.

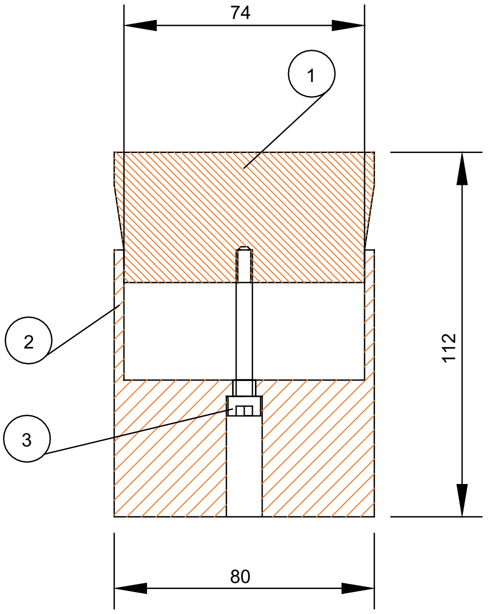


Figure 6-3. *Schematic drawing showing a copper expander.*

6.4 Installation and test start

The simulated borehole was built up step by step by adding new test tube sections. 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 test tube.

6.4.1 Sand filling

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

Figure 6-4 shows a photo of the upmost surface of the sand section installed at the top (left photo) and 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.

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 is considerably lower than what was achieved in the large-scale tests described in Chapter 8 (between 1 647 and 1 682 kg/m^3). The reason for this is unclear. The water content of the installed sand was 2.2 %.

6.4.2 Copper expander

In total four copper expanders were installed in the Mockup test, see Figure 6-1. The expanders were installed by lowering them into the test tube, standing on the material installed below, Figure 6-5. A hydraulic piston was then used to compress the expanders, Figure 6-6. The flanges on the steel tubes were used to mount a temporary anvil, see Figure 6-6, which after compression of the expander was removed again.

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 (Sandén et al. 2017) showed that an axial force of below 10 kN would be needed to compress and expand the copper so that it would seal against the simulated borehole wall. 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 was for all four expanders determined to between 14 and 16 mm.

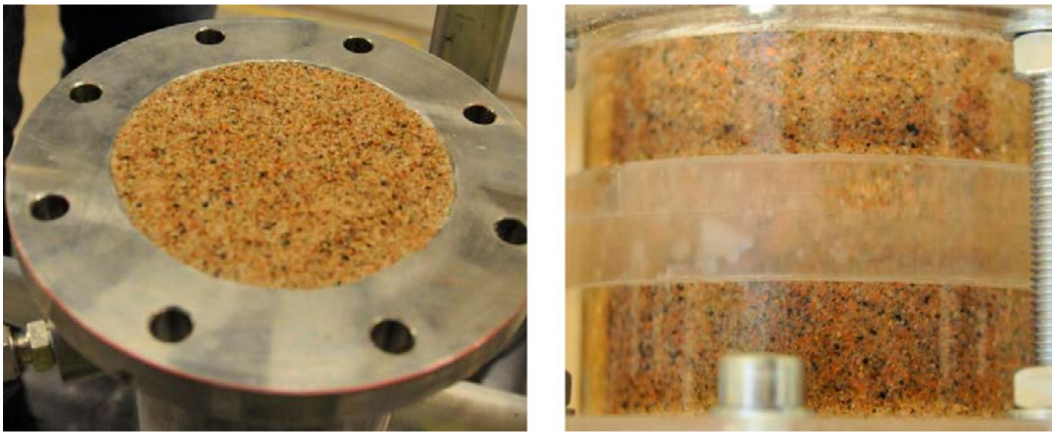


Figure 6-4. *Left: The top of the uppermost sand section. Right: Close-up of the lower sand filled section. The photo is taken through one of the Plexiglas sections.*

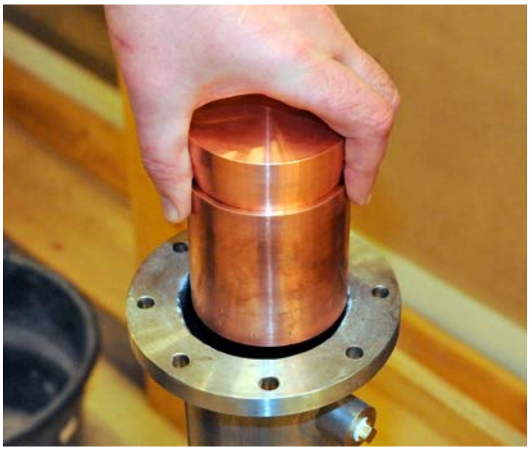


Figure 6-5. *Installation of a copper expander in the simulated borehole.*

Figure 6-6. *A hydraulic piston was used to compress the copper expander.*

6.4.3 Quartz based concrete

The quartz-based concrete was mixed just before installation in the simulated borehole. The concrete was installed by hand in the test tube. The concrete was rather stiff, and it was not possible to pour it into the test tube. It was later found out that the amount of Superplasticizer was too small since no compensation had been made for the water content in the as-delivered Superplasticizer. The amount given in the recipe, see Table 6-1, was for the dry mass. 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 (Sandén et al. 2017).

Figure 6-7 shows the upper surface of one of the concrete sections after curing (left) and a close up of the concrete seen through a Plexiglas section (right).

6.4.4 Bentonite plugs

The bentonite plugs were installed as two packages, see Figure 6-2. 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 6-8 (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 radial swelling pressure is continuously registered at three positions, see photo in Figure 6-8. In addition, one sensor is measuring the axial pressure at the top of the test equipment.

6.4.5 Water filling and test start

An overview of the test setup is shown in the photo in Figure 6-9. 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 feeding the filter mats.

After having finished the installation and started the registration of data, the test tube was filled up with water from the bottom and upwards. The uppermost inlets were used for de-airing. In total about 5.3 liters of water were injected. After having completed the water filling, a water pressure of 100 kPa was applied in all water inlets.

Figure 6-7. *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. The band that crosses at the mid-height of the photo is an extra reinforcement made of Plexiglas.*

Figure 6-8. *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.*

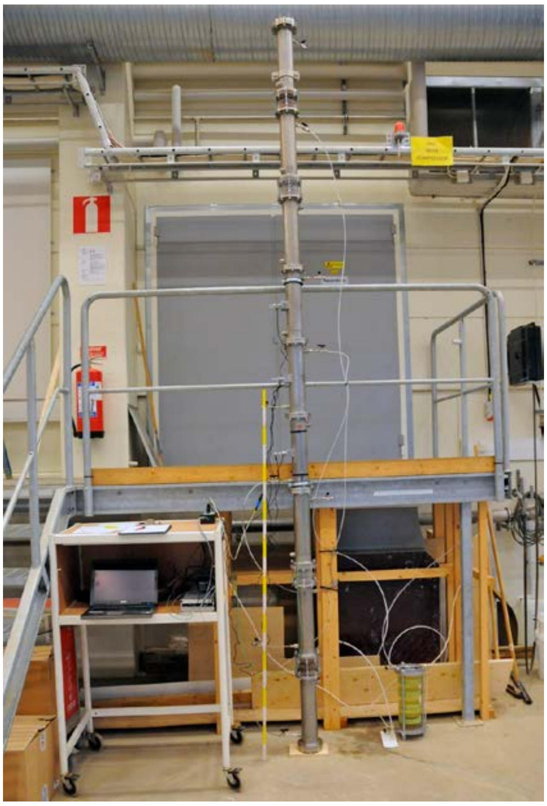


Figure 6-9. *Overview of the test setup after having finished the installation. The vessel on the floor to the right contains the pressurized water.*

6.5 Results

6.5.1 General

The test was terminated after about five and a half months test duration. In this section the results from the different measurements are provided, both those made when the test was running (water uptake, swelling pressure and hydraulic conductivity) but also the results from the measurements made after termination of the test (water content and density distribution in the bentonite specimen).

6.5.2 Water uptake

The injected water volume since test start was continuously measured, Figure 6-10. A certain water uptake by the bentonite was registered during the first month but has after that decreased to almost zero.

6.5.3 Swelling pressure

The registered pressure as a function of time is provided in the graph in Figure 6-11. The radial swelling pressure from the bentonite against the simulated rock walls have been between 1.5 and 1.9 MPa. Approximately one month before the test termination a water pressure of 500 kPa was applied in the lower filter section to measure the hydraulic conductivity of the installed bentonite sealing, see further description in Section 6.5.4. The increase in pore pressure can very evidently be seen in the graph of the measured total pressure (blue line).

6.5.4 Hydraulic conductivity

After completed saturation and homogenization, an estimation of the hydraulic conductivity has been made. By applying a hydraulic gradient between the two filter mats equipped with water inlets and measure the water flow, the hydraulic resistance along the section without filter have been measured. The measurements were done by increasing the water pressure in the lower filter mat (and the lower part of the test cell including sand and concrete) to 500 kPa. The water pressure in the upper filter was kept constant at 100 kPa,

Figure 6-12 shows the water volume injected by a GDS (advanced pressure/volume controller) as function of time. The average flow rate when reaching steady state flow rate was estimated to 0.006 ml/h.

A preliminary rough evaluation of the hydraulic conductivity has been done according to the same principle as described in Section 5.5.4 i.e. the boundary conditions have been simplified to one dimensional flow with the assumption that the flow goes from a filter applied perpendicular to the tube axis in the middle of the inflow filter to a filter applied perpendicular to the tube axis in the middle of the outflow filter. The drawing provided in Figure 6-13 illustrates the simplified model (the drawing also provides information regarding the position of the five sampling sections in the bentonite, see Section 6.5.6).

An approximate value of the hydraulic conductivity has been calculated as follows (see description of equations in Section 5.5.4):

In the test, the hydraulic head difference was set to $\Delta h = 40$ meter water column.

$A = 0.00502\ \mathrm{m}^2$

$\mathrm{L_f} = 0.550$ m (length of filters on wall)

$\mathrm{D} = 0.1$ m (distance between filters on wall)

$L = \mathrm{L_f}/2 + \mathrm{L_f}/2 + \mathrm{D} = 0.65$ m

$q = 0.006\ \mathrm{ml/h} = 1.7 \times 10^{-12}\ \mathrm{m^3/s}$

$k = 5.4 \times 10^{-12}$ m/s

Since the flow situation in the experiment is rather complex (as in the Homogenization test described in Chapter 5) and the analytical evaluation is too approximate, a more relevant evaluation by FEM-calculation should be done.

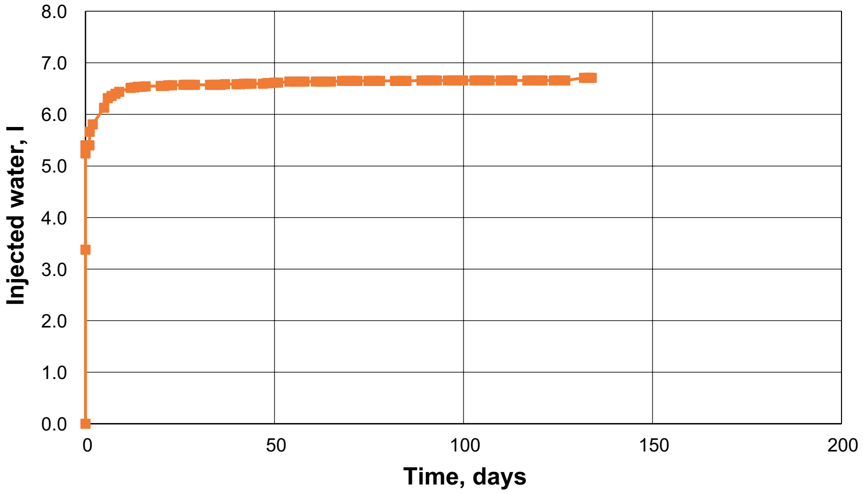


Figure 6-10. *Injected water volume plotted versus time.*

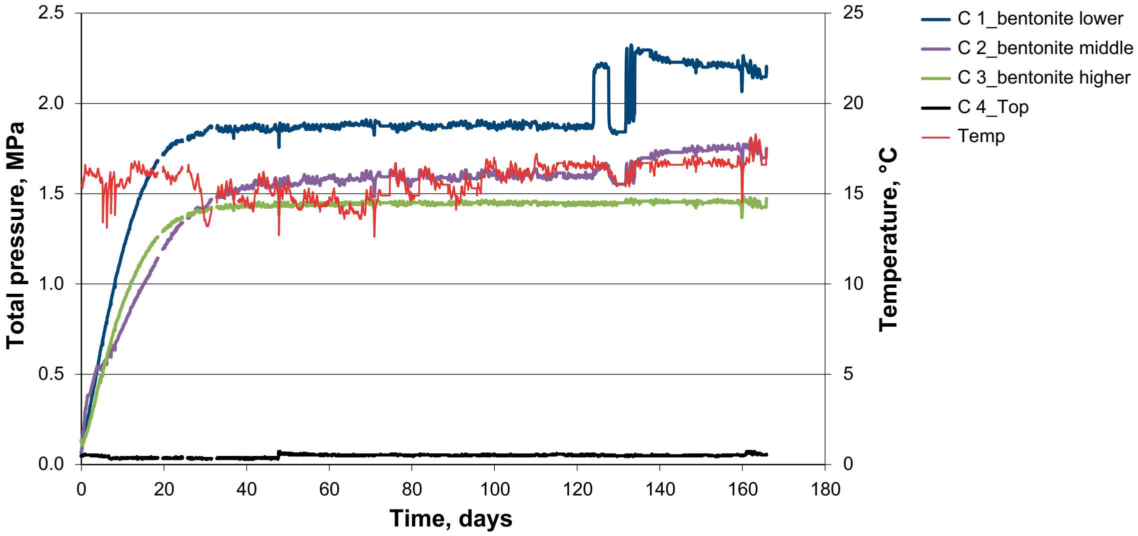


Figure 6-11. *Graph showing the pressure built up and the relative humidity plotted versus time for the homogenization test.*

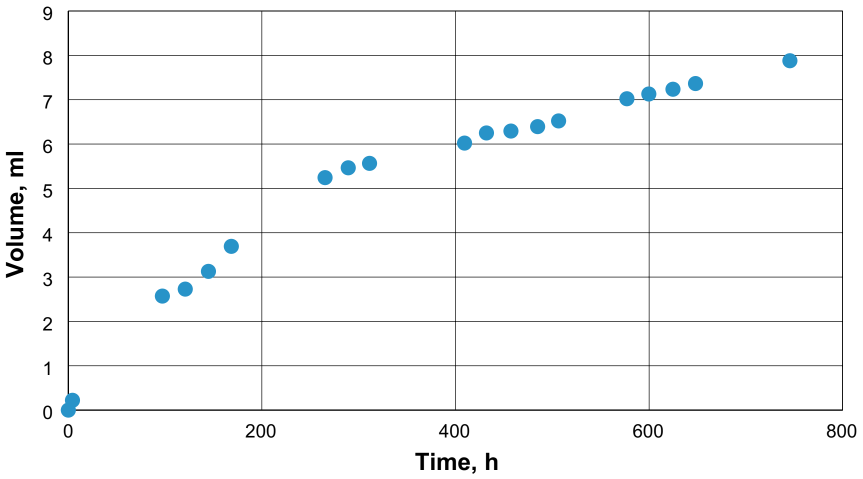


Figure 6-12. *Injected water volume (GDS) versus time.*

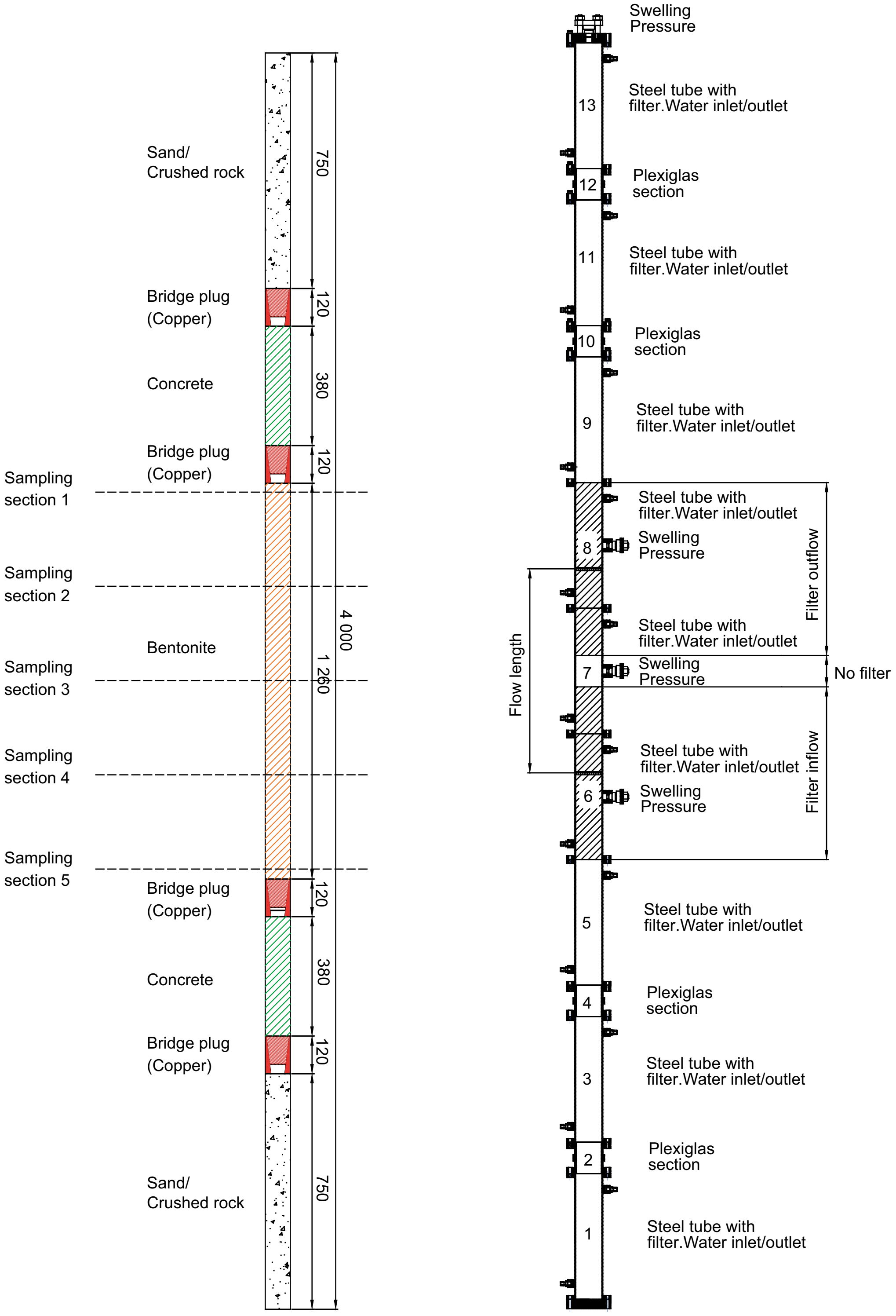


Figure 6-13. *Left: Schematic showing the sampling sections in the bentonite seal. Right: Illustration of the approximate flow model showing two imaginary filters perpendicular to the tube axis.*

6.5.5 Measurement of the installed lengths of the different components

General

The lengths of the different installed components after installation were measured in conjunction with the termination of the test.

Results

The results from the measurements are presented in Table 6-2. The accuracy of the measurements is believed to be within one mm.

Table 6-2. Compilation of data showing the length of the installed components determined at the test termination.

Material	Length, mm
Sand, upper	788
Copper exp. 4	99
Concrete, upper	401
Copper exp. 3	99
Bentonite	1 255
Copper exp. 2	99
Concrete, lower	470
Copper exp. 1	99
Sand, lower	690
Total length	4 000

6.5.6 Bentonite sealing

General

To check the achieved density and the homogeneity of the bentonite sealing in the simulated borehole, the water content and the density were determined at a number of positions.

Test matrix

After having pushed out the bentonite specimen from the test cell, slices were cut out at five levels, see Figure 6-13. From each of the slices, samples were sawed out according to the drawing provided in Figure 6-14. The bulk density and the water content were determined on every sample. With this data, the dry density, the void ratio and the degree of saturation could be calculated. The photo provided in Figure 6-15 shows the bentonite specimen after extrusion from the test cell.

Calculations

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 the equations provided in Section 5.5.5.

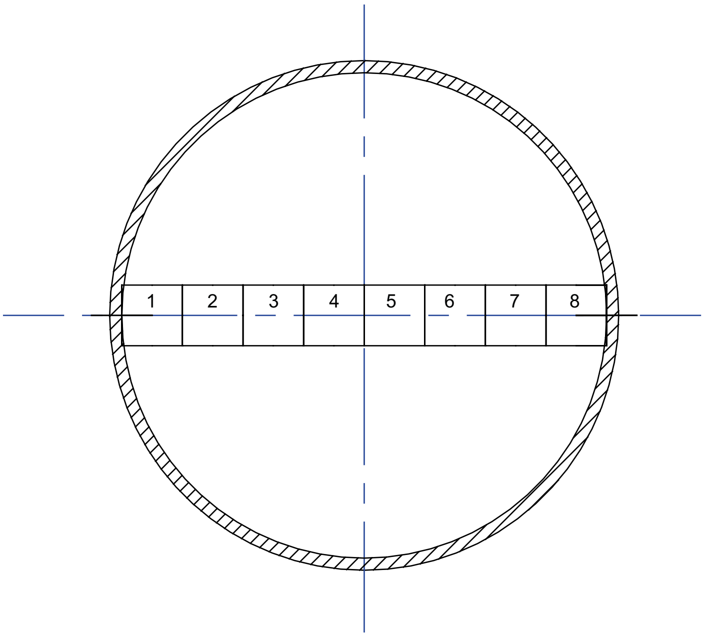


Figure 6-14. Schematic drawing showing the sampling of a slice cut out from the bentonite specimen.

Figure 6-15. Photo showing a part of the bentonite sealing after extrusion from the test cell.

Presentation of results

The results from the determinations of water content and dry density distribution are presented in Figure 6-16 and Figure 6-17. The determined values are plotted versus the distance along the simulated borehole diameter i.e. 40 mm on the x-axis corresponds to the center of the specimen. All figures, including the calculated void ratio and degree of saturation for every sample are provided in Table 6-3.

The results are like those from the Homogenization test i.e. the bentonite has swelled and filled up the initial gap between bentonite and rock wall. There are also in this test remaining differences in density between the center of the bentonite and in the former gap. The dry density in the center of the bentonite core is between 1 340 and 1 450 kg/m^3 and the density close to the simulated borehole walls are between 1 240 and 1 350 kg/m^3. The density is in all positions lower than in the Homogenization tests which depend on the somewhat smaller diameter of the installed bentonite plugs, see Section 6.4.4. The calculated degree of saturation varies in general between 91.8 and 98.6.8 %. The scatter is believed to partly depend on the fact that the water content and dry density used in the calculations are not made on the same clay sample, but on neighboring samples. It is, however, judged that all bentonite in the test is water saturated.

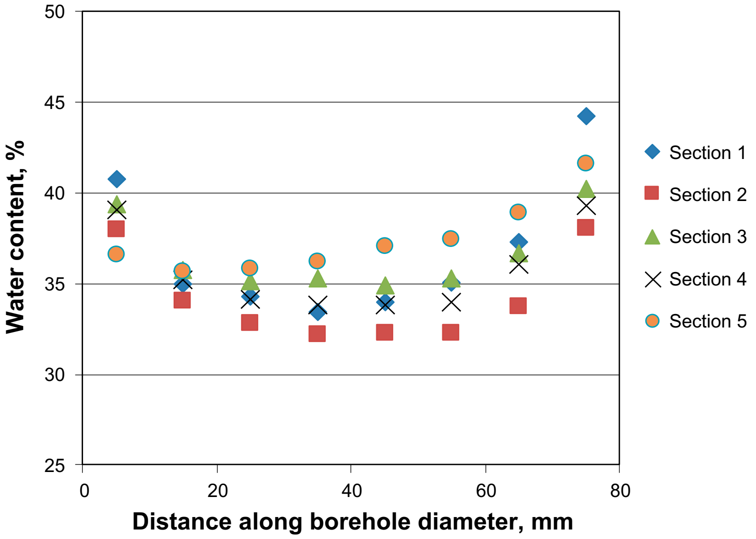


Figure 6-16. *Water content distribution determined at three levels of the bentonite.*

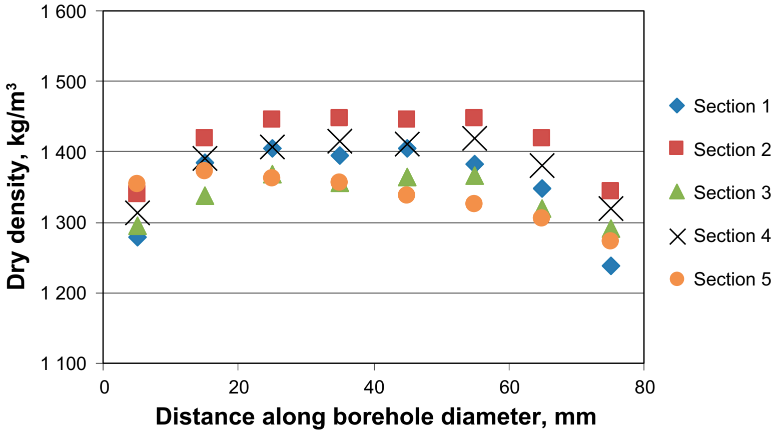


Figure 6-17. *Dry density distribution determined at three levels of the bentonite.*

Table 6-3. Compilation of results from the sampling of the bentonite from the Mockup test.

	Water content %	Bulk density kg/m³	Dry density kg/m³	Void ratio	Degree of saturation %
Section 1:1	40.7	1800	1279	1.181	96.2
Section 1:2	34.9	1867	1384	1.016	95.9
Section 1:3	34.2	1886	1405	0.986	96.9
Section 1:4	33.4	1861	1394	1.001	93.2
Section 1:5	34.0	1883	1405	0.985	96.2
Section 1:6	35.1	1866	1382	1.019	96.0
Section 1:7	37.3	1850	1347	1.071	97.2
Section 1:8	44.2	1786	1239	1.252	98.5
Section 2:1	38.0	1848	1339	1.083	97.9
Section 2:2	34.0	1903	1420	0.965	98.4
Section 2:3	32.8	1921	1446	0.929	98.6
Section 2:4	32.2	1915	1448	0.926	97.0
Section 2:5	32.3	1912	1446	0.930	96.9
Section 2:6	32.3	1916	1448	0.926	97.2
Section 2:7	33.8	1898	1419	0.966	97.5
Section 2:8	38.0	1854	1343	1.077	98.5
Section 3:1	39.4	1806	1296	1.154	95.2
Section 3:2	35.8	1816	1337	1.086	91.8
Section 3:3	35.1	1850	1369	1.038	94.3
Section 3:4	35.3	1835	1356	1.057	93.2
Section 3:5	34.9	1840	1364	1.046	93.2
Section 3:6	35.2	1847	1365	1.043	94.2
Section 3:7	36.7	1804	1320	1.114	91.9
Section 3:8	40.2	1811	1291	1.161	96.7
Section 4:1	39.0	1825	1313	1.125	96.8
Section 4:2	35.2	1880	1390	1.007	97.6
Section 4:3	34.1	1887	1407	0.983	96.8
Section 4:4	33.9	1893	1414	0.973	97.1
Section 4:5	33.8	1888	1411	0.978	96.5
Section 4:6	34.0	1901	1419	0.966	98.1
Section 4:7	36.0	1877	1380	1.021	98.4
Section 4:8	39.3	1837	1319	1.116	98.3
Section 5:1	36.6	1848	1353	1.062	96.2
Section 5:2	35.7	1862	1372	1.033	96.4
Section 5:3	35.8	1850	1362	1.049	95.3
Section 5:4	36.2	1848	1357	1.057	95.6
Section 5:5	37.0	1835	1339	1.084	95.3
Section 5:6	37.4	1823	1326	1.104	94.7
Section 5:7	38.9	1814	1306	1.136	95.5
Section 5:8	41.6	1803	1273	1.191	97.5

6.5.7 Concrete

General

The concrete was only visually inspected. After inspection, the material was pushed out from the tubes using a hydraulic press. The contact against the simulated rock walls was judged good and no cracks could be found. No further measurements were however made.

6.5.8 Sand filling

General

The sand filling was in all positions easily removed from the tubes, Figure 6-19.

Figure 6-18. *Photo showing an end part of the concrete section.*

Figure 6-19. *Photo showing the sand filling from the lower section during excavation.*

6.5.9 Copper expander

General

By use of a hydraulic press it was possible to remove one of the installed copper expanders from the test tube. The expander has worked as intended i.e. it has during compression, expanded and thereby sealed the simulated borehole very efficiency. The photo provided in Figure 6-20 shows the copper expander after extrusion from the test cell.

6.6 Comments and conclusions

The main objectives with the test have been to verify and demonstrate the function of all components and of the concept itself.

Another objective has been to study the homogenization of the bentonite sealing by registering the swelling pressure built up and by measuring the hydraulic conductivity. The dry density of the bentonite installed in the simulated borehole section varies between 1 230 kg/m^3 (at the test cell walls) and 1 450 kg/m^3 (at the central parts). The achieved average density is thus lower than intended which depends on the use of bentonite plugs with smaller diameter than intended (the bentonite plugs had a diameter of 70 mm which was adapted to a borehole diameter of 76 mm instead of 80 mm as in this test equipment). This has resulted in a rather low registered swelling pressure from the bentonite against the simulated rock wall, between 1.5 and 1.9 MPa. The calculated hydraulic conductivity of the sealing, 5.4×10^{-12} m/s, is slightly higher to what was determined for the Homogenization test. As for the Homogenization test, it is judged that a more relevant evaluation by FEM-calculation should be done since the flow situation is rather complex and the analytical evaluation is too approximate.

Figure 6-20. *Photo showing a copper expander after extrusion from the test cell.*

7 Large scale pellet installation tests

7.1 Background

During the site investigations for the final disposal of radioactive waste and for the planned extension of SFR, a large number both cored and percussion boreholes have been drilled. A large proportion of these boreholes are shallow, drilled in the regolith layer, or only a few meters down in the rock. These boreholes are assumed to have no hydraulic influence on the disposals and will not influence the safety after closure.

These shallow boreholes will mainly be classified to Class BHC 1, see description in Section 3.4.2, and are planned to be filled with bentonite pellets Similar design of a sealing, including bentonite pellets, is suggested for the uppermost meters of boreholes sealed with the sandwich design, see description in Chapter 4.

The tests described in this chapter are performed in the Multi Purpose Facilities at Äspö. The main purpose of the tests has been to test and demonstrate the installation of pellets in shallow boreholes both at dry and wet conditions.

7.2 Material

7.2.1 Bentonite pellets

Two types of pellets have been tested:

1. MX-80 pellets. The bentonite origins from Wyoming, USA. The pellets were manufactured with the roller compaction method at Hosokawa Alpine GmbH, Germany. The pellets are shaped as pillows (15 × 15 × 8 mm). This pellets type has been used in many of the full-scale tests performed at Äspö HRL.
2. Asha pellets. The bentonite origins from the Kutch area on the North West coast of India. The bentonite was produced by Ashapura Minechem Co and was delivered to Äspö in two batches 2010 and 2012. The pellets were manufactured at Äspö by extrusion (d = 6 mm, L = 6–25 mm). This pellets type has been used in e.g. the full-scale installation tests of backfill.

Photos of the two pellet types are provided in Figure 7-1. Some basic properties of the bentonite pellets used in the tests were determined in the laboratory, Table 7-1.

Figure 7-1. *Photo of the two pellet types used in the tests. Left: Asha pellets Right: MX-80 pellets.*

Table 7-1. Basic properties of the pellets used in the tests.

Material	Water content %	Bulk density of the filling kg/m^3	Dry density of the filling kg/m^3
MX-80 pellets	14.0	1 166	1 022
Asha pellets	17.6	1 103	938

7.2.2 Water

The water used in the wet tests had a salinity of 1 % by weight (NaCl/CaCl 50/50).

7.3 Test matrix

The original plans included tests with two pellet types, two installation rates and two types of boreholes (dry and wet) i.e. in total eight tests. It was, however, found that the installation in water filled boreholes had to be made with a rather low installation rate and the test matrix was therefore changed. It was also decided to perform two extra tests simulating sealing of inclined boreholes.

In total eleven tests have been performed, seven at dry conditions and four at wet conditions (water filled boreholes):

1. Dry boreholes: two materials and two installation rates. (4 tests).
2. Dry boreholes: one repetition, one shorter borehole. (2 tests).
3. Wet boreholes: two materials and 2 installation rates. (3 tests).
4. Inclined boreholes (65°): one dry and one wet test. (2 tests).

A compilation of the performed tests and the achieved results is also provided in Table 7-2.

7.4 Test equipment

The test equipment is manufactured of Plexiglas tubes which makes it possible to study how the pellets are falling down in the simulated borehole during installation. A test setup consists of ten units, each with a length of one meter, that are put together with flanged joints. This design is necessary in order to facilitate the handling of the test equipment during dismantling. The simulated boreholes have a length of 10 meters and an inner diameter of 140 mm.

The tests have been performed in the Multi Purpose Facilities at Äspö where there is a shaft, with a depth of eight meters available, see photo provided in Figure 7-2. This shaft has been used for the performance of the tests. The Plexiglas tubes have been fastened against the concrete walls in one of the corners. Two of the tests were performed simulating inclined boreholes. In these tests the Plexiglas tubes were fastened from one bottom corner of the shaft to the opposite corner at the top, Figure 7-3. The inclination of the Plexiglas tube was 65°.

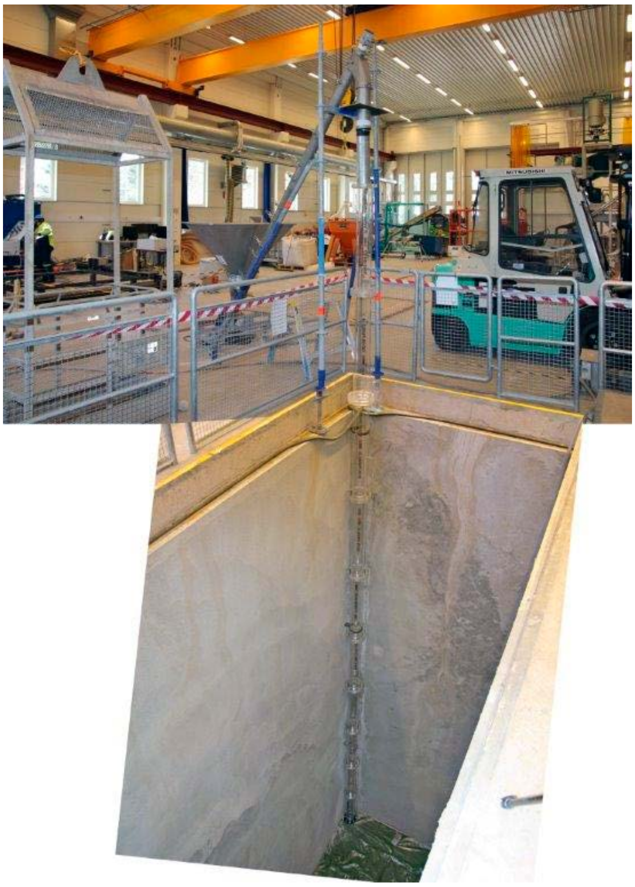


Figure 7-2. The simulated borehole (length = 10 m) is placed in an eight-meter-deep shaft in the laboratory (photo collage).

Figure 7-3. Photo showing the test setup for the tests performed simulating inclined boreholes.

7.5 Installation method

7.5.1 Dry boreholes

The top of the simulated borehole was positioned two meters above floor level. A conveyor screw with a hopper was used to transport the pellets up to the test tube opening, and then the pellets were flowing down in the tube by gravity, Figure 7-4 and Figure 7-5.

In conjunction with the test termination, the pellet installed in the test tube was sucked up by a large vacuum cleaner, collected and then weighed. This method was, however, only possible to use for the dry tests.

Figure 7-4. *Photo of the conveyor screw with a hopper. The simulated borehole ends up two meter above the floor level.*

Figure 7-5. *Close-up showing pellet installation in a simulated dry borehole.*

7.5.2 Water filled boreholes

The installation of pellets in simulated water filled boreholes required special arrangements in order to take care of the outflowing water from the test tube. A special collector was placed at the top of the simulated borehole and the outflowing water was led to a vessel, Figure 7-6.

The pellet mass placed in the hopper was weighed and then the remaining pellet mass in the hopper after completion of the installation was determined (including emptying the conveyor screw). The difference between the two weighing's could then be used to calculate the installed density in the test tube. The photos provided in Figure 7-7 and Figure 7-8 shows Asha pellets installed in a simulated water filled boreholes.

***Figure 7-6.** Photo showing the test setup for the tests including a simulated water filled borehole.*

***Figure 7-7.** Asha pellets installed in a simulated water filled borehole. The photo is taken during test termination.*

Figure 7-8. Photo showing Asha pellet installed in a simulated water filled borehole.

7.6 Results

A compilation of all tests performed, together with the achieved results is provided in Table 7-2.

The installation rate in dry test tubes varied between 9 and 17 kg/min without causing any problem. In the tests performed with water filled test tubes the installation rate varied between 4 and 9 kg/min. In the first test with a water filled test tubes, the outflowing water from the test tubes splashed upwards into the installation tube resulting in a local cloging of the pellets. The other tests simulating a water filled borehole, were performed with another equipment, where the outflowing water immediately was led away when reaching the test tube top without disturbing the installation.

Table 7-2. Compilation of data from the performed tests.

Pellet type	Wet/Dry test	Water content %	Installation rate kg/min	Bulk density kg/m^3	Dry density kg/m^3	Remark
MX-80 pillow	dry	14.0	16	1 367	1 200	
MX-80 pillow	dry	14.0	10	1 397	1 225	
MX-80 pillow	wet	14.0	9	1 047	919	Installation stop after 4 m.
MX-80 pillow	wet	14.0	5	984	863	
Asha extruded	dry	17.6	9	1 436	1 221	
Asha extruded	dry	17.6	17	1 449	1 232	
Asha extruded	dry	17.6	15	1 462	1 243	
Asha extruded	dry	17.6	12	1 397	1 188	2 m deep borehole
Asha extruded	dry	17.6	16	1 380	1 174	Inclined borehole (65°)
Asha extruded	wet	17.6	4	1 108	942	
Asha extruded	wet	17.6	5	1 169	994	Inclined borehole (65°)

The graph provided in Figure 7-9 shows the achieved dry density of the pellet fillings after installation in the simulated borehole for all tests performed. As shown in the graph, the achieved dry density for the tests performed at dry conditions are considerably higher than those achieved when installing pellets in water filled test tubes. For the Asha pellets, the achieved dry density in the dry test tubes varied between 1 174 and 1 243 kg/m^3 and in the water filled test tubes between 942 and 994 kg/m^3. Corresponding figures for the MX-80 pellets are between 1 200 and 1 225 kg/m^3 for the dry test tubes and between 863 and 919 kg/m^3 for the water filled test tubes.

The dry density of the pellet fillings was earlier determined in laboratory, see results provided in Table 7-1. These figures, 1 022 kg/m^3 for the MX-80 pellets and 938 kg/m^3 for the Asha pellets, were much lower than what was achieved in the large-scale tests performed in dry test tubes. The main reason for this is probably that the transport of pellets with the conveyor screw resulted in a certain milling of the pellets. The graph provided in Figure 7-10 shows the granule size distribution of the Asha pellets before and after installation in a simulated borehole. As shown in the graph, the amount of fine material has increased after installation. The fines in the material, formed at the installation, are filling the voids between the pellets resulting in a higher density.

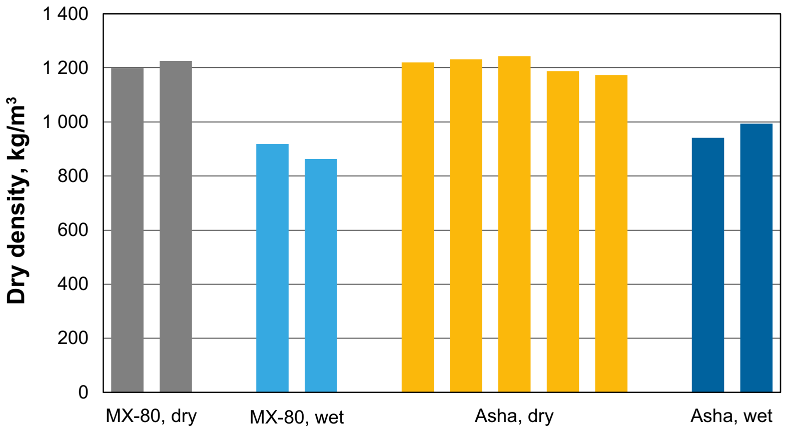


Figure 7-9. Graph showing the achieved dry density for all tests performed.

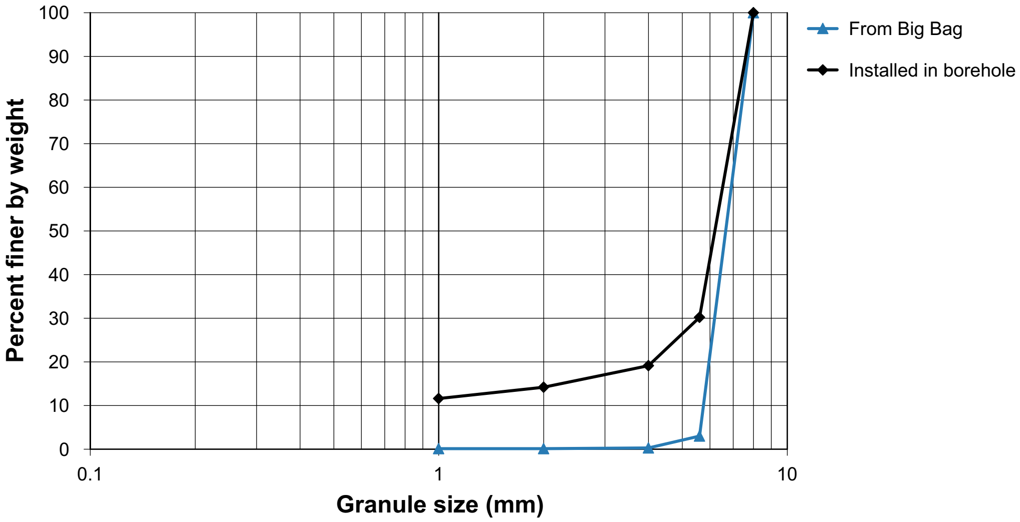


Figure 7-10. Granule size distribution of Asha pellet before and after installation.

Another reason for the high densities achieved in the dry tests may be that the pellets are falling from a certain height which also may lead to closer packing of the bentonite filling. To investigate if this was the case, an extra test was performed where the test length was reduced from ten meters to two meters (the second last test performed with Asha pellets under dry conditions, see Table 7-2). The achieved dry density in this test was somewhat lower compared to the other tests with this material, 1 188 kg/m^3 compared to between 1 221–1 243 kg/m^3.

The height of fall seems thus to have some minor influence on the results but the main reason for the high density achieved in the dry test tube tests is probably the change in granule size distribution caused by the transportation in a conveyor screw.

7.7 Comments and conclusions

It should be noted that the achieved results are relevant for filling of bentonite pellets in shallow boreholes (10 m was used in the laboratory tests). Installation in deep boreholes with this method will result in problems regarding early swelling of the bentonite pellets with following bridging in the borehole etc. The method can be improved by e.g. using coated pellets which are stable in water for longer time during installation. Studies where different pellet types have been tested are described in Sandén et al. (2017).

7.7.1 Installation rate

Installation of bentonite pellets in a water filled shallow borehole with a depth less than 30 m, can be made with an installation rate of approximately 5 kg/min (borehole d = 140 mm). Corresponding figure for dry boreholes is approximately 10 kg/min or higher.

7.7.2 Density of installed pellet filling

The achieved dry density achieved in the tests performed at dry conditions is considerably higher than when installing pellets in simulated water filled boreholes. For the Asha pellets, the achieved dry density in the dry test tubes varied between 1 174 and 1 243 kg/m^3 and in the water filled test tubes between 942 and 994 kg/m^3. Corresponding figures for the MX-80 pellets are between 1 200 and 1 225 kg/m^3 for the dry test tubes and between 863 and 919 kg/m^3 for the water filled test tubes.

7.7.3 Properties of the pellet filling

A bentonite filling of MX-80 with a dry density of 900 kg/m^3 will have a hydraulic conductivity of approximately 10^{-11} m/s and a swelling pressure of approximately 100 kPa (Åkesson et al. 2010). The values depend largely on the site conditions regarding e.g. the salinity of the water.

8 Large scale sand installation tests

8.1 Background

The Sandwich-concept implies that the main part of a borehole is filled with a permeable material such as sand, see the schematic drawing provided in Figure 4-1. Large scale sand installation tests have been performed in the Multi Purpose Facilities at Äspö.

8.2 Test description

8.2.1 Material

The sand used in the test is a commercial product denominated "Fogsand". It is a natural sand with grain size less than 2 mm. The sand has earlier been studied in Sandén et al. (2017).

In order to ensure that the sand could be installed according to the plans i.e. falling from a large vessel into a tube that was connected to the borehole, see description in next section, it was necessary to dry the sand. The sand was spread on the floor in the laboratory and was air dried for a few days. The water content of the sand was after drying about 2 %.

8.2.2 Test equipment

The tests have been performed in the Multi Purpose Facilities at Äspö where there is a shaft, with a depth of eight meters available (the same shaft was used for the bentonite pellet installation tests described in Chapter 7), see photos provided in Figure 8-1. A steel tube with an inner diameter of 80 mm was fastened along one of the walls, Figure 8-1. The inclination of the tube was 65° i.e. almost the same as the full-scale borehole that will be sealed (KAS 13), see Chapter 12. A hopper containing sand was placed above the simulated borehole and connected via a valve that was used to adjust the installation rate.

In the tests simulating a water filled borehole, the outflowing water during installation of sand was collected in a large vessel, see photo provided in Figure 8-2. The technique to lead away the water in horizontal direction instead of letting it flow upwards to the borehole entrance can be used also in full scale by mounting a special designed extender on the borehole. This will facilitate the installation of sand since the outflowing water will not disturb the sand flow to the same extent.

Figure 8-1. Photo showing sand installation in a simulated borehole.

Figure 8-2. *Photo showing the arrangement for collecting outflowing water from the simulated borehole.*

Some pre-tests were made simulating a borehole length of 2 m. One result from these tests was that a small disturbance of the installed sand would result in a higher density of the sand filling (Sandén et al. 2017). In the large-scale tests described in this chapter, the disturbance was obtained by pulling a large bolt fastened in a wire, Figure 8-3, through the installed sand. The bolt must thus be installed before starting the installation of sand.

8.2.3 Test matrix

In total five tests have been performed:

1. Two tests simulating a dry borehole.
2. Three tests simulating a water filled borehole.

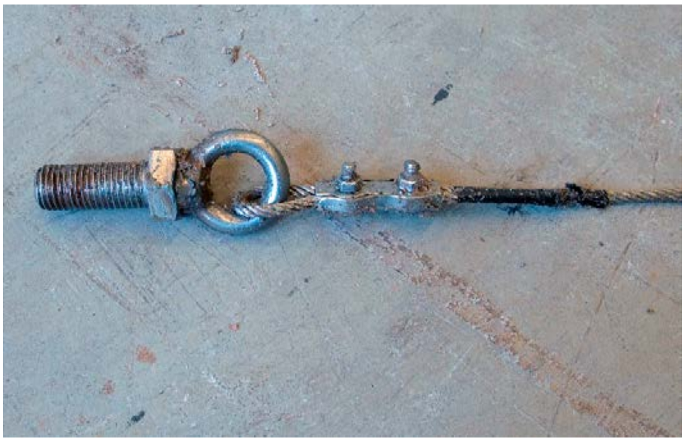


Figure 8-3. *Photo showing the bolt used to disturb the installed sand filling to achieve a higher density.*

8.3 Results

A compilation of results from the five tests is provided in Table 8-1. The valve used to adjust the installation rate was rather rough and the installation rate has varied between 3.7 and 7.7 kg/min. The use of a "compaction tool" i.e. a bolt that was pulled through the filling after installation was after having performed the tests assessed to be both difficult and unnecessary. The tool was hard to remove and didn't seem to increase the density of the sand filling. Two tests were performed without any tool at wet conditions and the reached density was in the same range as for the other comparable test (three tests were performed at wet conditions).

The achieved density was rather high for all tests, between 1 647 and 1 682 kg/m^3. The highest density was reached in the tests where the sand was installed at dry conditions. These figures should be compared to the densities determined in the laboratory tests performed in an earlier phase of the project (Sandén et al. 2017), i.e. approximately 1 500 kg/m^3 for both dry and wet conditions.

Tabell 8-1. Compilation of results from the sand installation tests.

Material	Wet/Dry test	Water content %	Installation rate kg/min	Installed mass kg	Installed borehole length m	Dry density kg/m^3	Remark
Fogsand	dry	2.0	7.7	69	8.0	1 682	Compaction tool hard to remove
Fogsand	dry	2.0	3.7	78	9.0	1 686	Compaction tool removed in steps
Fogsand	wet	2.0	4.9	78	9.2	1 663	Compaction tool hard to remove
Fogsand	wet	2.0	6.9	76	9.0	1 647	No compaction tool.
Fogsand	wet	2.0	3.8	76	9.0	1 647	No compaction tool. 20 h rest after installation.

8.4 Comments and conclusions

The sand installation tests have been performed in large scale simulating borehole depths of 10 meters. In reality, sand must be installed at several hundred of meters depth according to the Sandwich-concept. Even if the laboratory tests indicate that the tested method (installation by gravity) works as intended, it is assessed that tests also must be performed in larger scale to ensure that the technique works also at larger depths.

8.4.1 Installation rate

The laboratory tests show that installation of sand can be made at a rate of 5–8 kg/min (simulated borehole d = 80 mm) at both dry and wet conditions. As mentioned above, tests in larger scale i.e. borehole depths of several hundred meters, will be necessary.

8.4.2 Density of installed sand filling

The achieved density was high for all tests, between 1 647 and 1 682 kg/m^3. The highest density was reached in the tests where the sand was installed at dry conditions.

The use of a "compaction tool" i.e. a bolt that was pulled through the filling after installation was after having performed the tests assessed to be both difficult and unnecessary. The tool was hard to remove and didn't seem to increase the density of the sand filling.

8.4.3 Properties of the sand filling

The hydraulic conductivity of the sand filling has little significance for the Sandwich-concept but should be known in order to get the whole picture regarding a sealed borehole. With a dry density of 1 650 kg/m^3 the sand filling will have a hydraulic conductivity of approximately 10^{-5} m/s (Sandén et al. 2017).

A high installed density of the sand filling is important to minimize the compressibility of the installed sand filling. The achieved density in the tests is higher than expected which is favorable for the concept.

9 Sand installation test in field

9.1 General

In addition to the large-scale tests described in Chapter 8, an installation test in field was made. The test was made in a 256 m deep borehole positioned close to the Multi Purpose Facilities at Äspö.

9.2 Test description

9.2.1 Material

The same type of sand as used in the large-scale laboratory tests was also used in the field test. The sand is a commercial product denominated "Fogsand". It is a natural sand with grain size less than 2 mm. The sand was air-dried before use and had a water content of 2 %.

9.2.2 Test description

The same large hopper as was used in the laboratory tests was also used for the field test. The hopper was placed on a steel frame above the borehole. A large valve (light blue on the photo) was used to adjust the installation rate. From the valve, a flexible tube was connected to the borehole entrance.

Only one test was performed. Forty kilos of sand were released down in the borehole with a rate of about 8 kg/min, which was somewhat higher than the intended 5 kg/min. After installation, the height of the upper sand surface was determined by use of a special measuring cable where also a camera was positioned in the end, Figure 9-2. With this data the installed density of the sand filling could be calculated and thereby the quality of the installation process.

Figure 9-1. *The hopper filled with sand is positioned above the borehole. A valve is used to adjust the installation speed. The sand is led from the hopper to the borehole via a flexible tube.*

Figure 9-2. Photo showing the measuring cable equipped with a camera in the end.

9.2.3 Borehole

The borehole used in the test is denominated KAS13 and the borehole entrance is positioned about fifty meters from the Multi Purpose Facilities at Äspö. The borehole has an inner diameter of 76 mm, a length of 256 meters and an inclination of 62.2°. The borehole ends in the tunnel ramp, close to the elevator shaft at the –220 m level. Before the test start a mechanical packer was placed in the lower end of the borehole.

Water is standing in the borehole up to a level of –210 i.e. during the main part of the sand installation, the sand was falling through air.

9.2.4 Results

The installation of sand in the borehole was successful. All sand flow down to the bottom of the borehole and no tendency for bridging etc. could be observed. The upper surface of the installed sand filling was measured at three occasions:

- Immediately after installation. This measurement is judged to be wrong, probably depending on the fact that sand grains still were settling in the water column. This resulted in that the length of the filling was too short and that the calculated density of the sand filling was too high, 1 819 kg/m^3.
- Two and a half hours after installation. The calculated density was 1 626 kg/m^3.
- Five days after installation. The calculated density was 1 689 kg/m^3.

It is assessed that the installed density of the sand filling is in the range of 1 626 to 1 689 kg/m^3 which is well in accordance with the density determined in the large-scale laboratory tests described in Chapter 8.

10 Installation technique tests for bentonite packages and copper expanders

10.1 General

The Sandwich-concept implies that bentonite packages and copper expanders are positioned at certain levels in a borehole. These components are described in detail in Section 12.4. This chapter describes the tests performed regarding the technique to carry the components down in the borehole by use of the drill tubes and then loosen them at the right position by shearing of special bolts made of nylon.

10.2 Test description

The same technique is planned to be used for both bentonite packages and copper expanders. As shown in Figure 10-1, the copper expander (or the bentonite package) is attached to a special designed drill tube via bolts made of nylon. Two threaded holes in the drill tube are used to attach the copper expander. The bolts go into a central hole in the copper. The bolt heads should be removed before installation in a borehole. This is easily made by use of a metal saw.

After having lowered the expander to the right level in the borehole e.g. against a concrete or sand surface, a force will be applied on the drill tubes which will result in a shear failure of the two bolts. When installing a copper expander, the force will be additionally increased to expand the copper, about 10 to 20 kN is needed, but when installing a bentonite package the drill tubes will be lifted up after having sheared off the bolts.

The bolts are made of nylon and have a size of M8 x 20. Tests have been performed in a hydraulic press to determine the force needed to shear of the two bolts.

10.3 Results

A number of tests have been performed where the needed force to shear of two bolts have been measured. The force needed is about 6 kN which is estimated to be in the right range to do a safe installation.

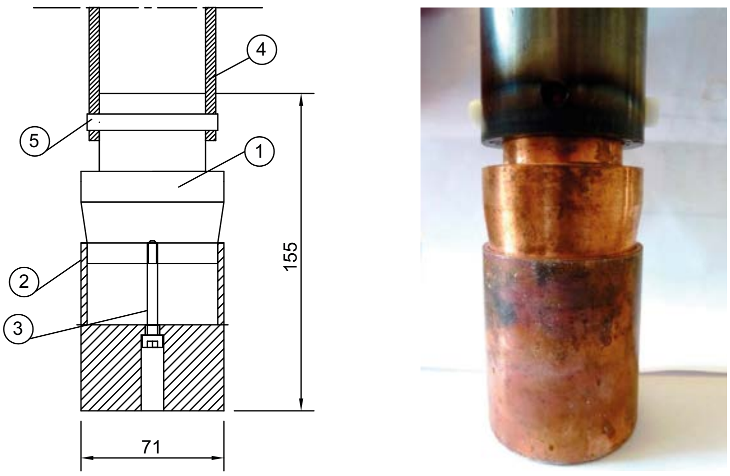


Figure 10-1. *Left: Schematic showing the copper expander connected to a special designed drill tube. 1) Inner cone made of standard copper (hard) 2) Cup made of annealed copper 3) Connecting screw. 4) Special designed drill tube. 5) Nylon shear bolts Right: Photo of a copper expander connected to the drill tube. Note that the bolt heads will be removed before installation.*

11 Concrete installation technique-laboratory tests

11.1 General

The technique and equipment for installation of concrete in a borehole were tested and developed at several occasions at the Multi Purpose Facilities at Äspö. The following items were investigated:

- The recipe of the two different concrete were tested.
- The equipment developed for installing the bentonite were tested.
- Full scale tests were made in the laboratory where installing larger volumes of concrete were tested both in dry and water filled boreholes.

11.2 Concrete mixing and quality tests

Two different types of concrete have been tested:

1. SKB concrete. A recipe has been developed by SKB in cooperation with CBI (Cement och Betong Institutet) within an earlier SKB project (Pusch and Ramqvist 2006).
2. Standard concrete. A standard concrete for casting underwater (Weber).

11.2.1 SKB concrete

The original recipe was adapted for the laboratory tests to achieve a suitable amount of concrete, Table 11-1. The amount of Superplasticizer was increased compared to the original recipe with 75 % in order to achieve a concrete that fulfilled the requirements on flowing, see description in Section 11.2.3.

Table 11-1. Recipe for the SKB concrete used for the laboratory test.

Components	kg
Cement (Aalborg Portland)	1.302
Water	3.388
Silica Fume	1.302
Fine sieved α quartz (M 300, Sibelco)	4.341
Fine sieved christobalite quartz (M 600, Sibelco)	3.256
Superplasticizer (Glenium 51)	0.238
Ballast 0–4 mm (Underås Jehanders Grus)	36.446

11.2.2 Weber

The concrete was mixed according to the recommendations from the manufacturer i.e. 3.6 liters of water was added to 25 kg dry concrete (cement and sand).

11.2.3 Mixing and testing the quality

At the mixing of the two concrete batches, a forced concrete mixer was used, see photos provided in Figure 11-1.

It is of great importance that the used concrete has low viscosity to enable an installation in narrow boreholes. This property was tested with the equipment shown in Figure 11-2. The procedure for testing the viscosity of the concrete batches was made according to Swedish standard (Betongföreningen 2002). A cone made of steel and with open ends was positioned on a plywood sheet and was thereafter filled with concrete, Figure 11-2. The cone was then lifted upwards and the concrete flow out on the plywood. The time for the concrete to reach a 500 mm diameter (t_{500}) was recorded. The maximum diameter of the concrete, which was assumed to be reached after 2 minutes, was also determined. The results from these tests are shown in Table 11-2.

Figure 11-1. *The forced concrete mixer used for mixing the concrete.*

Figure 11-2. *Equipment for testing the concrete after mixing.*

Table 11-2. Results from the measurements on the two concrete types.

	t_{500}, s	Diameter after 2 minutes, mm
SKB concrete	9	680–700
Weber concrete	1	~ 900

11.3 Development of equipment

The installation of concrete in a borehole was made by using standard drill tubes that were filled with concrete, see Chapter 12. Once the tip of the tube was at the position in the borehole where the casting should be made, the concrete was pushed out from the tube by applying a water pressure from above.

To keep the concrete in place inside the tubes during the preparation of the casting, an end plug, placed at the tip inside the tube, was needed. This plug should get loose once the casting starts. Several tests were made in the laboratory for designing this plug. It was important that the plug could withstand a water pressure of at least 2 MPa before it gets loose from the tube, it should be water tight towards the inside of the tube and, since the plug will be left in the borehole it should be made of materials which are acceptable to be left there. These requirements ended in a design of the plug shown in Figure 11-3. The plug is made of copper and has a length of 20 mm and a diameter about 0.2 mm smaller than the inner diameter of the drill tube. Furthermore, the plug is equipped with two O-rings. The plug is kept in place with four shear rods which are placed in holes at the tip of the drill tube and into the plug, see Figure 11-3.

Since water will be used to push out the concrete from the drill tube, a piston is required to minimize the risk that water will be mixed with the concrete. The requirements on the piston are that it is water tight towards the inner diameter of the drill tubes and that it can move easily inside the tubes and especially when passing joints between them. Several tests were made in conjunction with the design work. These tests ended up with a design of the piston shown in Figure 11-4. The piston is made of nylon with seals in both ends. It is important the piston will not fall into the borehole. This is avoided by welding a ring inside the drill tube on which the piston will stop at the installation, see Figure 11-4.

Figure 11-3. *Left: Installation of the end plug made of copper. Right: Mounting of the shear rods.*

Figure 11-4. *Left: The piston made of nylon with its seals Right: The welded ring inside the special drill tube that is preventing the nylon piston from falling into the borehole.*

11.4 Large scale test in the laboratory

Several tests were made in the laboratory where the design of the equipment together with the mixed concrete was tested under realistic conditions, see Figure 11-5. Simulations of casting, both in dry and water filled boreholes, were made. The installed concrete was tested afterwards concerning its homogeneity, strength and hydraulic conductivity. One important outcome from these tests was that the used concrete was very sensitive for how it was placed in a water filled borehole. It is essential that the tip of the rod is placed underneath the surface of the fresh concrete during the whole casting process to minimize the risk of separation. If the casting is made without occurrence of separation the concrete will have a good strength (44 MPa in compressive strength) and a low hydraulic conductivity (< 1E−11 m/s)

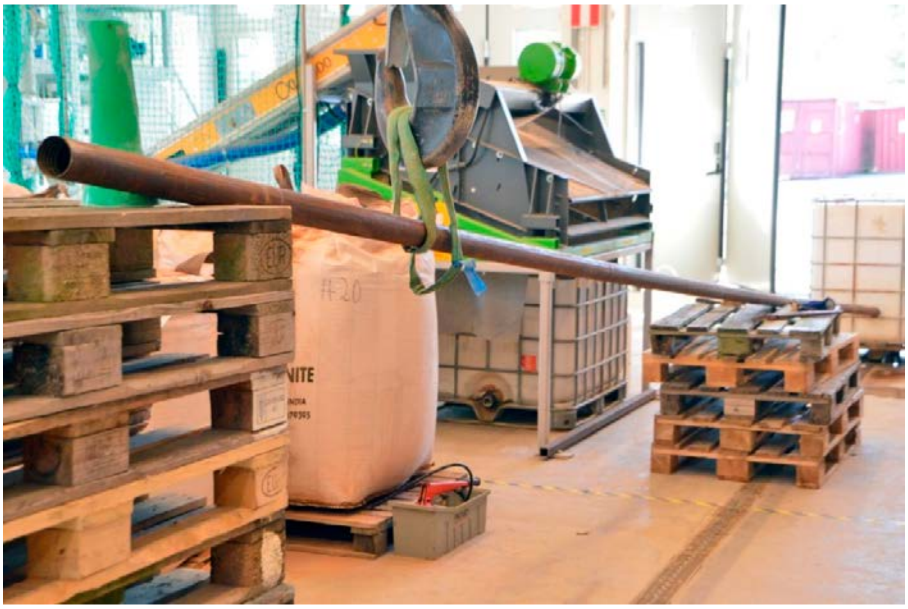


Figure 11-5. *A 18 m long rod used at the designing and testing of the equipment.*

12 Field test

12.1 General

A full-scale installation test has been performed where all different components in the Sandwich concept have been included. The test was performed in a borehole positioned close to the Multi Purpose Facilities at Äspö.

12.2 Borehole KAS 13

The borehole used in the test is denominated KAS13 and it was a part of the drilling program started ahead of the construction of the Äspö laboratory in the end of the 1980s. The telescopic part of the borehole was pre-drilled using a core-drill to a depth of about 100 m which then was reamed up with a percussion drill. After installation of a steel casing the core drilling continued with a diameter of 56 mm to a depth of 410 meters. During the construction of the Äspö HRL laboratory it was discovered that the borehole crossed the tunnel ramp close to the elevator shaft at the –220-meter level. In the performed installation test, only the upper part of the borehole has been used i.e. from ground surface and down to the −220-meter level. Since the tunnel ramp is going below the used borehole it will be possible to have access to the lower part of the borehole after the sealing. One suggestion has been to over-drill the lowest five meters to be able to take out a core and take samples of the installed components at this level. This activity will, however, in that case be performed within another project and is not further discussed in this report.

The ongoing water inflow into the Äspö facility creates over time a funnel shaped groundwater table. When the groundwater table had decreased below the telescopic part of KAS13, the borehole became less interesting for hydrogeological monitoring, and in the beginning of year 2000 the measuring equipment was removed. However, in 2001–2002, when it was decided to use the borehole for testing of different deviation measuring equipment it was necessary to reame the cored drilled section between 100–256 m to a diameter of 76 mm. In 2017, the groundwater table in KAS13 had decreased to about 150 meters below the ground level.

Technical data and dimensions for the KAS13 borehole are provided in Figure 12-1.

12.2.1 Preparatory work

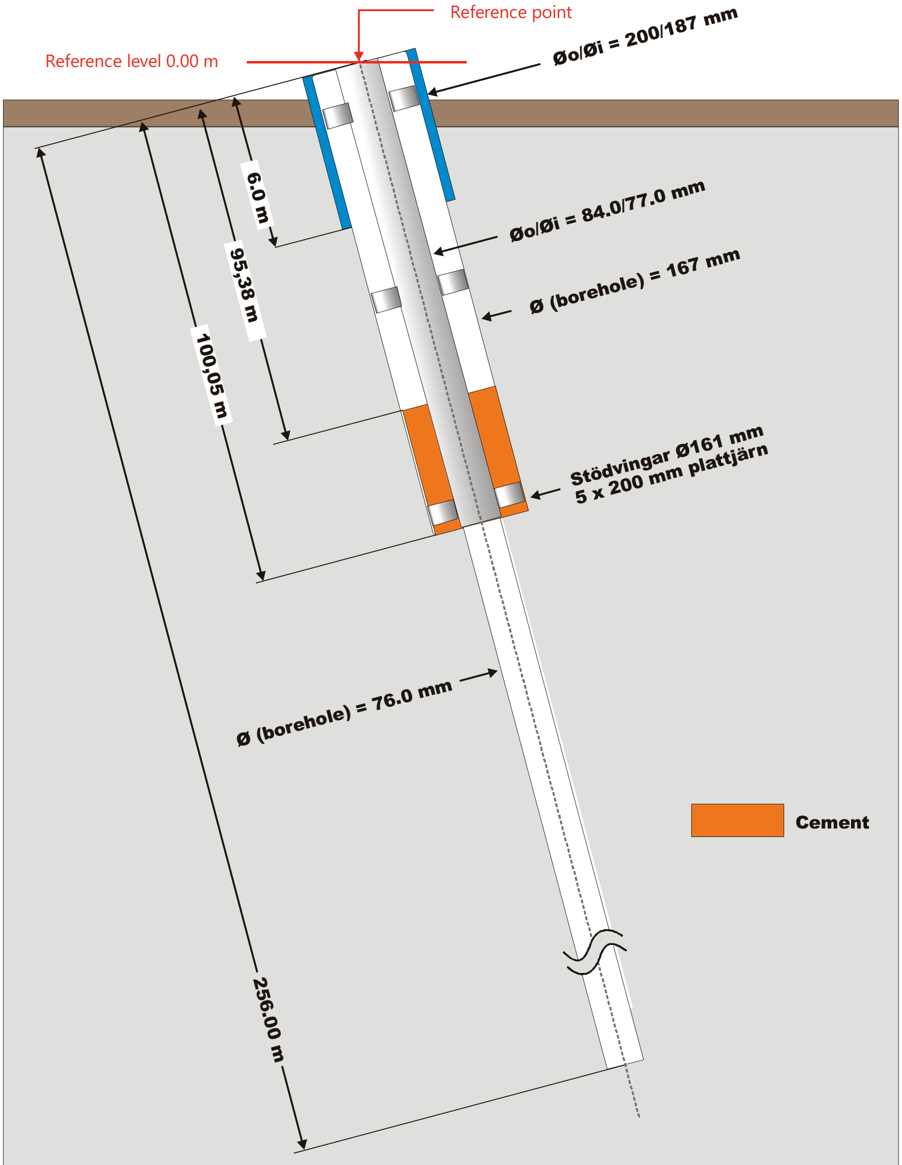
The KAS13 borehole that was used to demonstrate and test the sealing technique had been left without any activities for long time. Before the sealing work could start several different activities were performed:

- Exchange the inner casing tube (0–101 m).
- Cleaning the borehole.
- Reaming the borehole.
- Control of the borehole straightness.
- Check the borehole inclination.

The preparatory work is further described in Section 12.6.4.

Technical data

Borehole KAS13



Drilling reference point	
Northing:	**6367807.193 (m), RT90 2,5 gon V 0:-15**
Easting:	**1551462.372 (m), RT90 2,5 gon V 0:-15**
Elevation:	**3.845 (m), RHB 70**
Orientation	
Bearing (degrees):	**280.12°**
Inclination (degrees):	**-62.20°**
Borehole	
Length:	**256.00 m**

Percussion drilling period
Drilling start date: 1990-01-31
Drilling stop date: 1990-02-09
Core drilling period
Drilling start date: 1990-02-09
Drilling stop date: 1990-03-13
Reaming to 76 mm
Drilling start date: 2001-12-12
Drilling stop date: 2002-02-14

2017-04-26

Figure 12-1. *Technical data for KAS13.*

12.3 Sealing strategy

The planned sealing strategy is shown in Table 12-1 together with the geological mapping of the borehole KAS13. The strategy was chosen to fulfill the following requests on the installation test:

1. The lowermost five meters should include both types of concrete used in the test, one copper expander and a concrete plug including a section with enlarged diameter (250–255 m). Since this section is planned to later be over cored and investigated, it was decided to fill 20 meters of the borehole above with the standard concrete to ensure that no movements of the sections above the over-drilled section should occur.
2. The test should include a complete sealing section, see description in Chapter 4, consisting of highly compacted bentonite surrounded by the special developed quartz-based concrete and copper expanders at all material transitions. The position of this section is chosen to fulfill the requirements for a sealing section i.e. rock without any water bearing fractures.
3. The test should include installation of a large amount of sand, which is an important part of the Sandwich design.
4. It is suggested to position concrete plugs where a defined length of the borehole has larger diameter at the top of the sealed boreholes. This technique was suggested to be tested at two levels, whereas one included in the bottom part that possibly could be over-drilled at a later stage (102–102.5 m and 253.5–254 m).
5. The water level in KAS13 is standing at the −215 level. To demonstrate the installation of sand and bentonite in a water filled borehole, water should be poured into the borehole. This is assessed to be possible after installation of the concrete section below the bentonite section.

The exact planned position of every sealing component in the borehole is shown in Table 12-2.

Table 12-1. Table showing the geological mapping of KAS13 together with the planned sealing.

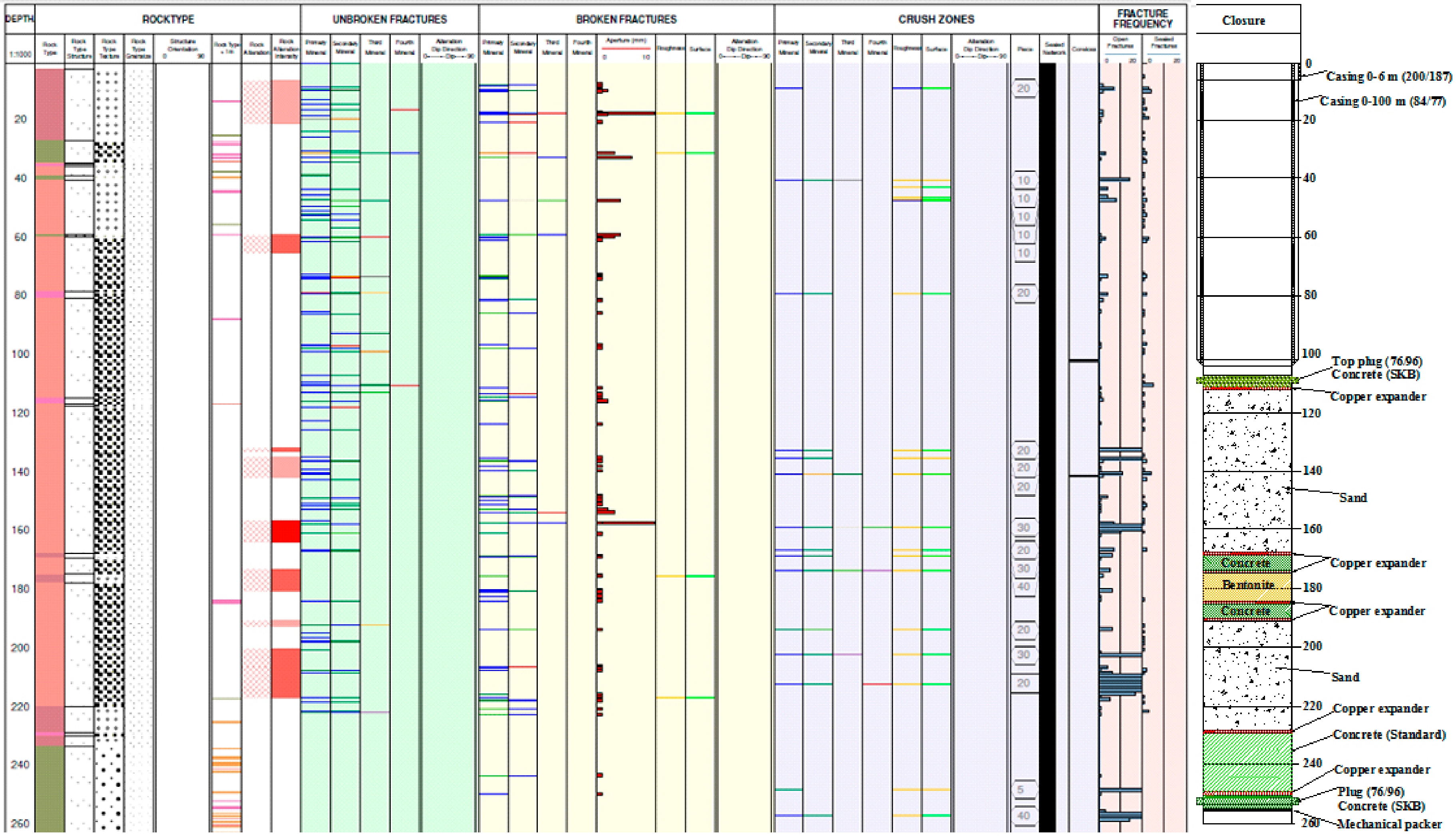
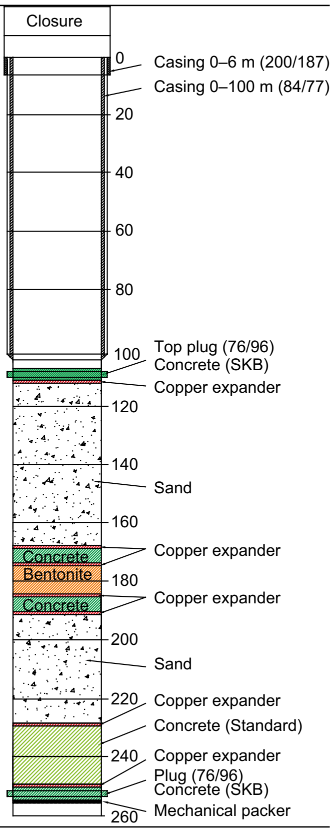


Table 12-2. Schematic drawing showing the planned position of the different sealing components.

Depth, m	Material	Remark
0–102	na	na
102–102.5	Plug d = 76/96 mm, concrete	SKB type
102.5–102.6	Copper expander	
102.6–170	Sand	< 2 mm
170–170.1	Copper expander	
170.1–175.1	Concrete	SKB-type
175.1–175.2	Copper expander	
175.2–185.2	Bentonite	MX-80
185.2–185.3	Copper expander	
185.3–190.3	Concrete	SKB-typ
190.3–190.4	Copper expander	
190.4–232.3	Sand	< 2 mm
232.3–232.4	Copper expander	
232.4–252.4	Concrete	Standard
252.4–252.5	Copper expander	
252.5–253.5	Concrete	SKB-type
253.5–254	Plug d = 76/96 mm, concrete	SKB-type
254–255–	Concrete	SKB-type
255–	Mechanical packer	Bottom of the borehole



12.4 Sealing components

The different components included in the full-scale installation test are described in detail in this section. The functions of the different components have partly been described in other chapters of this report e.g. Chapter 5 and 6.

12.4.1 Sand

The sand used is denominated "Fogsand < 2 mm". The grain size distribution is shown in the graph provided in Figure 12-2. This material was chosen because of the material investigations performed earlier in the project (Sandén et al. 2017). This material has a low compressibility and is assessed to be possible to install in deep boreholes to high density, see also the results from the large-scale installation tests provided in Chapter 8.

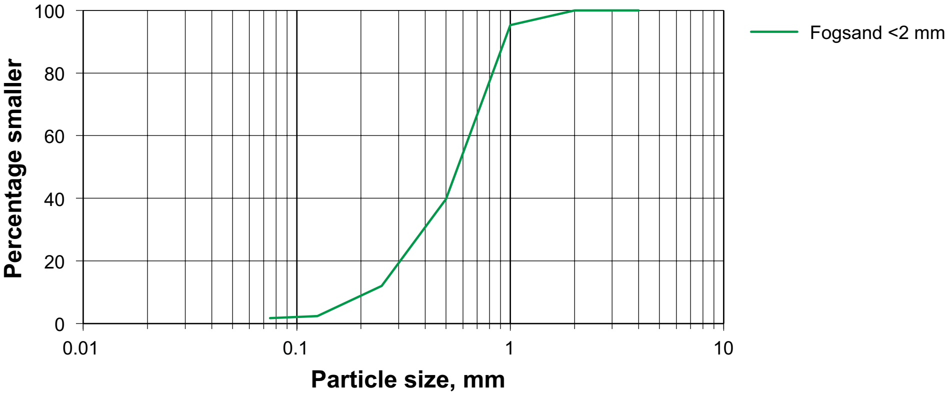


Figure 12-2. *Grain size distribution of the sand used in the installation test.*

12.4.2 Concrete

Two different types of concrete have been used in the test:

1. SKB concrete. A recipe has been developed by SKB in cooperation with CBI (Cement och Betong Institutet) within an earlier SKB project (Pusch and Ramqvist 2006).
2. Standard concrete. A standard concrete for casting underwater (Weber).

Pre-tests regarding mixing and installation technique were performed in laboratory, see Chapter 11.

SKB concrete

This 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, see recipe provided in Table 11-1.

Standard concrete (Weber)

The concrete was mixed according to the recommendations from the manufacturer i.e. 3.6 liters of water was added to 25 kg dry concrete (cement and sand).

12.4.3 Copper expander

The development of copper expanders has been performed within an earlier phase of the project (Sandén et al. 2017). The final design that has been used in the present field test is shown in Figure 10-1. The weight of a copper expander is 3.85 kg. In total seven copper expanders have been installed in the borehole.

12.4.4 Bentonite sealing

The sealing section consists of bentonite plugs manufactured of MX-80 bentonite from American Colloid Company. The plugs were compacted with a pressure of 60 MPa to a bulk density of about 2 100 kg/m^3 and with a water content of 10 % (dry density 1 909 kg/m^3). The plugs had a diameter of 70 mm and a height of 50 mm. A central hole with a diameter of 9 mm was drilled through every block. The plugs were then thread on a central rod made of stainless steel, with a diameter of 8 mm to packages, each with a length of 1.665 meter, Figure 12-3. The material of the central rod can in the future be exchanged to e.g. copper or titanium. Each package includes also a bottom plate and a top made of copper. Distance rings with a diameter of 72 mm, made of copper, are positioned at every 400 mm to minimize the contact between bentonite and rock surface during installation. Figure 12-4 shows the copper parts included in one package, approximately 1.55 kg.

After assembling, the bentonite plugs were painted with shellac in order to decrease the erosion of bentonite during installation in a water filled borehole, see investigations described in Sandén et al. (2017), Figure 12-5. 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.

The final dry density of the bentonite in the sealing section is calculated to 1 532 kg/m^3 (saturated density 1 983 kg/m^3).

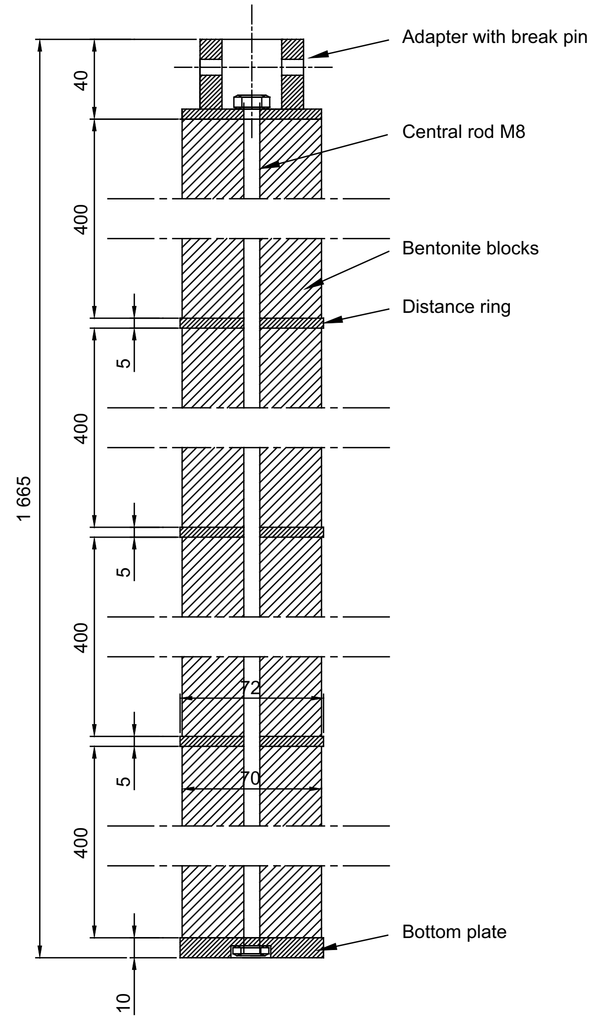


Figure 12-3. Schematic showing the design of a bentonite block package.

Figure 12-4. Photo showing the copper parts included in one bentonite package.

Figure 12-5. After assembling of the bentonite packages, they were hanged up and painted with shellac.

12.5 Installation technique

Different methods were used to install the different components in the borehole. The techniques were first tested in large scale laboratory tests and in some cases also in field tests, see Chapter 7 to 9.

12.5.1 Installation of sand

Method

The sand was installed in the borehole by pouring it down in the borehole at a constant rate of about 5 kg/min. The pre-test made in laboratory, see results provided in Chapter 8, showed that this technique and installation rate would be feasible.

The same equipment was used in the full-scale tests as in the laboratory tests i.e. a hopper filled with dry sand and a valve that was used to control the installation rate, see also photo provided in Figure 9-1.

Control

In order to control the installed mass and volume in the borehole after installation, the following work steps were included:

- The amount of sand needed to fill up a certain section of the borehole was calculated, and this mass was then determined by weighing before it was poured into the hopper.
- The level of the bottom of the borehole (top of previous installed component) was determined using the drill rig.
- After finishing the installation, the final top level of the sand section was determined. By comparing the installed mass with the installed volume, it was possible to calculate the achieved density of the sand filling. A number of these measurements were performed during the installation.

12.5.2 Installation of concrete

Method

The concrete was installed by using the drill tubes as a carrier of the material from the ground and into the borehole (same principle as for a conventional dump bailer), Figure 12-6. A plug made of copper was positioned at the bottom of the first drill tube, see photo provided in Figure 11-3. The plug was kept in place by a shear pin and sealed by an O-ring. The concrete was manually poured into the drill tubes, Figure 12-7 and at the top a nylon piston with seals was positioned, Figure 11-4. After having lowered down the drill tubes to the intended level in the borehole, a water pressure was applied above the nylon piston. The pressure was high enough to shear of the break pin keeping the bottom plug in place. The concrete was then pushed out into the borehole. When the nylon piston reached the tube end, it stopped due to a smaller diameter section in the drill tube. The installation method included thus that the bottom plug made of copper was left in the borehole.

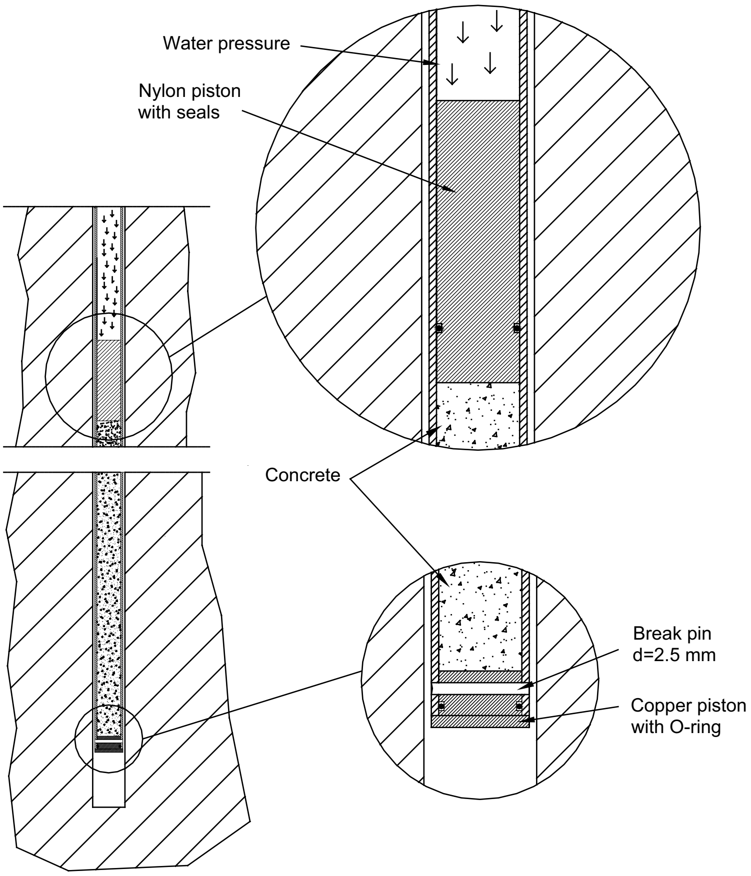


Figure 12-6. *Schematic showing the principle for the installation of concrete in the borehole.*

Figure 12-7. The concrete was manually poured into the drill tubes.

Control

In order to control the installed concrete volume and the position in the borehole after installation, the following work steps were included:

- The level of the last installed sealing material was determined by using the drill rig.
- The desired concrete volume to be installed in the borehole could easily be controlled by using a determined length of the drill tubes to be filled with concrete.
- After hardening, the final level of the concrete top section was determined by use of the drill rig.

12.5.3 Installation of copper expander

Method

The parts included in a copper expander, were mounted together before installation. The expanders were connected to a modified drill tube via shear bolts, Figure 10-1.The expander was then carried down in the borehole until reaching the top level of the earlier installed sealing material. A force was applied on the drill tube resulting in a shear bolts failure and after that also that the upper part of the expander was pushed down in the cup which expanded until reaching the borehole walls. The force needed for shearing of the bolts was about 6 kN, see Chapter 10, and to expand the copper between 10 and 20 kN.

Control

The first check of the installation was that the drill tube and the mounted copper expander have reached the expected level in the borehole before a force was applied on the drill tubes to shear of the nylon bolts. The next check was that the drill tube was empty after removal from the borehole i.e. the copper expander was left in the borehole.

12.5.4 Installation of bentonite sealing

Method

The six bentonite packages, see description in Section 12.4.4, were installed one by one. The packages have a length of about 1.655 meters and a weight of approximately 14.7 kg. A package was connected to a drill tube, Figure 12-8, in the same way as the copper expanders i.e. shear bolts were keeping the package fixed to the drill tube. The bentonite package was carried down in the borehole until reaching the top level of the previous installed sealing component. A force was then applied on the drill tube resulting in a shear bolts failure and then that the bentonite package was loosen from the drill tube.

Figure 12-8. A bentonite package is lowered down in the borehole and then connected to the drill tube with the shear bolts.

Control

All bentonite packages were weighed and measured before installation in the borehole. The first check of the installation was that the drill tube and the bentonite packages were reaching the expected level in the borehole before a force was applied on the drill tube to shear of the nylon bolts. The next check was that the drill tube was empty after removal from the borehole i.e. the bentonite package was left in the borehole.

12.6 Quality control

12.6.1 General

The full-scale test described in this chapter included sealing of a 256-meter-deep borehole with a diameter of 76 mm. The sealing was performed according to the suggested Sandwich concept. The test is not planned to be dismantled (with exception for five meters in the bottom that are planned to be over-drilled at a later stage but within another project). This means that the quality of the sealing cannot be verified by sampling or by making tests on the installed components. To ensure the quality of the performed work it has instead been necessary to have a detailed quality plan. The quality plan was divided according to the following:

- Preparatory tests in laboratories.
- Organization.
- Borehole data.
- Preparatory work in the borehole.
- Drilling rig and equipment.
- Material data.
- Installation.

The quality control described in this chapter concerns the current borehole but can of course also be used for other boreholes. An adaption to the specific borehole should, however, be made.

12.6.2 Organization

In conjunction with all field work it was stated in all quality documents, who participated in the work and who was responsible. In addition to these quality documents which mainly relates to the installation of different components in field, a logbook was used to describe all work steps during the work.

12.6.3 Borehole data

The available data for the borehole of interest, KAS13, was reviewed and compiled, see description in Section 12.2. This data was then used to plan the preparatory work in the borehole.

12.6.4 Preparatory work in borehole

To achieve a high quality on the borehole sealing it was assessed necessary to perform several preparatory activities in the borehole:

- **Exchange the inner casing tube (0–101 m)**. This tube was about 15–25 years old and it was assessed as a risk that it should broke when rotating drill equipment should be used. The tube was therefore exchanged to a new.
- **Cleaning the borehole**. The packer placed in the bottom was removed and the borehole was then flushed with water. The performance of this activity was specific for the KAS13 borehole since it was possible to open the bottom of the borehole. In an ordinary borehole the flushing must be made from the bottom and the outflowing water will come out at the borehole entrance.
- **Reaming the borehole**. In order to remove possible mineral deposits etc. on the borehole walls, it was decided to use a reaming tool. The original borehole diameter was by this operation increased from 76 to 76.5 mm. The reaming was performed to a depth of 245 meters. Because of the reaming it was assessed that no additional measurements of the borehole diameter were necessary.
- **Control of the borehole straightness**. Since the sealing includes among other things installation of bentonite packages with a length of 1.66 meters, it was assessed necessary to control the borehole straightness. This was made with a 2-meter-long dummy with an outer diameter of 74 mm. It was discovered that there were difficulties to pass with the dummy about halfway down in the inner casing tube. However, it was assessed that the bentonite packages that had somewhat smaller diameter, 72 mm, and were more flexible still should be able to pass through the inner casing.
- **Check the borehole inclination**. To facilitate a later over-drilling of the five meters at the bottom of the borehole (from the underlaying tunnel) it was decided to control the borehole inclination. This activity was made when the bottom packer was removed. The drill string was lowered down until the end was coming out from the borehole (at the ceiling in the tunnel). A measurement of the borehole inclination was then performed with a total station.

The preparatory work in the borehole resulted in delays. The main problems occurred due to the exchange of the casing tube installed in the first 100 meter of the borehole. However, when the installation of components finally started, the total installation time was rather fast, approximately two weeks.

12.6.5 Drilling rig and down-hole equipment

The drilling rig and the drilling equipment together with skilled drillers are of crucial importance to receive high quality of the installed components in the borehole. To complete the test means that the drill rods must be lifted up and down a large number of times and at the same time keep full control over the position in the borehole. These requirements were clarified in the procurement, and resulted in the following deliveries:

- Cleaned and well served drilling rig.
- A drilling rig with digital control system that facilitates rods handling and registers rod length.
- Drill rods in standard dimension with thread connections suitable for sealing adapters.
- On site testing that all equipment fits on the drill pipes and that the pistons fit inside the rods.

12.6.6 Material data

Basic material data of the sealing components was determined before the installation started. This data, together with measurements of the positions in the borehole, was then used to calculate e.g. the final density of sand and bentonite after installation, see also data provided in Section 12.4 and 12.8.

Bentonite packages

The following was measured/determined before the installation started:

- Diameter and height of the bentonite plugs.
- Mass of the bentonite plugs.
- Total mass of every bentonite package including copper details, threaded rod etc.
- Water content and density of the compacted plugs.

The above-mentioned parameters were measured/determined in conjunction with the manufacturing of the bentonite plugs and the assembling of the bentonite packages. At the installation in the borehole, the final position and the occupied borehole length was measured. With this data the final installed density of the bentonite can be calculated.

Concrete

Two types of concrete were installed in the borehole, see recipes provided in Section 12.4.2. To fill up a certain borehole length with concrete, the corresponding drill tube length to achieve the same volume was calculated.

Sand

The expected bulk density of the sand filling after installation in a borehole was determined in laboratory test and in full scale tests, see Chapter 8 and 9.

In conjunction with the installation in the borehole the mass of the installed sand was determined by weighing (all sand poured into the hopper was weighed). After installation of one batch of sand, the drill rig was used to determine the position of the upper level of the sand filling. With this data, the occupied volume in the borehole could be calculated and then also the bulk density of the installed sand filling. In the performed sealing of KAS13 there are two sand filled sections with a length of 62.91 and 46.64 meter respectively. The installation of these sections was divided into three batches each.

Copper expander

The dimensions and weight of the copper expanders were controlled before installation. The height after compression was known by the laboratory tests (155 mm before compression and 120 mm after compression). In conjunction with the installation the force applied to expand the copper was measured/controlled to 20 kN.

12.6.7 Installation

Before starting the installation of sealing components in the borehole, the following was checked:

- All equipment should be in good condition.
- The organization should be clear.
- All quality documents should be available.
- The logbook should be available.
- All sealing components that are planned to be installed should be available together with backup material.

In conjunction with the installation, all quality documents were followed, and all relevant test parameters noted. The most important parameters needed, in order to assess the quality of the installation after wards, are the positions of every component in the borehole and also the installed masses/volumes of the different components.

12.7 Installation in field

The installation of the different components in the borehole took about two weeks including one weekend. All data regarding borehole sections, installed components, achieved density etc. is compiled in Table 12-3. A description of the work steps and the achieved results is provided below:

1. **30–31 May**. Establishment of the drill rig. Preparing for generator, access to water etc. The borehole was flushed with water during the night.
2. **1 June**. Reaming of the section 253.5–254 m from d = 76 mm to d = 82 mm. The reaming tool was working with an overpressure of 30 bars and 500 rpm, see photo provided in Figure 12-9. The feed rate was between 1 and 3 cm/min. The reaming worked well but problems occurred in conjunction with the removal of the tool from the borehole. The water pressure was still acting on the tool segments which meant that it was not possible to lift the tool. It was decided to wait until the pressure had evened out.
3. **4 June**. Two main activities during the day:
    a. The reaming tool was removed after some problems. The bottom packer was then removed, and the borehole flushed. After remounting of the packer, the borehole was ready for installation of the first component, SKB concrete.
    b. Installation of SKB concrete. A first test of the injection tubes including the nylon piston and the bottom plug was made above ground. Everything worked according to plans. The injected volume (the length of the injection tubes was controlled) differed from the installed (the upper level was checked when the next copper expander was installed). The difference was about 8 %. The difference may be due to problems to fill the injection tubes properly i.e. there may be trapped air in the concrete. There was no evident drop in pressure during the extrusion of concrete from the injection tubes (a pressure drop was expected when the bottom plug was loosened from the tube). Maximum pressure on the concrete was 45 bars. SKB concrete was installed in section 252.51–255.19 m.
4. **5 June**. Two main activities during the day:
    a. Installation of the first copper expander. The length of the expander after compression is 120 mm. The expander was compressed with 20 kN and the final position in the borehole is 252.39–252.51 m.
    b. Installation of standard concrete for casting under water (Weber). The injected volume was almost accurate with the calculated volume in the borehole. The standard concrete was installed in section 231.64–252.39 m.
5. **6 June**. Four main activities during the day:
    a. Installation of the second copper expander. There was an evident change in pressure when the shear bolts were broken at 6 kN. The expander was then compressed with 20 kN and the final position in the borehole was 231.52–231.64 m.
    b. Installation of sand. The sand was installed by gravity by use of a large hopper equipped with a valve which makes it possible to adjust the installation rate, see also photo provided in Figure 9-1. The sand was installed in three different steps with measuring of the installed volume in between. The installation rate varied between 8 and 20 kg/min. The installed density varied between 1 539 and 1 651 kg/m^3. The lowest 40 meter of the borehole was filled with water which meant that the sand initially fell through an empty (air filled) borehole. The sand was installed in borehole section 188.88–231.52 m.
    c. Installation of the third copper expander. There was an evident change in pressure when the shear bolts were broken at 6 kN. The expander was then compressed with 20 kN and the final position in the borehole was 188.76–188.88 m.
    d. Installation of SKB concrete. The injected volume (the length of the injection tubes is controlled) differed quite a lot from the installed (the upper level was checked when the next copper expander was installed). The difference was about 14 %. The difference may be due to problems to fill the injection tubes properly i.e. there may be trapped air in the concrete. The SKB concrete was installed in borehole section 183.69–188.67 m.

6. **7 June**. Two main activities during the day:
    a. Installation of the fourth copper expander. There was an evident change in pressure when the shear bolts were broken at 6 kN. The expander was then compressed with 20 kN and the final position in the borehole was 183.57–183.69 m.
    b. Installation of bentonite. The borehole was filled with water to give conditions more like the expected in the main part of the boreholes that are going to be sealed. Six bentonite packages (see photo provided in Figure 12-5) were lowered down in the borehole, one by one. The installation was made without any problems and all six packages were installed within one day. The bentonite packages were installed in borehole section 173.65–183.57 m.
7. **8 June**. Two main activities during the day:
    a. Installation of the fifth copper expander. There was an evident change in pressure when the shear bolts were broken at 5.5 kN. The expander was then compressed with 20 kN and the final position in the borehole was 173.53–173.65 m.
    b. Installation of SKB concrete. The installation was made according to the plans. The injected volume (the length of the injection tubes is controlled) was almost the same as the installed (the upper level was checked when the next copper expander was installed). The difference was 0.5 %. The SKB concrete was installed in borehole section 167.67–173.53 m.
8. **9 June**. Two main activities during the day:
    a. Installation of the sixth copper expander. The expander was compressed with 20 kN and the final position in the borehole was 167.55–167.67 m.
    b. Installation of sand. The borehole was filled with water to give conditions more like the expected in the main part of the boreholes that are going to be sealed. The sand was installed by gravity by use of a large hopper equipped with a valve which makes it possible to adjust the installation rate, see also photo provided in Figure 9-1. The sand was installed in two different steps with measuring of the installed volume in between (the last batch of sand was installed after the reaming, see bullet 9). The installed density of the two batches was determined to 1 632 and 1 736 kg/m^3, respectively. The sand was installed in borehole section 123.57–167.55 m.
9. **12 June**. Four main activities during the day:
    a. Reaming of the section 102–102.5 m from d = 76 mm to d = 82 mm. The reaming tool was working with an overpressure of 30 bars and 500 rpm. The feed rate was between 1 and 3 cm/min. The tool works well and there were no problems to remove it afterwards.
    b. Installation of sand. The last batch of sand was installed with the same method as earlier. The installed density was determined to 1 725 kg/m^3. The sand was installed in borehole section 104.64–123.57 m.
    c. Installation of the seventh copper expander. The expander was compressed with 20 kN and the final position in the borehole was 104.52–104.64 m.
    d. Installation of SKB concrete. The SKB concrete was installed in borehole section 101–104.52 m. The upper level of the concrete was, however, not checked.

Figure 12-9. *Photo showing the reaming tool used to increase the borehole diameter at two levels.*

Tabel 12-3. Compilation of installation data (from top and downwards).

Borehole section						Installation	Concrete	Bentonite and Sand		Copper exp.	
Depth, upper edge m	Depth, lower edge m	Diameter mm	Water filled	Length m	Volume dm^3	Material	Installed volume dm^3	Installed dry mass kg	Density kg/m^3	Applied load kN	Remark
101.00	102.00	76.5	Yes	1.00	4.60	SKB concrete					
102.00	102.50	82.0	Yes	0.50	2.64	SKB concrete					Reamed plug section
102.50	104.52	76.5	Yes	2.02	9.28	SKB concrete	16.17				Installed volume includes all three sections above.
104.52	104.64	76.5	Yes	0.12	0.55	Copper exp.				20	
104.64	167.55	76.5	Yes	62.91	289.16	Sand		490	1695		Average density of three sections
167.55	167.67	76.5	Yes	0.12	0.55	Copper exp.				20	
167.67	173.53	76.5	Yes	5.86	26.93	SKB concrete	26.71				
173.53	173.65	76.5	Yes	0.12	0.55	Copper exp.				20	
173.65	183.57	76.5	Yes	9.92	45.60	Bentonite		68	1523		Dry density = 1523 kg/m^3 Saturated density = 1977 kg/m^3
183.57	183.69	76.5	Yes	0.12	0.55	Copper exp.				20	
183.69	188.76	76.5	Yes	5.07	23.30	SKB concrete	26.71				
188.76	188.88	76.5	Yes	0.12	0.55	Copper exp.				20	
188.88	231.52	76.5	0–215 m: air, 215–255: water	42.64	195.99	Sand		315	1607		Average density of three sections
231.52	231.64	76.5	0–215 m: air, 215–255: water	0.12	0.55	Copper exp.				20	
231.64	252.39	76.5	0–215 m: air, 215–255: water	20.75	95.37	Std. concrete	94.53				
252.39	252.51	76.0	0–215 m: air, 215–255: water	0.12	0.54	Copper exp.				20	
252.51	253.50	76.0	0–215 m: air, 215–255: water	0.99	4.49	SKB concrete					
253.50	254.00	82.0	0–215 m: air, 215–255: water	0.50	2.64	SKB concrete					Reamed plug section
254.00	255.19	76.0	0–215 m: air, 215–255: water	1.19	5.40	SKB concrete	13.57				Installed volume includes all three sections above.
255.19											Upper edge of packer

12.8 Expected properties of the installed components

12.8.1 Sand

In total, almost 106 meters of the KAS13-borehole were filled with sand. A compilation of data from the installed sand sections is provided in Table 12-4. Two sections were filled with sand, 104.64–167.55 and 188.88–231.52 m. Each of the sand filled sections were filled with three batches of sand with measurements of the achieved top level of the last filling before the next batch was installed. These measurements made it possible to calculate the installed density of every batch.

The installation of sand in the lower section was mainly made in an empty (air-filled) borehole. The water level was standing at the 215-meter level which means that only the first batch was installed in a water filled borehole, however, after falling through air the first 215 meters. After installation of sand, the borehole was flushed with water to ensure that no sand was left on the borehole walls. Concrete was installed in section 183.69–188.76 m and then the upper part of the borehole was filled with water. This means that the three last batches of sand were installed into a water filled borehole.

The expected density of a sand filling after installation in a borehole vary between 1 647 to 1 686 kg/m^3 (large scale tests in laboratory, Chapter 8) and 1 626–1 689 kg/m^3 (field test, Chapter 9). No evident difference between dry and water filled boreholes was found in these tests.

The calculated average bulk density of the lower sand filled section (188.88–231.52 m) was 1 607 kg/m^3 which thus is a little bit lower than expected. The density of the last batch installed in this section was clearly lower than the others, 1 539 kg/m^3, and the reason for this is not known. The average bulk density for the upper sand filling (104.64–167.55 m) is 1 695 kg/m^3 which is somewhat higher than expected.

The hydraulic conductivity of the sand filling has little significance for the Sandwich-concept but should be known to get the whole picture regarding a sealed borehole. With a dry density of 1 650 kg/m^3, the sand filling will have a hydraulic conductivity of approximately 10^{-5} m/s (Sandén et al. 2017). A high installed density of the sand filling is, however, important to minimize the compressibility of the installed sand filling. The achieved density in the tests is high for five of the installed batches while the density of the last batch in the lower sand filled section is lower than expected. The reason for this is not known.

Table 12-4. Compilation of data from the installed sand filled sections. Note that the data is provided in the same order as the installation order.

	Borehole section						Sand	
Sand installation	**Depth, upper edge m**	**Depth, lower edge m**	**Diameter mm**	**Water filled**	**Length m**	**Volume dm^3**	**Installed dry mass kg**	**Density kg/m^3**
Batch 1:1	218.32	231.52	76.5	No	13.20	60.67	100	1 648
Batch 1:2	205.14	218.32	76.5	No	13.18	60.58	100	1 651
Batch 1:3	188.88	205.14	76.5	No	16.26	74.74	115	1 539
Average								**1 607**
Batch 2:1	144.88	167.55	76.5	Yes	22.67	104.20	170	1 631
Batch 2:2	123.57	144.88	76.5	Yes	21.31	97.95	170	1 736
Batch 2:3	104.64	123.57	76.5	Yes	18.93	87.01	150	1 724
Average								**1 695**

12.8.2 Bentonite

Six bentonite packages, each with a length of 1.665 m were installed in the borehole. The theoretical length after installation should be 9.99 m but according to measurements the total length of the bentonite section was 9.92 m. The bentonite packages were rather flexible and since a force of 6 kN were applied at the top of each package (to shear of the nylon bolts) it is possible that each package was compressed about one cm. Each of the six bentonite packages included 12.5 kg compacted bentonite (water content = 10 %), 1.55 kg copper and a threaded rod made of stainless steel with a weight of 0.65 kg.

The dry density of the bentonite installed in the borehole section (173.65–183.57 m) is calculated to 1 532 kg/m^3 and the corresponding saturated density is 1 983 kg/m^3. The bentonite section is expected to after saturation have a hydraulic conductivity of approximately 10^{-13} m/s and a swelling pressure of approximately 4–6 MPa (Åkesson et al. 2010). The exact values depend also on the site conditions regarding e.g. water salinity.

12.8.3 Concrete

In total five batches of concrete were installed, one batch using a standard concrete for casting underwater (Weber standard concrete) and four batches using a special developed concrete (SKB concrete), Table 12-5.

To fill up a certain borehole length with concrete, the corresponding drill tube length to achieve the same volume was calculated. Since the installed length in the borehole was determined afterwards, it was possible to calculate the difference. The difference between the two measurements was small for three of the batches but for two of the batches with SKB concrete the difference was larger, 7.92 and 14.66 % respectively. The difference is believed to depend on problems to fill the injection tubes properly i.e. there may have been trapped air in the concrete which means that the injected volume is overrated.

The borehole sections filled with concrete are believed to have a very low permeability. The adhesion between concrete and rock have been tested in laboratory (Sandén et al. 2017) for the SKB concrete. These tests indicated a maximum shear stress between concrete and rock of more than 300 kPa after five to eight days. This means that a concrete filled borehole section with a length of one meter can withstand an overload of 72 kN. This load corresponds to an axial swelling pressure from the bentonite of more than 15 MPa. The long-term performance of the concrete is, however, under discussion.

The installation of concrete as described in Chapter 11 is very sensitive how this is made. In order to minimize the risk of separation, the installation should be made with the rod tip below the surface of the fresh concrete inside the borehole. However, this was very hard to ensure in this test and thus it is not ruled out that a separation of the concrete might have occurred. This is of course affecting the properties of concrete. As described in Chapter 12 the lower part of the borehole will be over cored. At this stage it will be possible to investigate the homogeneity of the two types of installed concrete.

Table 12-5. Compilation of data from the installed concrete sections.

	Borehole section						**Concrete**		
Concrete installation	**Depth, upper edge m**	**Depth, lower edge m**	**D mm**	**Water filled**	**Length m**	**Volume dm^3**	**Installed volume kg**	**Diff. %**	**Remark**
SKB conc. 1	252.51	255.20	76.5	Yes	2.69	12.58	13.57	7.92	The volume includes a reamed section with d = 82 mm
Standard concrete	231.64	252.39	76.5	Yes	20.75	94.57	94.58	0.00	
SKB conc. 2	183.69	188.76	76.5	No	5.07	23.30	26.72	14.66	
SKB conc. 3	167.67	173.53	76.5	No	5.86	26.58	26.72	0.51	
SKB conc. 4	101.00	104.52	76.5	No	3.52	16.52	16.17	−2.11	The volume includes a reamed section with d = 82 mm

12.8.4 Copper expander

A schematic drawing of a copper expander is provided in Figure 10-1. The weight of a copper expander is 3.85 kg and the total length after compression 120 mm. In total seven copper expanders have been installed in the borehole, see data provided in Table 12-6.

The copper expander is after installation expected to effectively seal the borehole and prevent the different materials from mixing and interacting with each other both during installation but also in the long term.

Table 12-6. Compilation of data from the installed copper expanders.

	Borehole section					
Copper expander	**Depth, upper edge m**	**Depth, lower edge m**	**Diameter mm**	**Water filled**	**Length m**	**Volume dm^3**
Copper exp. 1	252.39	252.51	76.0	Yes	0.12	0.54
Copper exp. 2	231.52	231.64	76.5	Yes	0.12	0.55
Copper exp. 3	188.76	188.88	76.5	No	0.12	0.55
Copper exp. 4	183.57	183.69	76.5	No	0.12	0.55
Copper exp. 5	173.53	173.65	76.5	No	0.12	0.55
Copper exp. 6	167.55	167.67	76.5	No	0.12	0.55
Copper exp. 7	104.52	104.64	76.5	Yes	0.12	0.55

12.9 Comments and conclusions

The full-scale installation test in a borehole with a length of 255 meter was successful. Some comments to the tests are provided below:

- The main problems and delays with the project occurred in conjunction with the preparatory work in the borehole. The exchange of the old casing to a new resulted in several problems e.g. regarding material that got stuck in the borehole (both pieces from the steel casing but also from material that was filling up the gap between the casing and the borehole walls). This is something that must be planned for in the future work with sealing of boreholes.
- The suggested installation techniques for the different components included in the Sandwich-design were successfully demonstrated.
- The quality control resulted in that the position of every component installed in the borehole was known together with the installed density and/or volume. With this data, the material properties such as swelling pressure, hydraulic conductivity can be predicted.
- Installation of concrete by using the drill tubes as a bailer worked according to the plans. For two of the five batches there was a deviation between the injected volume and the installed volume. The difference is believed to depend on problems to fill the injection tubes properly i.e. there may be trapped air in the concrete which means that the injected volume is overrated.
- The installation of bentonite packages and copper expanders was also made by using the drill tubes as a carrier. The technique to apply a force and shear of the nylon bolts that attached the copper expander, or the bentonite package, to the drill tube worked well.
- A special developed reaming tool was used at two levels to achieve a section in the borehole with larger diameter that after casting will work as a plug. The tool worked as intended but there was a problem to get the cutters back into the house in conjunction with removal.

13 Conclusions

13.1 General

New modeling results show that the tightness of the sealed boreholes only marginally will affect the groundwater flow at the depth of a repository. This has resulted in suggestions for mitigated requirements on the closure of boreholes close to the repository with hydraulic connections to the repository area via water bearing fractures.

A new concept, the Sandwich-concept, has been suggested for sealing of boreholes. This concept is based on that the main part of a borehole is filled with granular material, sand, while sealing sections consisting of highly compacted bentonite, are positioned in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. The main components included in this design are the sand filling, the bentonite plugs, the quartz-based concrete and the copper expanders. The results from several large-scale installation tests, completing tests performed in laboratory and finally a field test where a 250-meter-deep borehole has been sealed, are provided in this report.

In addition, a suggestion for a borehole characterization is provided together with different sealing strategies. This work is, however, still ongoing.

13.2 Borehole characterization

The purpose with the characterization is to classify the boreholes and after that perform a detailed design of the closure for every individual borehole. The work with classification is ongoing and is therefore only briefly described in this report but the preliminary outcome is that all boreholes will be divided into three different classes. The classification will be made based on borehole depth, distance to the repository and on the presence of hydraulic connections between the borehole and the repository area.

13.3 The Sandwich-concept

The new Sandwich-concept implies that the main part of a borehole is filled with a permeable material such as sand or gravel, while strategically positioned bentonite seals are placed in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. 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. 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 installed to separate different materials. 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 top seal is placed in the uppermost part of the rock. The top seal has a larger diameter than the borehole and will serve as a mechanical lock of the borehole.

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 in selected borehole sections with good rock quality i.e. there are no water bearing fractures present. The hydraulic conductivity of the seals will be in the order of 10^{-13} m/s. This implies that a requirement of a certain hydraulic conductivity along the whole borehole length of 10^{-6} m/s will not be fulfilled, but locally the hydraulic conductivity will be much lower.

By using the hydraulic conductivity of the different sealing components that are installed a certain length in the borehole, one can instead calculate the hydraulic resistance for axial flow in the borehole. The presence of tight seal sections will result in a resistance against axial flow that is higher than if the whole borehole was filled with a material with a hydraulic conductivity of 10^{-8} m/s. With this way of looking at the sealing of a borehole, the sealing can be substantially simplified and still fulfill the requirements on preventing water from flowing in axial direction of the borehole.

13.4 Laboratory tests on components

Since no investigations and measurements after installation of the full-scale field test were made, completing tests have been performed in laboratory, one smaller homogenization test and one larger Mockup test including installation of all components.

13.4.1 Homogenization test

The main objectives with the test were to measure and demonstrate the swelling pressure built up and the sealing effect of dense bentonite installed in a rock section. The dry density of the bentonite installed in the simulated borehole section varied between 1 440 kg/m^3 (at the test tube walls) and 1 580 kg/m^3 (at the central parts).

The registered swelling pressure from the bentonite against the simulated rock wall was around 5 MPa which is well in agreement with the expected 4–6 MPa (Åkesson et al. 2010). The calculated hydraulic conductivity of the sealing, 3.4×10^{-12} m/s, is higher than expected for the density, 10^{-13} m/s (Åkesson et al. 2010). It is judged that a more relevant evaluation by FEM-calculation should be done since the flow situation is rather complex and the analytical evaluation is too approximate.

13.4.2 Mockup test

The main objectives with the test have been to verify and demonstrate the function of all components and of the concept itself. Another objective has been to study the homogenization of the bentonite sealing by registering the swelling pressure built up and by measuring the hydraulic conductivity. The dry density of the bentonite installed in the simulated borehole section varies between 1 230 kg/m^3 (at the test tubes walls) and 1 450 kg/m^3 (at the central parts). The achieved average density is thus lower than intended which depends on the use of bentonite plugs with smaller diameter than intended (the bentonite plugs had a diameter of 70 mm which was adapted to a borehole diameter of 76 mm instead of 80 mm as in this test equipment). This has resulted in a rather low registered swelling pressure from the bentonite against the simulated rock wall, between 1.5 and 1.9 MPa. The calculated hydraulic conductivity of the sealing, 5.4×10^{-12} m/s, is slightly higher to what was determined for the Homogenization test. As for the Homogenization test, it is judged that a more relevant evaluation by FEM-calculation should be done.

13.5 Installation tests in laboratory and field

13.5.1 General

The different components included in the Sandwich-concept were installed with different techniques:

- **Bentonite pellets and sand.** These components were installed by gravity i.e. they were poured down into the borehole with a controlled rate.
- **Concrete**. The concrete was installed by filling a certain length of drill tubes with concrete and then after bringing them down to the right level, push out the concrete with help of an applied water pressure.
- **Bentonite packages and copper expanders**. These components were installed by attaching them to the drill tubes and then bring them down to the desired level in the borehole.

The installation techniques were developed and tested in laboratory and thereafter demonstrated in a full-scale field test.

13.5.2 Bentonite pellets

A large proportion of the boreholes that will be sealed are shallow boreholes, 0–30 m, drilled in regolith layer or only a few meters into the rock. These boreholes, and the uppermost meters of the deep investigation boreholes, are planned to be filled with bentonite pellets. Large scale tests were performed in laboratory. The tests included installation of bentonite pellets in an artificial borehole with a length of ten meters. The tests were made at both dry and wet (water filled borehole) conditions. The tests showed that bentonite pellets can be efficiently installed in both dry and water filled boreholes (d = 140 mm) with a maximum length of 10 m, by gravity i.e. they are dropped from the surface down into the borehole. If bentonite pellets are planned to be installed in deeper boreholes i.e. 10 to 30 m, the method can be improved by using coated pellets. The coating prevents early swelling of the bentonite and the problems that accompany this, such as bridging. It is recommended that tests on coated pellets should be performed in the future.

Installation of bentonite pellets in a water filled shallow borehole, 0–10-meter-deep, can be made with an installation rate of approximately 5 kg/min (borehole d = 140 mm). Corresponding figure for dry boreholes is approximately 10 kg/min or higher.

The achieved dry density of the bentonite in the boreholes was between 1 174 and 1 243 kg/m^3 in dry boreholes and between 863 and 994 kg/m^3 in water filled boreholes. The rather high density achieved in the dry boreholes was assessed to depend on that the conveying screw, that was transporting the pellets to the borehole entrance, partly shallow the pellets and that the fines produced, filled up the macro voids between the pellets.

13.5.3 Sand

The Sandwich-concept includes that the main part of the borehole is filled with a permeable material e.g. sand or gravel. The installation is planned to be made by gravity, i.e. the sand is poured into the borehole at a constant rate. The tests included installation of sand in an artificial borehole with a length of ten meters. The tests were made at both dry and wet (water filled borehole) conditions. In addition, a full-scale installation test of sand in a borehole with a length of 255 m was performed.

The laboratory tests showed that installation of sand can be made at a rate of 5–8 kg/min (borehole d = 76 mm) at both dry and wet conditions. In boreholes with larger diameter it is assessed that the installation rate can be increased.

The achieved density was high for all tests, between 1 647 and 1 682 kg/m^3. The highest density was reached in the tests where the sand was installed at dry conditions.

The sand installation test performed in field showed that the same installation technique as was used in the laboratory tests also could be used in field. The test was performed in a borehole with a length of 255 m. The installed density of the sand filling was in the range of 1 626 to 1 689 kg/m^3 which is well in accordance with the density determined in the large-scale laboratory tests.

13.5.4 Concrete

The installation of concrete in a borehole was made by using standard drill tubes that were filled with concrete. Once the tip of the tube was at the position in the borehole where the casting should be made, the concrete was pushed out from the tube by applying a water pressure above via a piston positioned in the drill tube. The pre-tests included development of e.g. an end plug, shear rods and a nylon piston.

Several tests were made in the laboratory where the design of the equipment together with the mixed concrete was tested under realist conditions. Simulations of casting, both in dry and water filled boreholes, were made. One important outcome from the tests was that the used concrete was very sensitive for how it is placed in a water filled borehole. It is essential that the tip of the rod is placed underneath the surface of the fresh concrete during the whole casting process to minimize the risk of separation.

13.5.5 Bentonite packages and copper expanders

The same technique was used for installation of both bentonite packages and copper expanders. The copper expander (or the bentonite package) was attached to a special designed drill tube via bolts made of nylon. After having lowered down the expander to the right level e.g. against a concrete or sand surface, a force was applied on the drill tubes which resulted in a shear failure of the two bolts. When installing a copper expander, the force was additionally increased to expand the copper (20 kN), but when the bentonite packages were installed, the drill tubes were lifted after having sheared off the bolts.

Tests were performed in laboratory in a hydraulic press to determine the force needed to shear of the two bolts (6 kN).

13.6 Full scale sealing of borehole

The borehole used for the full-scale installation test is situated close to the Multi Purpose Facilities at Äspö. The borehole is denominated KAS13. The borehole has a length of 255 meters. The test was performed as a pure installation test and focus of the work was to demonstrate the installation techniques used for the different components but also on the quality control regarding the sealing components and in which borehole section they were installed.

The installation included several different components: a special developed concrete with a very low cement content, a standard concrete, sand, highly compacted bentonite and copper expanders (bridge plugs). The sand was installed by gravity (controlled installation rate) while the installation of the other components required access to the drill rig. The installation was made according to the plans and the techniques developed and tested in laboratory also worked in the full scale. The total installation time was rather fast, approximately two weeks.

To ensure the quality of the performed work it was necessary to have a detailed quality plan including organization, available borehole data, preparatory work, drilling rig, material data and a controlled installation procedure. The quality of the borehole sealing was assessed to be successful regarding e.g. achieved density of the bentonite section and the two sections filled with sand. Regarding the concrete sections, there was a difference between injected volume and filled borehole volume for two of the five sections. The difference was believed to depend on problems to fill the injection tubes properly i.e. there may be trapped air in the concrete which means that the injected volume was overrated.

The KAS13 borehole crosses the tunnel ramp close to the elevator shaft at the −220-meter level. This means that it will be possible to have access to the lower part of the borehole. It is planned to over core the lowest five meters of the borehole from the bottom to be able to take out samples and study the quality of the installed components i.e. two types of concrete and one copper expander. This activity will, however, in that case be performed within another project.

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