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Äspö Hard Rock Laboratory

Concrete and Clay

Installation report

Per Mårtensson

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00
skb.se

SVENSK KÄRNBRÄNSLEHANTERING

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Per Mårtensson, Svensk Kärnbränslehantering AB

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Update notice

The original report, dated January 2015, was found to contain factual errors which have been corrected in this updated version. The corrected factual errors are presented below.

Updated 2016-12

Location	Original text	Corrected text
Page 47, Table B-1, heading	…hole KR0009G01 in…	…hole KR0014G01 in…
Page 47, Table B-2, heading	…hole KR0009G01 in…	…hole KR0014G01 in…
Page 47, Table B-3, heading	…hole KR0009G01 in…	…hole KR0014G01 in…
Page 48, Table B-4, heading	…hole KR0014G01 in…	…hole KR0009G01 in…
Page 48, Table B-5, heading	…hole KR0014G01 in…	…hole KR0009G01 in…
Page 48, Table B-6, heading	…hole KR0014G01 in…	…hole KR0009G01 in…
Page 49, Table C-1, heading	Specimens emplaced in the lower concrete…	Specimens emplaced in the topmost concrete…
Page 49, Table C-2, heading	Specimens emplaced in the lower concrete…	Specimens emplaced in the middle concrete…

Summary

Low- and intermediate level radioactive waste, LILW, are today deposited in the final repository for short-lived low- and intermediate level radioactive waste, SFR, or stored temporarily while waiting for the final repository for long-lived low- and intermediate level radioactive waste, SFL, to be completed. The LILW consists of a complex mixture of different types of materials including both organic as well as inorganic materials. This waste is conditioned in various types of containers containing a mixture of waste and cement mortar but bitumen is also used. Finally, the containers are placed in the repository in which different types of cement-based materials and bentonite are used or are planned to be used.

In the safety assessments conducted at the facilities planning, construction, and operation and before their closure good knowledge of the processes that occur when the waste, conditioning grout and the materials used in the engineered barriers interact with each other under the influence of an anoxic groundwater is required. To increase SKB's knowledge and understanding of these processes the project *Concrete and Clay* has been implemented.

This report describes all the steps from preparation of niches to installation of the experiment packages, including the production of certain equipment required. The work which has been carried out during the years 2010 to 2014 has included the installation of a total of 9 experiment packages in three different niches in the Äspö Hard Rock Laboratory. These nine packages are distributed as follows:

- Concrete and clay phase 1 comprising field scale concrete experiments: 2 packages containing concrete cylinders with material samples representative of LILW deposited in niche NASA0507A.
- Concrete and clay phase 2 comprising field scale concrete experiments: 1 package containing concrete cylinders with material samples representative of LILW and one package containing concrete cylinders without material specimens deposited in niche NASA2861A.
- Concrete and clay phase 3 comprising field scale bentonite experiments: 5 packages containing bentonite blocks deposited in TAS06. Each block contains 4 small cylinders of cement paste or bentonite each of which also contains a metal powder or a powder of a metal chloride representative of low and intermediate level waste or container material. As an alternative, some bentonite blocks instead contain a solid cylindrical specimen of steel or stainless steel.

As a complement to the field scale concrete experiments laboratory scale experiments are also conducted. Here, 20 stainless steel containers have been manufactured and filled with groundwater from Äspö, a little crushed cement and the same type of material specimens as used in the field scale concrete experiments. The main purpose of the laboratory scale experiments is to serve as a guide in the decision on when to retrieve the first field scale concrete experiments. The first retrieval of the field scale concrete experiments will be scheduled when the analyses of the laboratory scale experiments indicate incipient decomposition of the material specimens placed in the containers. Before this has occurred, the probability that decomposition of the material specimens in the concrete cylinders has started is expected to be low and retrieval thus not motivated.

Sammanfattning

Låg- och medelaktivt radioaktivt avfall deponeras idag i Slutförvaret för kortlivat låg- och medelaktivt radioaktivt avfall, SFR, eller mellanlagras i väntan på att slutförvaret för långlivat låg- och medelaktivt radioaktivt avfall, SFL, ska stå färdigt. Det låg- och medelaktiva avfallet består av en komplex blandning av olika typer av material inkluderande både organiskt såväl som oorganiskt material. Detta avfall konditioneras i olika typer av behållare innehållande en blandning av avfall och cementbruk men även bitumen används i vissa fall. Slutligen placeras behållarna i förvar i vilka olika typer av cementbaserade material och bentonit används eller planeras att användas.

I de säkerhetsanalyser som genomförs vid anläggningarnas planering, uppförande, drift och inför deras förslutning krävs god kunskap om de processer som sker när avfallet, konditioneringsbruket samt de material som används i de tekniska barriärerna interagerar med varandra under inverkan av ett syrefritt grundvatten. För att öka SKB:s kunskap och förståelse av dessa processer genomförs därför projektet *Concrete and Clay*.

Denna rapport beskriver samtliga steg från iordningställande av nischer till installering av de färdiga experimentpaketen samt tillverkning av viss specialutrustning inom projekt *Concrete and Clay*. Arbetet vilket har genomförts under åren 2010 till 2014 har omfattat installationen av totalt 9 stycken experimentpaket i 3 olika nischer i Äspö-laboratoriet. Dessa 9 paket fördelas enligt följande:

- 2 paket innehållande betongcylindrar med materialprover representativa för låg- och medelaktivt avfall deponerade i nisch NASA0507A.
- 1 paket innehållande betongcylindrar med materialprover representativa för låg- och medelaktivt avfall och ett paket innehållande betongcylindrar utan avfall deponerade i nisch NASA2861A.
- 5 paket innehållande bentonitblock deponerade i TAS06. Varje bentonitblock innehåller 4 stycken små provcylinderar av cementpasta eller bentonit var och en även innehållande ett metallpulver eller ett pulver av en metallklorid representativa för låg- och medelaktivt avfall eller behållare för detta. Vissa bentonitblock innehåller i stället cylindriska provbitar av stål eller rostfritt stål som alternativ till cement- och bentonitproverna.

Som komplement till ovanstående experiment genomförs även experiment i laboratorieskala. Dessa innefattar totalt 20 stycken provbehållare av rostfritt stål vilka tillverkats och fyllts med grundvatten från Äspö, lite krossad cement samt samma typ av materialprover som placerats i betongcylindrarna i de tre förstnämnda experimentpakten.

Den exakta tidpunkten för återtag av de första av de experiment som placerats i Äspötunneln är ännu ej bestämd utan kommer att avgöras genom analyser av det vatten som finns i de rostfria provbehållarna. Det första återtaget kommer att planeras in när analyser av experimenten i laboratorieskala visar på begynnande nedbrytning av det i behållarna placerade avfallsmaterialet. Innan detta har skett bedöms sannolikheten för att något ska ha skett med experimenten i Äspötunneln som låg och ett återtag därför inte motiverat.

Contents

1 Introduction

1.1 Background

Low- and intermediate level radioactive waste, LILW, are today deposited in the final repository for short-lived low- and intermediate level radioactive waste, SFR, or stored temporarily while waiting for the final repository for long-lived low- and intermediate level radioactive waste, SFL, to be completed. The LILW consists of a complex mixture of different types of materials including both organic as well as inorganic materials. This waste is conditioned in various types of containers containing a mixture of waste and cement mortar but bitumen is also used. Finally, the containers are placed in the repository in which different types of cement-based materials and bentonite are used or are planned for use.

In SFR which has been under operation for more than 25 years, concrete and other cement based materials are extensively used in the engineered barrier system, either alone or in combination with bentonite as in the Silo (SKB 2008). In SFR a majority of the waste is conditioned in a cement matrix but some is also conditioned in bitumen. A certain fraction of the ion exchange resins deposited in the repository sections for concrete tanks, 1BTF and 2BTF is simply just dried.

For SFL which is currently planned to be taken into operation in the year 2045 the SFL concept study has just been finalised (Elfwing et al. 2013). In this study it was suggested that the core components as well as the PWR reactor pressure vessels from the nuclear power plants should be disposed of in a rock vault in which the engineered barrier system is based on the use of concrete alone. The legacy waste currently stored at the Studsvik site and which comprises a complex mixture of different materials and nuclides was suggested to be disposed of in a rock vault in which bentonite clay alone is used in the engineered barrier system. However, also in this repository section it is expected that the waste will be placed inside a concrete structure in order to provide for radiation shielding during the operational phase of the repository.

In these repositories interactions will take place between the materials in the engineered barriers, the different waste form materials, the ground water itself as well as species dissolved in the ground water. During the extremely long periods of time covered by the safety analyses these interactions will cause changes in the physical and chemical properties of the barrier materials as well as a degradation of the waste leading to the formation of species that may further affect the properties of the materials in the engineered barriers.

In the safety analyses that need to be performed at facilities planning, construction, operation and before their final closure detailed knowledge of the processes that occur when the waste, conditioning grout and the material used in the engineered barriers interact under the influence of an anoxic groundwater is required. To increase SKB's knowledge and understanding of these processes are therefore implemented the project Concrete and Clay.

1.2 Objectives

The objective of this project is to increase the understanding of the processes that occur when the waste, conditioning grout and the material used in the engineered barriers interact under the influence of an anoxic groundwater. Typically, the following processes and interactions can be expected to occur in a repository for low- and intermediate level waste:

- Decomposition of different waste form materials in a cement based matrix.
- Transport of waste form degradation products in a cement based matrix.
- Alterations of the cement minerals due to interactions with waste form degradation products and bentonite.

- Mineral transformations in bentonite as a consequence of interactions with waste for degradation products and cement pore water.
- Transport of degradation products in bentonite.

These processes, which are not further discussed in this report, formed the basis when the experiments described in this report were designed and materials as well as material combinations chosen.

1.3 Experimental concept

During the time period 2010–2014 a total of 9 packages comprising concrete cylinders or bentonite blocks each containing different types of waste form materials were emplaced in 3 different niches in the Äspö Hard Rock Laboratory according to the following:

- Concrete and clay phase 1 comprising field scale concrete experiments: 2 packages containing concrete cylinders with material samples representative of LILW deposited in niche NASA0507A.
- Concrete and clay phase 2 comprising field scale concrete experiments: 1 package containing concrete cylinders with material specimens representative of LILW and one package containing concrete cylinders without material specimens deposited in niche NASA2861A.
- Concrete and clay phase 3 comprising field scale bentonite experiments: 5 packages containing bentonite blocks deposited in TAS06. Each block contains 4 small cylinders of cement paste or bentonite each of which also contains a metal powder or a powder of a metal chloride representative of low and intermediate level waste or container material. As an alternative, some bentonite blocks instead contain a solid cylindrical specimen of steel or stainless steel.
- Laboratory scale experiments: 20 stainless steel containers were manufactured and filled with about 1,000 ml of Äspö ground water, about 50 grams of crushed hardened cement paste and material specimens of the same type as used in the field scale concrete experiments. The containers which were prepared during 2011 are currently stored in niche NASA2861A. Water will be retrieved from the containers at regular intervals and analysed for decomposition products from the material specimens. From these analyses a suitable time for the retrieval of the first field scale concrete experiments will be decided.

1.3.1 Field scale concrete experiments

The concrete cylinders were cast in plastic cylinders with the dimensions Ø 300 mm and a length of 1,000 mm in the bentonite laboratory at Äspö. The cylinders were then transported to the experimental site and deposited in Ø 350 mm holes in the tunnel floor. 3 cylinders were deposited on top of each other in each hole.

According to present plans the first field scale concrete experiment will be retrieved during 2015 or 2016, i.e. 5–6 years after emplacement. This rather early retrieval is motivated by that this experiment contains Al and Zn which both have a very high corrosion rate in an alkaline environment. After retrieval of the first experiment, experiments will be retrieved and analysed at regular intervals and the last will be left for as long as possible, concerning the operational time of the Äspö laboratory.

1.3.2 Field scale bentonite experiments

The bentonite blocks (Ø 280 mm and height 100 mm) used in the field scale bentonite experiments were pressed to a dry density of about 1,600 kg/m^3 at AB POD in Kristdala and prepared for installation in the bentonite laboratory in Äspö. In each bentonite block 4 different specimens were placed. The specimens were manufactured from standard cement grout and low-pH-cement grout or the same type of bentonite as the block itself and contained either a metal powder or a powder of a metal chloride representative of low- and intermediate level radioactive waste. The deposition packages were prepared by stacking 30 bentonite blocks on top of each other in a cage made of titanium. Altogether a total of 150 bentonite blocks were deposited in 5 packages in TAS06 during 2014.

1.3.3 Laboratory scale experiments

As a complement to the field scale concrete experiments described in Section 1.3.1 also a number of laboratory scale experiments were prepared. In these experiments different types of material specimens were placed in steel containers filled with a mixture of Äspö ground water and hardened and crushed cement paste. The containers were flushed and finally filled with nitrogen gas to mimic the oxygen free conditions in the bedrock after closure and resaturation of the repository. The objective of these specimens is to serve as a guide for the decision on when to retrieve the field scale concrete experiments (Section 1.3.1). Samples of the water can be retrieved and analysed at regular intervals in order to detect the presence of waste form degradation products. The experiments were initially prepared and stored at the cement laboratory at the Ringhals Nuclear Power Plant but were transferred to Äspö during 2013 and are currently stored in the niche NASA2861A. About half of the containers are stored under ambient temperature and the remaining at about 50°C in heated water; see Table D-1 for details.

1.4 Purpose of this report

The purpose of this report is to present the details of the experiments included in the project Concrete and Clay and to serve as a guide to the work of retrieving and analysing the experiments. The following main topics are covered in this report:

- Preparation and characterisation of the niches in which the field scale experiments are placed.
- Special equipment developed for the experiments.
- Materials used in the experiments.
- Methods used for manufacturing of the specimens.
- Assemblage and installation of the experiments.

In the appendices detailed and essential information regarding the experiments can be found. However, as the appendices are not entirely complete due to the vast amount of data originating from this work reference must also be made to the SICADA database at the time of retrieval of the experiments.

2 Overview of the experiments

2.1 Field scale concrete experiments

4 experiments each comprising 3 concrete cylinders (Ø 300 mm and length 1,000 mm each) were prepared and installed in the niches NASA0507A and NASA2861A during 2010 and 2011 respectively. The aim of these experiments was to study the interactions between material specimens representative of low- and intermediate level radioactive waste and concrete and also to study the long term degradation of the concrete itself in a repository-like environment. Two of these experiments were deposited in deposition holes with good access to ground water whereas the third was placed in a dry hole in order to study the influence of the amount of available water on the degradation process. A schematic illustration of the field scale concrete experiments is shown in Figure 2-1.

2.2 Field scale bentonite experiments

5 experiments comprising stacks of bentonite blocks were prepared and installed in TAS06 during 2014. Each experiment comprised 30 bentonite blocks with material specimens and 4 bentonite blocks used to reach the correct height of the stack of bentonite blocks. The bentonite blocks (Ø 280 mm and height 100 mm each) were held together inside a titanium cage. In each bentonite block 4 different specimens were placed. The specimens were manufactured from standard cement grout and low-pH-cement grout or the same type of bentonite as the block itself and contained either a metal powder or a powder of a metal chloride representative of low- and intermediate level radioactive waste. A schematic illustration of the experiments not showing the titanium cage is shown in Figure 2-2.

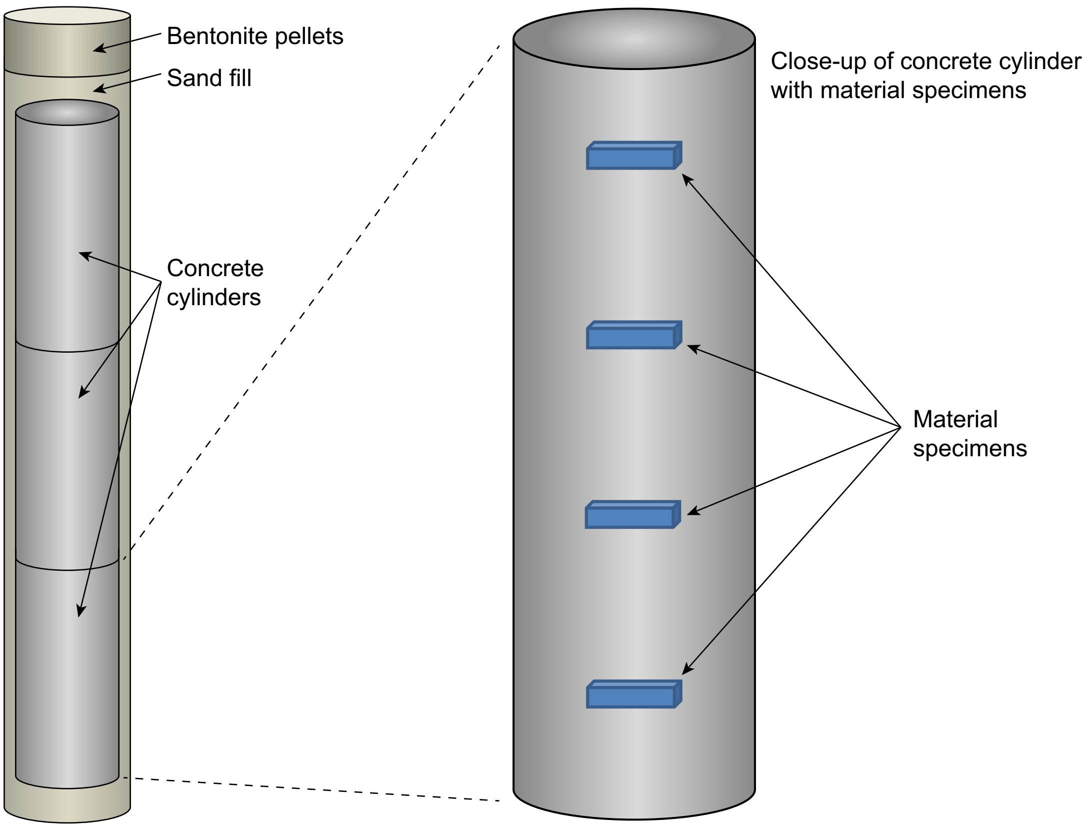


Figure 2-1. *A schematic illustration of the field scale concrete experiments.*

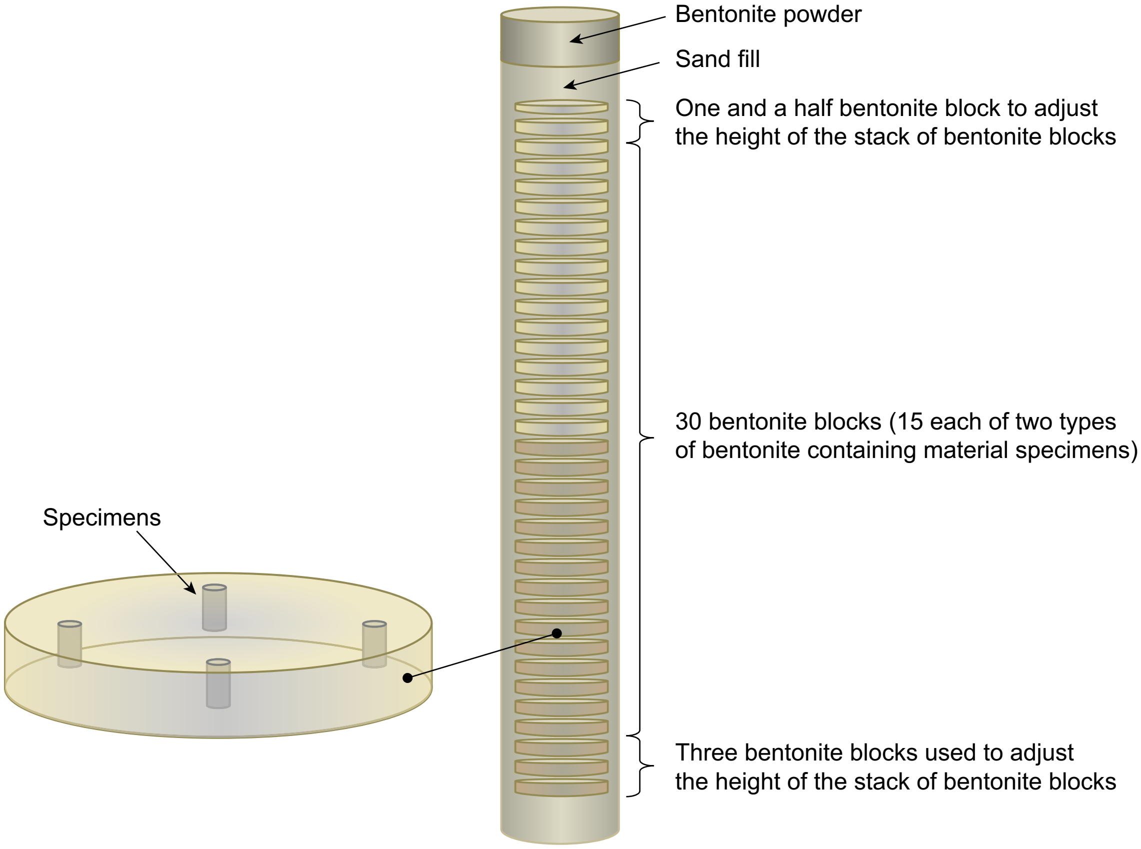
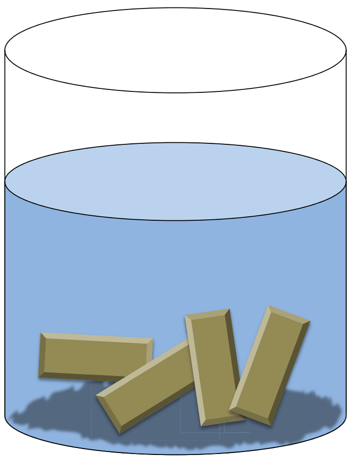


Figure 2-2. *A schematic illustration of the field scale bentonite experiments.*

2.3 Laboratory scale experiments

Steel containers, Figure 2-3, were filled with Äspö ground water, about 50 grams of crushed hardened cement paste and material specimens of the same type as used in the field scale concrete experiments, Section 2.1. About half of the experiments are heated to 50°C in order to increase the rate of decomposition of the organic materials whereas the remaining are kept at the temperature prevailing in the Äspö tunnel, see Table D-1 for details. A schematic illustration of the laboratory scale experiments is shown in Figure 2-3 together with an image of the heated steel containers.



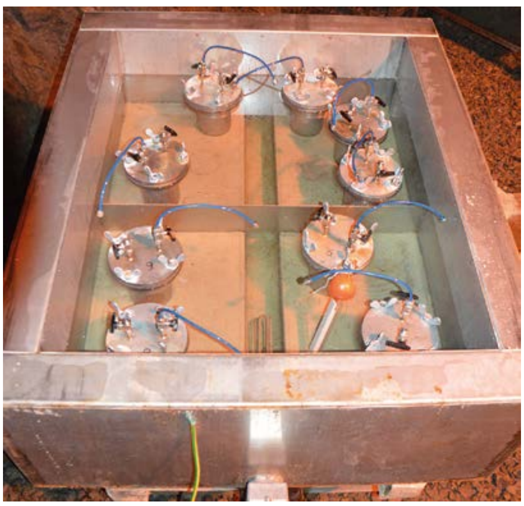


Figure 2-3. *A schematic illustration of the laboratory scale experiments (left image) and the heater used to keep the temperature in some of the experiments at about 50°C. During operation a lid is placed on the heater for insulation.*

3 Experimental sites

Three different sites were used for the field scale experiments: NASA0507A, NASA2861A and TAS06.

3.1 NASA0507A

3.1.1 Location and overview

NASA0507A is located 507 meters down in the main tunnel at a depth of –69 meters, Figure 3-1. The niche is about 10 meters deep and about 5 meters in height. An illustration of the niche is shown in Figure 3-2.

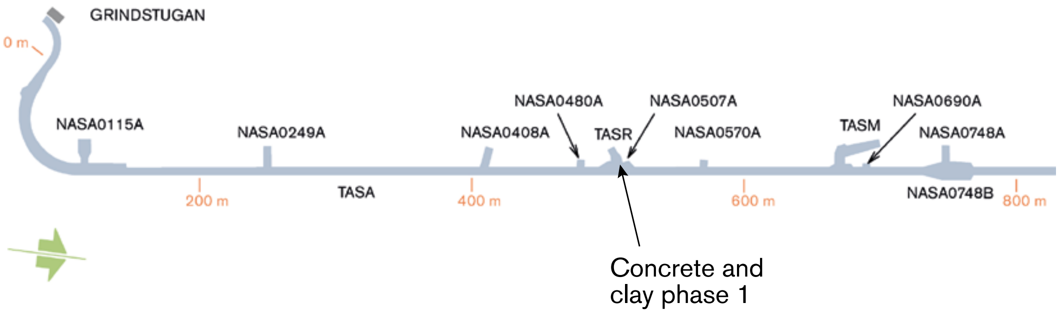


Figure 3-1. Location of NASA0507A.

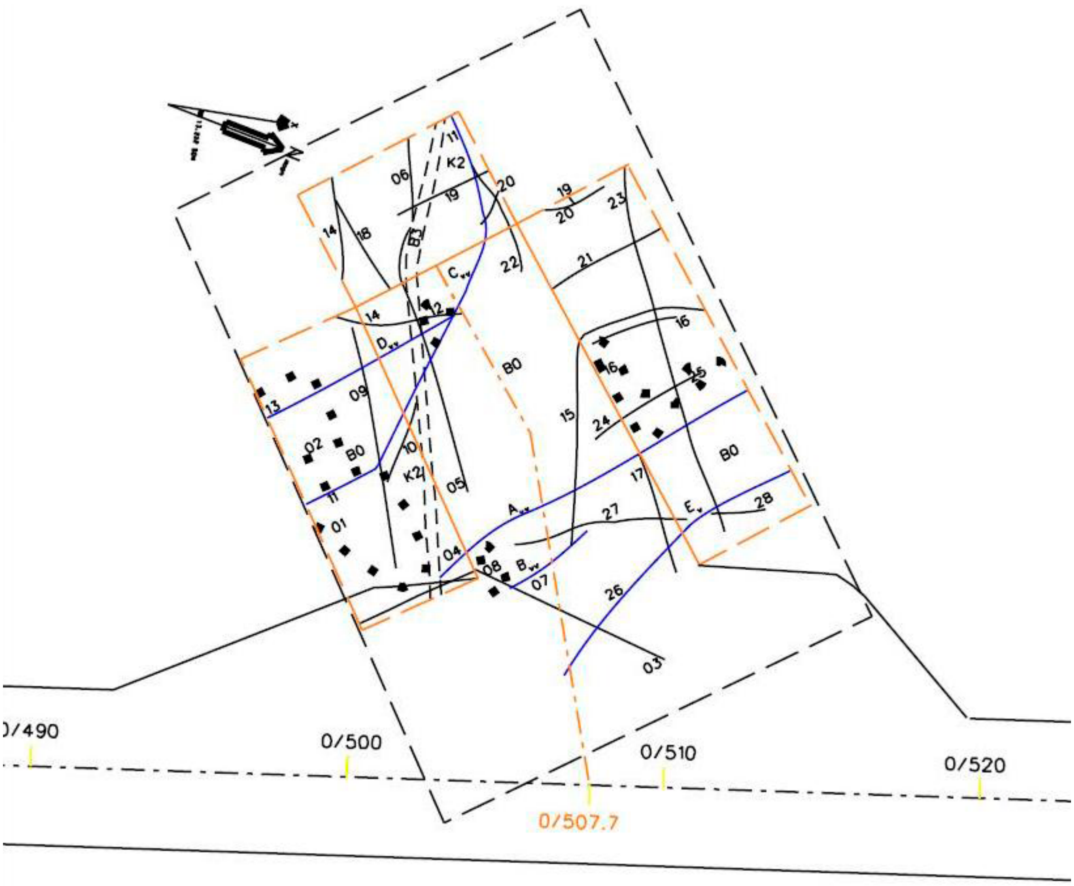


Figure 3-2. An illustration of the niche NASA0507A.

3.1.2 Characterisation and preparation

When the niche was made available to the project it had previously been mapped and found to contain a number of water bearing fractures with water flows between 0.003 and 0.04 l/min each. Based on the results from the previous mapping, two pilot holes denominated KR0009G01 and KR0013G01 with a diameter of 76 mm were drilled. During this work it was noticed that KR0013G01 intersected with a surface reaching fracture and for that reason this hole was abandoned and a new hole, denominated KR0014G01 was drilled. The depth of KR0009G01 and KR0014G01 were 4.4 and 4.8 meters respectively.

The cores obtained from the drilling of the pilot holes were photographed both dry and wet and a core mapping protocol was prepared. A photograph of the wet cores from KR0009G01 also representative for KR0014G01 is shown in Figure 3-3.

After measuring the ground water pressure in the pilot holes, Table 3-1, the pilot holes were over cored to Ø 350 mm and a depth of about 3.7 and 3.9 meters for KR0009G01 and KR0014G01 respectively.

The last step in the preparation of the site was to cast the concrete bases to which to attach the lids after emplacement of the concrete cylinders, Figure 3-4.

***Figure 3-3.** The wet cores from KR0009G01.*

***Figure 3-4.** Casting of the base for one of the experiments in NASA0507A.*

Table 3-1. The measured ground water pressure in the pilot bore holes in NASA0507A.

Pilot bore hole	Ground water pressure (bar)
KR0009G01	2
KR0014G01	2.5

3.2 NASA2861A

3.2.1 Location and overview

NASA2861A is located 2,861 meters down in the main tunnel at a depth of –383 meters, Figure 3-5. An illustration of the niche is shown in Figure 3-6.

3.2.2 Characterisation and preparation

When the niche was made available to the project it had already been mapped in a previous investigation and found to contain a number of water bearing fractures with water flows between 0.01 and 0.03 l/min each. Based on the results from the previous mapping and the requirements for the two experiments two pilot holes denominated KA2862G01 and KA2862G02 with a diameter of 76 mm were drilled to a depth of about 4.1 meters each.

The cores were photographed both dry and wet and a core mapping protocol was prepared. A photograph of the wet cores from KA2862G02 representative also for KA2862G01 is shown in Figure 3-7.

In order to verify that the holes fulfilled the requirements the water flow in the pilot holes was measured, Table 3-2.

After measuring the ground water flow, both pilot holes were over cored to Ø 350 mm and a final depth of about 4.0 meters.

The last step in the preparation of the site was to cast the concrete bases to which to attach the lids after emplacement of the concrete cylinders. This was done following the same procedure as was used in NASA0507A shown in Figure 3-4.

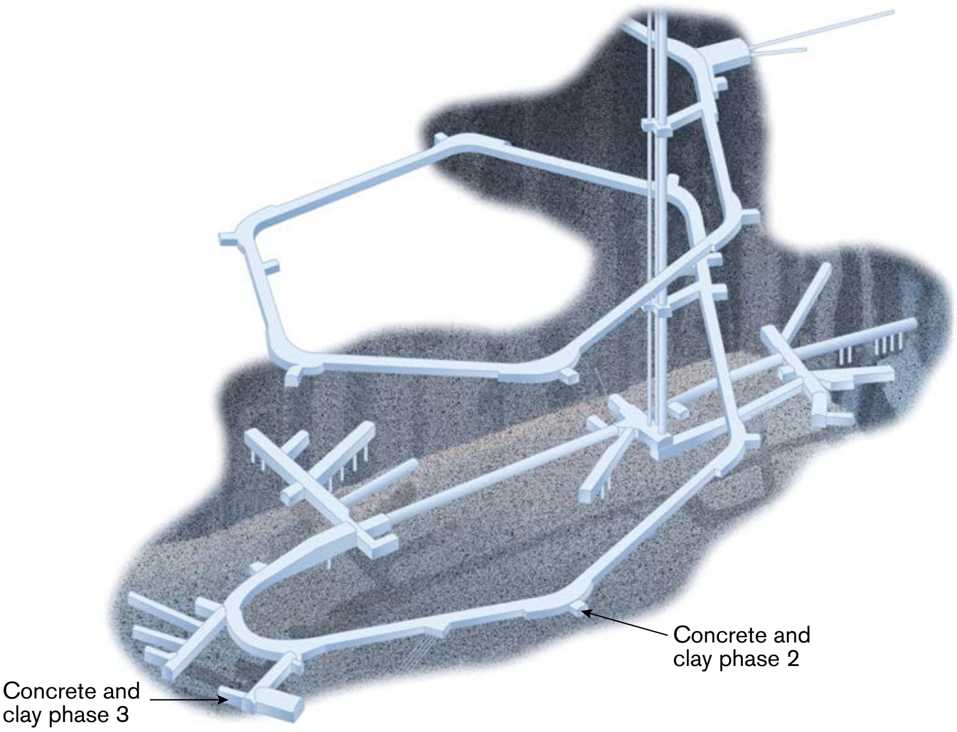


Figure 3-5. *Location of NASA2861 (Concrete and clay phase 2) and TAS06 (Concrete and clay phase 3).*

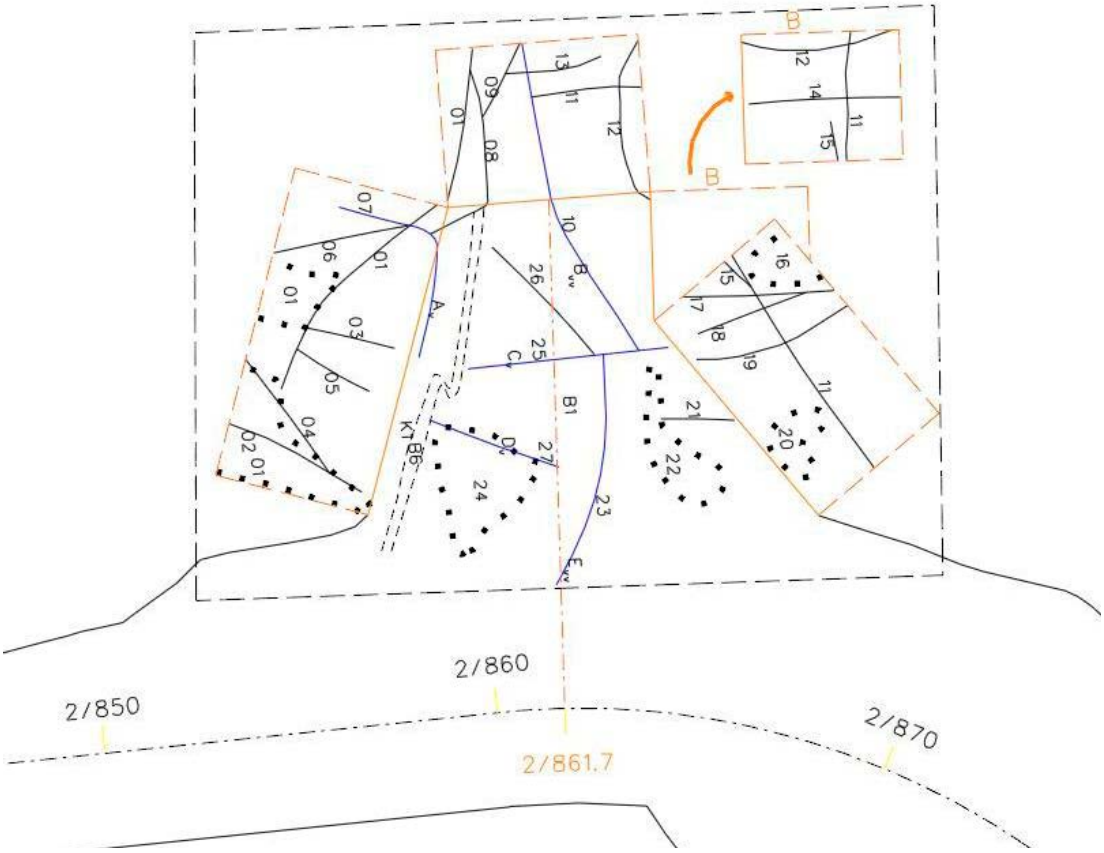


Figure 3-6. Niche NASA2861A.

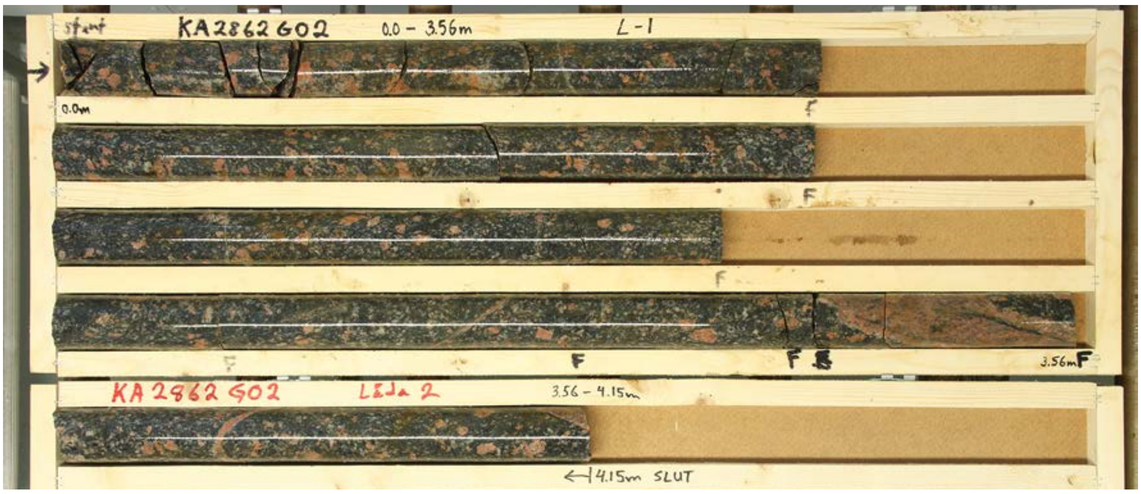


Figure 3-7. The wet cores from the pilot hole KA2862G02 representative for both pilot holes in NASA2861A.

Table 3-2. The measured water flow in the pilot bore holes in NASA2861A.

Pilot bore hole	Water flow (l/min)
KA2862G01	0.01400
KA2862G02	0 (The hole was dry)

3.3 TAS06

3.3.1 Location and overview

TAS06 is located in the TASU tunnel 3,007 meters down in the main transport tunnel at a depth of about –400 meters, Figure 3-5. The niche is about 15 meters deep and about 6 meters in height. This niche is a part of the Äspö extension project and was prepared for the project during 2012 and 2013. A schematic illustration of the niche also showing the positions of the pilot holes is shown in Figure 3-8.

3.3.2 Characterisation and preparation

A visual inspection of TAS06 indicated relatively large amounts of intruding water and thus promised good access to water bearing fractures. A rudimentary mapping of the floor of the niche was conducted in order to identify fractures, fracture zones as well as zones less suitable for drilling due to e.g. hard and brittle bedrock and zones without fractures. The mapping of the tunnel floor showed a relatively large number of fractures which was promising from the point of view of accessible water.

Based on this mapping, the positions for the drilling of seven pilot holes, denominated K06006G01, K06006G02, K06008G01, K08006G02, K10006G01, K12006G01, K12006G02 were selected as shown in Figure 3-8.

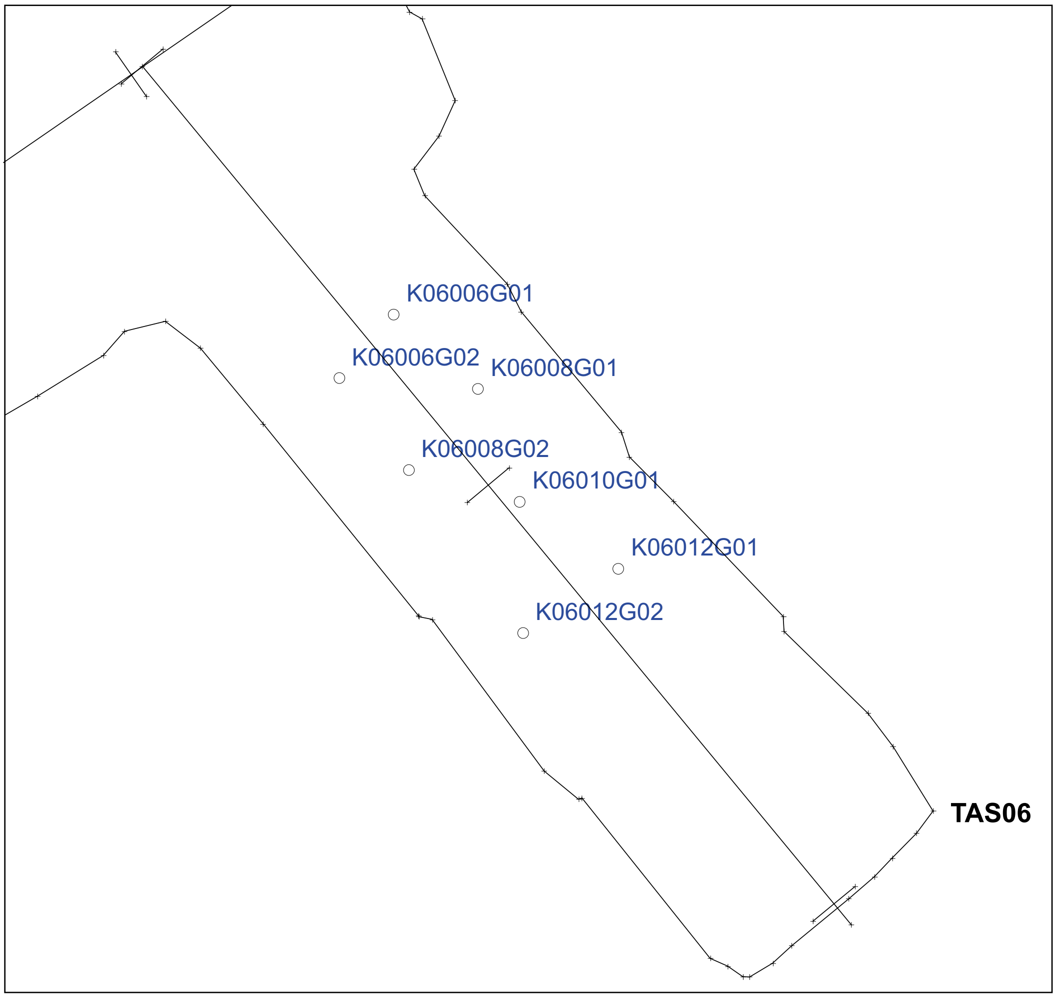


Figure 3-8. *A schematic illustration of the niche TAS06 showing the position of the pilot holes.*

The cores from the pilot holes were photographed both dry and wet and core mapping protocols were prepared. Finally, the water flow in the pilot holes was measured, Table 3-3. A photograph of the wet cores from the pilot hole K06008G02 representative for a majority of the pilot holes in TAS06 is shown in Figure 3-9.

Unexpectedly the measurements revealed that the flow of water in the fractures was very low, Table 3-3. For that reason it was decided to use a system for artificial saturation of the experiments in TAS06, see Section 4.2.

After measuring the ground water flow, the pilot holes were over cored to Ø 300 mm and a final depth of between 3.8 and 4.0 meters.

The last step in the preparation of the site was to cast the concrete bases on which to cast the lids after emplacement of the concrete cylinders. This was done following the same procedure as previously used and the process is shown in Figures 3-10 and 3-11. However, only the five holes selected for the experiments were provided with a base whereas no base was cast at K06012G01 and K0612G02.

Table 3-3. The measured water flow in the pilot bore holes in TAS06.

Pilot bore hole	Water flow (l/min)
K06006G01	0.000400
K06006G02	0.000280
K06008G01	0.000350
K06008G02	0.000028
K06010G01	0.001200
K06012G01	0.001800
K06012G02	0.000000 (The hole was dry)

Figure 3-9. *The wet cores from the pilot hole K06008G02 representative of a majority of the cores in TAS06.*

Figure 3-10. *Casting of the bases in TAS06.*

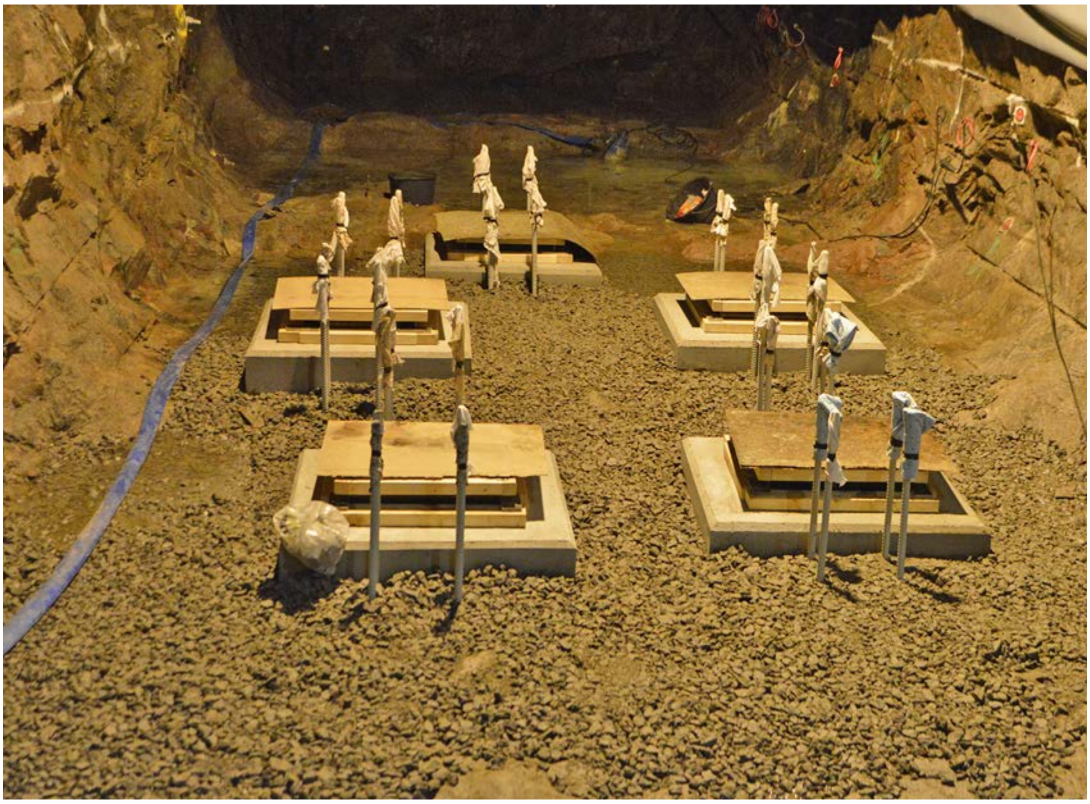


Figure 3.11. *TAS06 is ready for installation of the experiments.*

4 Development of equipment required for the experiments

4.1 Titanium cages for the field scale bentonite experiments

The titanium cages used for holding the bentonite blocks together in the deposition package shown in Figure 4-1 were manufactured by Örnalp Unozon AB in Örnsköldsvik. The dimensions of the titanium cages were $Ø_{outer}$: 284.6 mm, $Ø_{inner}$: 271 mm and a total length of 3,500 mm.

The bottom plate was fixed (Figure 4-3 right image) whereas the upper plate was allowed to move some distance in order allow the bentonite blocks to expand when saturated without breaking the titanium cage. A lifting eye which was used for lifting the titanium cage was attached to the top plate as shown in Figure 4-1, right image.

4.2 System for artificial saturation of the field scale bentonite experiments

Due to the very scarce availability of water in the fracture system in TAS06 it was decided to design and install a system for artificial saturation of the field scale bentonite experiments. The design of this system was inspired by the design of the system used for saturation of the experiments in the project Alternative Buffer Material, ABM, described by Eng et al. (2007).

The system comprises a pressurised tank, a system of valves, plastic tubes (Figure 4-2) and perforated titanium tubes attached to the titanium cages for distributing the water in the sand bed between the bentonite blocks and the bedrock in the deposition hole, Figure 4-3. The tank (approximate volume of about 150 dm^3) was filled with Äspö ground water and pressurized to an absolute pressure of about 1.2 atm. by means of nitrogen gas.

__Figure 4-1.__ The lower part of three of the titanium cages used in the field scale bentonite experiments (left image) and the top part with the adjustable section and lifting eye (right image).

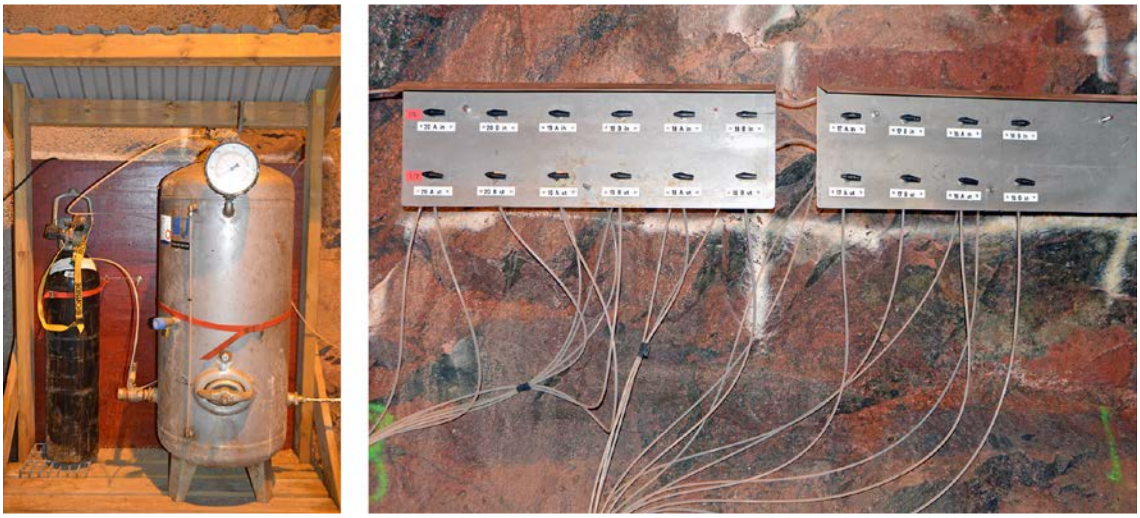


Figure 4-2. *The pressurised tank and system of valves and plastic tubes used to distribute the water to the different experiments.*

Figure 4-3. *Images showing details of the titanium tubes used to distribute the water in the sand surrounding the bentonite blocks. The left image shows how the tubes are attached by means of welding to the titanium cage and the right image shows the bottom plate with the titanium tube placed in a slit in the lowermost bentonite block.*

4.3 Stainless steel containers for the laboratory scale experiments

In total 20 stainless steel containers (see Figure 4-4) with the following main components were manufactured for the laboratory scale experiments:

- A body consisting of a stainless steel tube.
- A stainless steel bottom welded onto the tube.
- A top flange welded to the steel tube.
- A lid attached to the welded flange by means of bolts and wing nuts and sealed towards the flange with a rubber seal.
- Two valves welded to the lid which were mainly used for flushing the container with nitrogen gas to reduce the amount of oxygen inside the container.

Figure 4-4. *The stainless steel container used in the laboratory scale experiments.*

4.4 Water bath with heater for the laboratory scale experiments

A water bath with a heater, Figure 4-5, with the internal dimensions 860·1,032·360 (w·l·h) was manufactured from SS 2343 stainless steel. The temperature of the water is controlled by means of a thermostat and a lid visible in the top right corner in Figure 4-5 is used for insulation during operation.

Figure 4-5. *The heated water bath used to heat some of the containers in the laboratory scale experiments to about 50°C.*

5 Specimen preparation

In this chapter the materials and recipes as well as methods used for manufacturing of the specimens are described. Details concerning assemblage and installation of the experiments are presented in chapter 6.

5.1 Field scale concrete experiments

5.1.1 Materials used in the experiments

Concrete

The concrete cylinders containing material specimens were cast from a mixture of fibre grout 50 VF and water whereas the concrete cylinders without any material specimens were cast from standard *Weber Grovbetong,* i.e. a standard pre-mixed concrete. The 50 VF grout is used in the conditioning plant at Ringhals Nuclear Power Plant and thus found to be a suitable choice in these experiments. For each concrete cylinder 156.0 kg of 50 VF dry mixture was mixed with 18.75 kg of water corresponding to a water cement ratio of 0.42. The composition of the 50 VF is found in Table 5-1 and the composition of the cement in Table 5-2.

Material specimens

Different types of material specimens were placed at different positions in the concrete cylinders. The following types of materials were used:

- Stainless steel SS2333.
- Zinc.
- Reinforcement bars.
- Aluminium.
- Ion exchange resin (sulphonate).
- Ion exchange resin (carboxylate).
- Ion exchange resin (anion).
- Filter aid (UP2).
- Plastic bag (Blue and transparent).
- Rubber gloves (blue).
- Cotton (Cloth from an overall).
- Paper (Wiping paper).

For more detailed information, please refer to Appendix A, B and C.

Table 5-1. Composition of 50 VF Fibre grout.

Component	Type
Cement	Degerhamn Anläggningscement
Ballast	Sand 0–4 mm
Fibres	Polypropylene, KRENIT®
Cement content:	7.2 kg / 25 kg dry product

Table 5-2. Composition of Degerhamn anläggningscement (Gaucher et al. 2005).

Component	Content (% by weight)
CaO	65.5
SiO_2	22.7
Al_2O_3	3.56
Fe_2O_3	4.32
MgO	0.45
K_2O	0.57
Na_2O	0.05
SO_3	2.07

Figure 5-1. Metallic specimens used in the field scale concrete experiments deposited in NASA0507A (left image) and NASA2821A (right image).

5.1.2 Manufacturing of the specimens

Preparation of the material specimens

Each material specimen was cut into a suitable size if required and weighed prior to emplacement in the wet concrete. Details on the materials use in the experiments are found in Section 5.1.1 and Appendix A, B and C.

Manufacturing of the concrete cylinders

The concrete cylinders were cast in ordinary sewage pipes with an inner diameter of 300 mm, Figure 5-2. In each concrete cylinder a few pieces of the material specimens were placed at 4 different levels, see Appendix B and C for details. For most of the specimens this procedure worked well but some of the specimens sank slightly in the wet and yet not hardened concrete as noted in the rightmost column in the tables in Appendix B and C.

Figure 5-2. *The Sewage pipes used for casting of the concrete cylinders in Concrete and Clay phase 1 and 2 (left image) and the interior of the mould during casting of concrete cylinders containing specimens of stainless steel (right image).*

5.2 Field scale bentonite experiments

5.2.1 Materials used in the experiments

Bentonite

The bentonite blocks (Ø 280 mm and height 100 mm) were manufactured from Asha, MX-80 Ibeco RWC and FEBEX bentonite. These types of bentonite were also used to prepare the small cylinders containing a mixture of bentonite and a metal powder or a powder of a metal chloride, Section 5.2.2.

Cement paste and low-pH cement paste

The specimen cylinders used in the field scale bentonite experiments were prepared from standard and low-pH cement respectively according to the basic recipes shown in Table 5-3.

A large number of specimens containing a mixture of either of the cement pastes and a metal powder or a powder of a metal chloride were also prepared according to the recipes shown in Appendix E.

It should be noted that the original recipe for the low-pH cement (Bodén and Pettersson 2011) also contained a certain amount of a water reducing agent (Glenium 51). However, in these experiments it was decided to exclude this agent in order not to cause any undesired or unexpected processes in the materials.

Solid metal specimens

The following solid metal specimens were used in the experiments:

- Carbon steel grade S235 JR.
- Stainless steel EN 1.4301 (Corresponding to SS2333).

Table 5-3. Composition of cement paste and low-pH cement paste. From the amount of paste shown here about 27 specimens could be prepared.

Component	Cement paste	Low-pH cement paste
Cement	900 g	457 g
Silica	–	305 g
Water	360 g	365 g

Metal powders

The metal powders used in the experiments are shown in Table 5-4.

Metal chlorides

The metal chloride powders used in the experiments are shown in Table 5-5.

5.2.2 Manufacturing of bentonite blocks and specimens

Preparation of the bentonite blocks

In total 45 bentonite blocks of each of the four types of bentonite used in these experiments were manufactured at AB POD in Kristdala. The dimensions of the blocks were: Ø: 280 mm and height: 100 mm. The target dry density for the pressed bentonite blocks was about 1,600 kg/m^3. After pressing, the bentonite blocks were stored in separate sealed plastic bags until the time of assemblage of the experiments. The average measured weight and calculated dry density of the blocks of the four different types of bentonite are presented in Table 5-6. In Table 5-6 also the calculated installed dry density is shown. In these calculations it has been assumed that the bentonite blocks can swell freely in the radial direction but not axially and also that the sand initially surrounding the stack of bentonite blocks has been washed away.

At Äspö grooves were cut into the bentonite blocks in order to make them fit into the titanium cage, Figure 5-3. Also four holes, each with a diameter of 34 mm, were drilled into the blocks for the specimen cylinders. The centre of each hole was located 60 mm from the periphery of the bentonite block and deep enough for the specimens to be placed in the centre of the block, Figure 5-3.

Table 5-4. The metal powders used in the experiments.

Type of metal	Purity (% by weight)	Particle size (μm)
Iron	99.9	About 10
Nickel	99.7	About 10
Chromium	99.2	Below 315
Molybdenum	99.9	Below 150

Table 5-5. The metal chlorides used in the experiments.

Metal chloride	Purity (% by weight)
CsCl	99.95
$SrCl_2 \cdot 6H_2O$	99
$EuCl_3 \cdot 6H_2O$	99.999 and 99.9

Table 5-6. Measured and calculated data of the different types of bentonite blocks.

Type of bentonite	Average weight (kg)	Average volume (dm^3)	Water content at pressing (%)	Pressed dry density (kg/m^3)	Installed dry density (kg/m^3)
Asha	12.45	6.0	20.1	1,630	1,390
Febex	12.03	6.04	18.5	1,620	1,380
Ibeco RWC	11.70	6.05	18.6	1,570	1,350
Wyoming MX-80	11.9	6.08	19.2	1,580	1,360

Figure 5-3. *The final shape of a bentonite block with holes for the material specimens and grooves made to make the block fit into the titanium cage. The red tape which corresponds to North in the bentonite package was removed when the package was assembled.*

Casting of the cement and low-pH-cement specimens

All specimens containing paste of cement or low-pH cement were cast in small moulds made of a plastic water pipe with an inner diameter of 30 mm, Figure 5-4. The recipes for each of the mixtures are presented in Appendix E. The water to cement ratio was slightly adjusted compared to the basic recipes (Table 5-3) to achieve the desired workability for the different types of pastes.

After casting, the specimens were allowed to cure in the moulds for one or several days under a plastic cover in order to avoid extensive drying during the curing process. After sufficient time the specimens were demoulded, weighed and stored in sealed plastic bags until the time when they were placed in the bentonite blocks.

Figure 5-4. *Casting of the paste specimens.*

Pressing of the bentonite specimens

All small specimen cylinders comprising a mixture of a bentonite powder and a metal or metal chloride powder were manufactured at Äspö using a small press. The specimens had an approximate weight of about 25 grams each and a height of about 15 mm. Data showing the mixing proportions of the specimens are presented in Appendix F.

Preparation of the steel specimens

Specimens made of standard carbon steel (grade S235 JR) and stainless steel (grade EN 1.4301, comparable to SS2333) were prepared from Ø 10 mm rods. The average length and weight of the specimens were 25 mm and 15.5 grams respectively.

Final preparation of the bentonite blocks

The final steps in the preparation of the bentonite blocks comprised placing the small sample cylinders in the holes previously drilled in the bentonite blocks and sealing the hole afterwards as shown in Figure 5-5. Sealing of the holes was done with bentonite powder of the same type as in the bentonite block itself and the powder was packed in the hole using a flat stick or simply ones thumb. After final preparation, the bentonite blocks were labelled and again placed in separate sealed plastic bags until the time of assemblage of the experimental packages.

5.3 Laboratory scale experiments

As mentioned in Section 1.3.3, the main purpose of the laboratory scale experiments was to act as a guide in the decision on when to retrieve the field scale concrete experiments. For that reason the same types of material specimens were used in these experiments as in the field scale concrete experiments, Section 5.1.

5.3.1 Materials used in the experiments

Cement

Standard Degerhamn anläggningscement was cast, cured and crushed prior that it was mixed with Äspö ground water and the material specimens. The nominal composition of the cement is presented in Table 5-2.

Figure 5-5. *Final preparation of a bentonite block. Left image shows how the block has been given its final shape with grooves made to fit with the titanium cage and holes drilled for the small specimen cylinders. In the centre image a cement cylinder has been placed in the small hole and the right image finally shows how the holes have all been filled with bentonite powder of the same type as the bentonite block itself.*

Water

Äspö ground water with the nominal composition shown in Table 5-7 was used in all experiments.

Waste form materials

The following types of materials were used in the experiments:

- Stainless steel SS2333
- Carbon steel C1070
- Reinforcement bars
- Ion exchange resin (sulphonate)
- Ion exchange resin (carboxylate)
- Ion exchange resin (anion)
- Filter aid (UP2)
- Plastic bags
- Rubber gloves
- Cotton (Cloth from an overall)
- Paper (Swiping paper)
- Bitumen

Aluminium and zinc were excluded in these experiments due the risk for a pressure build up caused by extensive formation of hydrogen gas in the sealed containers. For a more detailed list on the materials used in these experiments, please refer to Appendix D.

5.3.2 Manufacturing of the specimens

Solid specimens were simply cut into pieces of suitable size whereas powders or grains such as ion exchange resins and filter aid were used as such without any further preparation.

Table 5-7. Nominal composition of the Äspö ground water used in the experiments.

Component	Na	K	Ca	Mg	HCO_3	Cl	SO_4	Br	F	Si	Fe	Mn	Li
Content (ppm)	1,860	16.9	651	78.2	130	4,080	326	19.3	1.42	8.22	0.522	0.599	0.481

6 Assemblage and installation of the experiments

6.1 Field scale concrete experiments

6.1.1 Assemblage

No assemblage of the concrete cylinders was required prior to installation and the concrete cylinders were simply installed according to the sequence described in Section 6.1.2.

6.1.2 Installation

Final preparation of the deposition holes

Prior to installation of the concrete cylinders some sand was poured into the deposition hole in order to level the surface of the bottom of the hole. During the process the depth of the deposition hole was also adjusted and measured as shown in Figure 6-1.

Emplacement of the concrete cylinders

The concrete cylinders were placed in the deposition hole by means of wires and a chain as shown in Figure 6-2. After the deposition of each of the concrete cylinders the slit between the concrete cylinders and the bedrock was filled with sand. This was made with the purpose of stabilising the concrete cylinders in the centre of the deposition hole but the sand also filled the purpose of distributing any water from the bedrock evenly within the deposition hole.

Figure 6-1. *Levelling the bottom and measuring the depth of the deposition hole.*

Figure 6-2. *Installation of one of the concrete cylinders in the deposition hole.*

Sealing and closure of the deposition hole

When the three concrete cylinders had all been placed in the deposition hole and the slit between the cylinders and the rock filled with sand (Figure 6-3 top left). Sand was also placed on top of the concrete cylinders. As a final step before the lid was put in place (Figure 6-3 lower right) bentonite pellets and sand were placed on top of the sand bed in order to seal the experiment from intruding surface ground water (Figure 6-3 top right and lower left).

As a final step the lid was secured by the use of steel bars which were bolted into the bedrock as shown in Figure 6-4.

Figure 6-3. *Sealing and closure of the field scale concrete experiments.*

Figure 6-4. *Both experiments in NASA0507A are ready and the lids bolted to the bedrock.*

6.2 Field scale bentonite experiments

6.2.1 Assemblage

The deposition packages were assembled in the bentonite laboratory at Äspö according to the sequence illustrated in Figure 6-5, 6-6 and 6-7. Each deposition package comprised 3 buffer blocks in the bottom of the stack, 30 experiment blocks and about one and a half buffer blocks on top to reach the desired height of the stack. The assemblage involved the following steps.

- Raising the titanium cage and securing it in an upright position.
- Placing the bentonite blocks inside the titanium cage, Figure 6-5 left image.
- Attaching the lid and securing it with 8 bolts, Figure 6-5 right image.
- Lifting the entire package and wrap it with a protective plastic cover, Figure 6-6 left image.
- Attaching the support cage used to stabilize the package during handling and transport, Figure 6-6 right image and finally loading onto the truck for transport down to TAS06 (Figure 6-7).

The purpose of the support cage was to stabilize the deposition package during transport when the deposition package was placed horizontally on the transport truck.

6.2.2 Installation

Final preparation of the deposition holes

Prior to installation of the bentonite packages some sand was poured into the deposition hole in order to level the surface of the bottom of the hole and to adjust the depth of the deposition hole as shown in Figure 6-8 right image.

Figure 6-5. *The titanium cage was raised towards the steel construction and the bentonite blocks emplaced from the top. After that all the blocks had been emplaced the lid with the lifting eye was mounted to the cage with 8 bolts.*

Figure 6-6. *Wrapping the protective plastic cover around the bentonite package (left image) and attaching the steel support cage (right image).*

Figure 6-7. *Loading the bentonite package onto the truck for further transport to TAS06.*

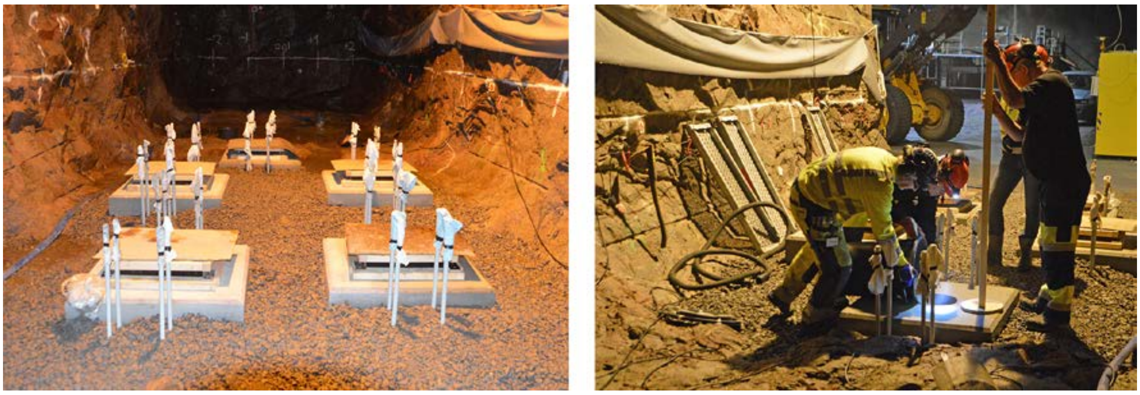


Figure 6-8. *The 5 bases which were cast a few months before the installation of the bentonite packages are shown in the left image. The right image shows the levelling of the bottom of the deposition hole by means of sand and the device used to ensure the correct depth of the hole.*

Emplacement of the bentonite package

The bentonite packages were lowered into the deposition holes by means of a winch as shown in Figure 6-9. The procedure was very swift and required less than an hour's work for each of the bentonite packages.

Sealing and closure of the deposition hole

When the bentonite package had been safely placed in the deposition hole the slit between the bentonite blocks and the rock wall was filled with sand, see Figure 6-10. The sand was also filled on top of the package up to about 50 mm below the rock/concrete interface. At the interface bentonite powder was instead used in order to seal the interface. Finally sand was placed on top of the bentonite in order to avoid any interaction between the bentonite and the wet concrete during casting of the lid.

Figure 6-9. Lowering the bentonite package into the deposition hole. Please note the marking "N" on the titanium cage facing towards the end of the niche.

Figure 6-10. Filling the slit between the bentonite package and the rock wall as well as some of the volume on top of the bentonite package with sand.

***Figure 6-11.** Installation completed and system for artificial saturation of the experiments connected.*

6.3 Laboratory scale experiments

6.3.1 Assemblage

In each of the steel containers, about 1,000 ml of Äspö ground water, about 50 grams of crushed hardened cement paste and a material specimen of the same type as used in the field scale concrete experiments were placed. When the container had been sealed it was flushed with nitrogen gas in order to remove any oxygen from inside the container. Details on type and amount of waste in each container are found in Appendix D.

6.3.2 Installation

Installation of the laboratory scale experiments only involved the step of placing the steel containers in the heated water bath or beneath a protective cover in NASA2861A as shown in Figure 6-12.

***Figure 6-12.** The steel containers in the heated bath (left image) and placed under a protective cover in NASA2861A (right image). During operation a lid is placed on the heated bath for insulation.*

7 Observations

One observation was made during the installation of the field scale bentonite experiments which is briefly discussed below.

7.1 Bolts holding the lid of the titanium cage

The bolts that hold the lid of the titanium cage were mounted in a way that they may obstruct the retrieval of the bentonite package. According to present plans the sand and any bentonite in the slit between the titanium cage and the bedrock in the deposition hole will be removed prior to retrieval of the package. However, as shown in Figure 7-1 this procedure may be obstructed by the heads of the bolts holding the lid of the titanium cage. This means that in order to be able to utilise the planned procedure the heads of the bolts may have to be removed and repositioned in the initial stage of the retrieval process.

Figure 7-1. *The head of the bolt holding the lid of the titanium cage will obstruct the removal of sand and bentonite from the slit between the bentonite package and the bedrock in the deposition hole.*

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Appendix A

Composition of cement paste containing Ion Exchange Resins or Filter aid used in the field scale concrete experiments

Table A-1. Types of ion exchange resins and filter aid used in the field scale concrete experiments in NASA0507A.

Material type	Brand name	Denomination	Dry substance (% of total mass)
Filter aid	AQUA CHEM RICEM UP2	UP2a and UP 2b	98.8
Cation exchange resin. Sulphonate	AQUA CHEM	SA	67.0
Cation Exchange resin. Carboxylate	AQUA CHEM	WA	91.9
Anion Exchange Resin	AQUA CHEM	SB	41.9

Table A-2. Compositions of the cement pastes containing ion exchange resins or filter aid used in the field scale concrete experiments in NASA0507A.

Material type	Dry weight of substance (g)	Celite (g)	Lime (g)	Cement (g)	W/C	Additive* (g)
SA	135.0	15.0	17.5	625.0	0.62	4.0
SB	135.0	15.0	17.5	625.0	0.87	4.0
WA	135.0	15.0	17.5	625.0	0.71	4.0
UP 2a	150.0	–	17.5	625.0	1.95	4.0
UP 2b	150.0	–	17.5	831.3	1.24	4.0

* Ethylene glycol was used as additive in the preparation of the specimens.

Table A-3. Total weight of specimens containing filter aid or Ion Exchange Resin used in the field scale concrete experiments in NASA0507A. The volume of each of the specimens was 117 ml. The mix proportions are shown in Table A-2.

Specimen #	Weight (g)				
	UP2A	SA	SB	WA	UP2b
1	133.2	201.2	179.6	194.5	161.6
2	133.0	200.9	180.0	194.1	162.2
3	135.3	200.2	179.3	196.3	162.8
4	135.0	202.3	178.7	196.4	161.0
5	136.7	198.9	181.4	196.8	160.4

Table A-4. Types of ion exchange resins and filter aid used in the field scale concrete experiment emplaced in deposition hole KA2861G02 in NASA2861A.

Material type	Brand name	Dry substance (% of total mass)
Filter aid	AQUA CHEM RICEM UP2	98.8
Ion exchange resin (Mixed bed)	Suprex* N-21	40.3
Ion Exchange resin (Mixed bed)	Lewatit* SM 1000-KR	43.2
Ion Exchange Resin (Mixed bed)	Suprex* H-21	32.3

*The Suprex IER is based on a polystyrene cross-linked with Divinyl benzene and Lewatit IER is based on Crosslinked polystyrene but no info was found on type of additive.

Table A-5. Compositions of the cement pastes containing ion exchange resins or filter aid used in the experiment emplaced in deposition hole KA2861G02 in NASA2861A.

Material type	Dry weight of substance (g)	Celite (g)	Lime (g)	Cement (g)	W/C	Additive* (g)
UP2	150	–	17.5	625	1.31	4.0
Lewatit	117.2	–	17.5	800	0.38	4.7
H-21	135.0	15.0	17.5	625	1.16	4.0
N-21	135.0	15.0	17.5	625	0.96	4.0

* Ethylene glycol was used as additive in the preparation of the specimens.

Table A-6. Total weight of specimens containing filter aid or ion exchange resin used in the filed scale concrete experiment emplaced in deposition hole KA2861G02 in NASA2861A. The volume of each of the specimens was 117 ml. These specimens were cast from the mixtures described in Table A-5.

Specimen #	Weight (g)			
	UP2	Lewatit	H-21	N-21
1	153.1	198.0	189.8	188.7
2	151.4	197.7	185.6	188.1
3	152.4	198.2	180.2	188.9
4	153.8	204.5	184.0	188.6
5	154.7	196.3	190.3	190.0

Appendix B

Data of specimens emplaced in deposition holes in NASA0507A

Table B-1. Specimens emplaced in the topmost concrete cylinder (denominated I-1B) emplaced in deposition hole KR0014G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Weight	Comments
85	Stainless Steel SS2333	87.285	Steel Sheet
85	Stainless Steel SS2333	87.717	Steel Sheet
85	Stainless Steel SS2333	88.833	Steel Sheet
85	Stainless Steel SS2333	84.758	Steel Sheet
85	Stainless Steel SS2333	86.030	Steel Sheet
60	Zinc	139.515	Material for boats
60	Zinc	147.711	Material for boats
60	Zinc	140.744	Material for boats
60	Zinc	148.051	Material for boats
60	Zinc	145.007	Material for boats
35	Reinforcement bars	41.913	Sank during casting
35	Reinforcement bars	43.234	Sank slightly during casting
35	Reinforcement bars	41.277	
35	Reinforcement bars	42.574	
35	Reinforcement bars	41.544	
10	Aluminium	63.339	Rod
10	Aluminium	60.699	Rod
10	Aluminium	63.639	Rod
10	Aluminium	62.093	Rod
10	Aluminium	61.131	Rod

Table B-2. Specimens emplaced in the middle concrete cylinder (denominated I-2B) emplaced in deposition hole KR0014G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Comments
85	Ion Exchange Resin (Sulphonate. SA3)	See table A-1 to A-3 for details
85	Ion Exchange Resin (Sulphonate. SA4)	See table A-1 to A-3 for details
60	Filter aid (UP2. UP2a3)	See table A-1 to A-3 for details
60	Filter aid (UP2. UP2a4)	See table A-1 to A-3 for details
35	Ion Exchange Resin (Anion. SB3)	See table A-1 to A-3 for details
35	Ion Exchange Resin (Anion. SB4)	See table A-1 to A-3 for details
10	Ion Exchange Resin (Carboxylate. WA3)	See table A-1 to A-3 for details
10	Ion Exchange Resin (Carboxylate. WA4)	See table A-1 to A-3 for details

Table B-3. Specimens emplaced in the lower concrete cylinder (denominated I-3B) deposited in deposition hole KR0014G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Weight
85	Plastic bag. Blue and transparent	5 pieces. each 50·100 mm
60	Rubber gloves (blue)	5 pieces. each 50·50 to 100·100 mm
35	Cotton (overall. blue and yellow)	5 pieces. each about 25–90 cm^2
10	Paper (for wiping)	5 pieces. each a few grams

Table B-4. Specimens emplaced in the topmost concrete cylinder (denominated I-3A) deposited in deposition hole KR0009G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Comments
85	Plastic bag. Blue and transparent	5 pieces. each about 50·100 mm
60	Rubber gloves (blue)	5 pieces 50·50 and 100·100 mm
35	Cotton (overall. blue and yellow)	5 pieces each about 25–90 cm^2
10	Paper (for wiping)	5 pieces. each a few grams

Table B-5. Specimens emplaced in the middle concrete cylinder (denominated I-1A) deposited in deposition hole KR0009G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Weight (g)	Comments
85	Stainless Steel SS2333	87.599	Steel Sheet
85	Stainless Steel SS2333	85.378	Steel Sheet
85	Stainless Steel SS2333	84.622	Steel Sheet
85	Stainless Steel SS2333	85.608	Steel Sheet
85	Stainless Steel SS2333	86.226	Steel Sheet
60	Zinc	140.318	Material for boats
60	Zinc	145.756	Material for boats
60	Zinc	138.000	Material for boats
60	Zinc	136.395	Material for boats
60	Zinc	143.612	Material for boats
35	Reinforcement bars	42.036	Sank slightly
35	Reinforcement bars	41.526	Sank slightly
35	Reinforcement bars	40.814	
35	Reinforcement bars	42.648	
35	Reinforcement bars	42.746	
10	Aluminium	61.947	Rod
10	Aluminium	62.010	Rod
10	Aluminium	63.178	Rod
10	Aluminium	61.506	Rod
10	Aluminium	61.893	Rod

Table B-6. Specimens emplaced in the lower concrete cylinder (denominated I-2A) deposited in the deposition hole KR0009G01 in NASA0507A.

Distance from bottom of cylinder (cm)	Type of material	Comments
85	Ion Exchange Resin (Sulphonate. SA1)	See table A-1 to A-3 for details
85	Ion Exchange Resin (Sulphonate. SA2)	See table A-1 to A-3 for details
60	Filter aid (UP2. UP2a1)	See table A-1 to A-3 for details
60	Filter aid (UP2. UP2a2)	See table A-1 to A-3 for details
35	Ion Exchange Resin (Anion. SB1)	See table A-1 to A-3 for details
35	Ion Exchange Resin (Anion. SB2)	See table A-1 to A-3 for details
10	Ion Exchange Resin (Carboxylate. WA1)	See table A-1 to A-3 for details
10	Ion Exchange Resin (Carboxylate. WA1)	See table A-1 to A-3 for details

Appendix C

Data of specimens emplaced in deposition hole KA2862G02 in NASA2861A

Table C-1. Specimens emplaced in the topmost concrete cylinder deposited in the deposition hole KA2862G02 in NASA2861A.

Distance from bottom of cylinder (cm)	Type of material	Weight (g)	Comments
85	Stainless steel	39	
85	Stainless steel	41	
85	Stainless steel	38	
85	Stainless steel	35	
85	Stainless steel	41	
60	Zinc	158	
60	Zinc	135	
60	Zinc	151	
60	Zinc	129	
60	Zinc	152	
35	Reinforcement bars	45	
35	Reinforcement bars	46	
35	Reinforcement bars	47	
35	Reinforcement bars	35	
35	Reinforcement bars	43	
10	Aluminium	13	
10	Aluminium	14	
10	Aluminium	14	
10	Aluminium	13	
10	Aluminium	13	

Table C-2. Specimens emplaced in the middle concrete cylinder deposited in the deposition hole KA2862G02 in NASA2861A.

Distance from bottom of cylinder (cm)	Type of material	Comment
85	Ion Exchange Resin Suprex H-21	See Table A-4 to A-6 for details
60	Filter Aid UP-2	See Table A-4 to A-6 for details
35	Ion exchange resin Lewatit SM 1000 KR	See Table A-4 to A-6 for details
10	Ion exchange resin Suprex N-21	See Table A-4 to A-6 for details

Table C-3. Specimens emplaced in the lower concrete cylinder deposited in the deposition hole KA2862G02 in NASA2861A.

Distance from bottom of cylinder (cm)	Type of material	Dimensions
85	Plastic bag (5 pieces)	50·70 mm
60	Pieces of rubber gloves (5 pieces)	50·60 mm
35	Cotton. pieces from an overall (5 pieces)	80·70 mm
10	Wiping paper (5 pieces)	70·60 mm

Appendix D

Data of the waste emplaced in the steel cylinders in the laboratory scale experiments

Table D-1. Experimental details and content of the laboratory scale experiments.

Steel cylinder #	Material type	Dimensions	Weight (g)	Temperature (°C)
1	Cellulose. cloth from overall	Total area: 381.6 cm^2	7.1	50
		Thickness 0.40 mm		
2	Cellulose. paper	Total area 500 cm^2	0.66	50
		Thickness 0.07 mm		
3	Rubber (gloves)	Total area 432 cm^2	15.9	50
		Thickness 0.40 mm		
4	Plastic bag	Total area 372.5 cm^2	1.5	50
		Thickness 0.04 mm		
5	Ion exchange resin (Carboxylate)	Powder	25.0	50
6	Ion Exchange Resin (Anion)	Powder	25.0	50
7	Ion Exchange Resin (Sulphonate)	Powder	25.0	50
8	Filter Aid (UP2)	Powder	15.0	50
9	Bitumen	Total volume 10.0 ml	10.0	50
		Diameter of individual drops 3-8 mm		
10	Ion exchange resin (Carboxylate)	Powder	25.0	22/12*
11	Ion Exchange Resin (Anion)	Powder	25.0	22/12*
12A	Reinforcement bars		114.3	22/12*
12B	Reinforcement bars		120.8	22/12*
13A	Stainless steel SS2333	Thickness 1.40 mm	93.1	22/12*
13B	Stainless steel SS2333	Thickness 1.40 mm	94.3	22/12*
14A	Carbon steel C1070	Thickness 3.0 mm	189.6	22/12*
14B	Carbon steel C1070	Thickness 3.0 mm	189.4	22/12*
15	Cellulose. cloth from overall	Total area: 381.6 cm^2	7.1	22/12*
		Thickness 0.40 mm		
16	Cellulose. paper	Total area 500 cm^2	0.66	22/12*
		Thickness 0.07 mm		
17	Rubber (gloves)	Total area 432 cm^2	15.9	22/12*
		Thickness 0.40 mm		
18	Plastic bag	Total area 372.5 cm^2	1.5	22/12*
		Thickness 0.04 mm		
19	Reference 1	Contains only 50 g of standard OPC and Äspö ground water		
20	Reference 2	Contains only 50 g of Fiberbruk 50VF and Äspö ground water		

* The temperature in the cement laboratory at Ringhals NPP and in the Äspö tunnel was about 22°C and 12°C respectively. Each steel cylinder also contains 1,000 g of Äspö ground water and 50 g of crushed cement paste made from *Degerhamn Anläggningscement*.

Appendix E

Composition of the specimens used in the field scale bentonite experiments

Table E-1. Composition of the specimens containing cement paste used in the field scale bentonite experiments.

Cement powder (g)	Water (g)	Additive (g) Fe	Ni	Mo	Cr	CsCl	$SrCl_2$	$EuCl_3$	w/c ratio	Number of specimens
1,250	500								0.40	42
1,250	500	420							0.40	42
900	360		270						0.40	27
900	360			270					0.40	30
900	360				270				0.40	27
900	300					110			0.33	27
900	360						135		0.40	27
900	339							125	0.38	30

Table E-2. Composition of the specimens containing low-pH cement paste used in the field scale bentonite experiments.

Cement powder (g)	Silica (g)	Water (g)	Additive (g) Fe	Ni	Mo	Cr	CsCl	$SrCl_2$	w/c ratio	Number of specimens
305	203	250							0.82	18
457	305	365	270						0.80	27
457	305	365		270					0.80	27
457	305	425			270				0.93	32
457	305	365				270			0.80	27
305	203	250					90		0.82	18
400	270	250						90	0.62	18

Appendix F

Mix proportions of the bentonite specimens used in the field scale bentonite experiments

Table F-1. Mix proportions of specimens manufactured from FEBEX bentonite.

Type of additive	Amount of bentonite (g)	Amount of additive (g)	Number of specimens
Iron	100.175	25.005	5
Chromium	100.109	25.037	5
Nickel	100.023	25.002	5
Molybdenum	100.147	25.077	5
CsCl	100.174	25.156	5
$SrCl_2$	100.131	25.094	5
$EuCl_3$	100.043	25.018	5

Table F-2. Mix proportions of specimens manufactured from Ibeco RWC bentonite.

Type of additive	Amount of bentonite (g)	Amount of additive (g)	Number of specimens
Iron	100.066	25.010	5
Chromium	100.149	25.153	5
Nickel	100.050	25.055	5
Molybdenum	100.115	25.108	5
CsCl	100.175	25.195	5
$SrCl_2$	100.170	25.199	5
$EuCl_3$	100.104	25.039	5

Table F-3. Mix proportions of specimens manufactured from Asha bentonite.

Type of additive	Amount of bentonite (g)	Amount of additive (g)	Number of specimens
Iron	100.006	25.120	5
Chromium	100.079	25.087	5
Nickel	100.089	25.029	5
Molybdenum	100.171	25.039	5
CsCl	100.028	25.079	5
$SrCl_2$	100.040	25.070	5
$EuCl_3$	100.112	10.770	5

Table F-4. Mix proportions of specimens manufactured from MX-80 bentonite.

Type of additive	Amount of bentonite (g)	Amount of additive (g)	Number of specimens
Iron	100.300	25.220	5
Chromium	100.120	25.05	5
Nickel	100.180	25.020	5
Molybdenum	100.033	25.047	5
CsCl	100.140	25.040	5
$SrCl_2$	100.120	25.000	5
$EuCl_3$	100.085	24.025	5

Appendix G

Composition of the installed bentonite blocks

Table G-1. The bentonite blocks in experiment 16*.

Block #	Bentonite block	Specimen N	Specimen S	Specimen E	Specimen W
CC16_01	WYO_02	SS_38	SS_35	CS_09	CS_13
CC16_02	WYO_01	CEMFE_05	CEMFE_38	CEMCR_05	CEMCR_03
CC16_03	WYO_09	CEMCS_26	CEMCS_17	CEMSR_11	CEMSR_09
CC16_04	WYO_16	CEMNI_25	CEMNI_19	CEMMO_13	CEMMO_14
CC16_05	WYO_39	WUOEU_05	WUOEU_04	LOWCS_06	LOWCS_10
CC16_06	WYO_07	LOWNI_26	LOWNI_13	CEMFE_26	CEMFE_42
CC16_07	WYO_18	LOWCR_02	LOWCR_10	LOW_02	LOW_03
CC16_08	WYO_17	CEM_26	CEM_42	LOWFE_11	LOWFE_27
CC16_09	WYO_42	WYOMO_01	WYOMO_04	WYOCS_05	WYOCS_04
CC16_10	WYO_35	WYOCR_04	WYOCR_05	WYOSR_02	WYOSR_01
CC16_11	WYO_37	LOWMO_07	LOWMO_08	CEMEU_10	CEMEU_04
CC16_12	WYO_21	CS_18	CS_14	SS_34	SS_23
CC16_13	WYO_40	WYOFE_01	WYOFE_05	CEM_05	CEM_03
CC16_14	WYO_48	LOWSR_02	LOWSR_18	WYONI_05	WYONI_03
CC16_15	WYO_20	–	–	–	–
CC16_16	ASH_21	–	–	–	–
CC16_17	ASH_15	SS_33	SS_12	CS_07	CS_15
CC16_18	ASH_13	CEMFE_37	CEMFE_21	CEMCR_02	CEMCR_20
CC16_19	ASH_01	CEMCS_18	CEMCS_14	CEMSR_04	CEMSR_24
CC16_20	ASH_33	CEMNI_16	CEMNI_21	CEMMO_04	CEMMO_06
CC16_21	ASH_14	ASHEU_02	ASHEU_05	LOWCS_02	LOWCS_08
CC16_22	ASH_37	LOWNI_22	LOWNI_20	CEMFE_18	CEMFE_23
CC16_23	ASH_05	LOWCR_13	LOWCR_23	LOW_09	LOW_04
CC16_24	ASH_27	CEM_06	CEM_14	LOWFE_08	LOWFE_25
CC16_25	ASH_02	ASHMO_01	ASHMO_05	ASHCS_02	ASHCS_04
CC16_26	ASH_12	ASHCR_04	ASHCR_03	ASHSR_01	ASHSR_03
CC16_27	ASH_29	LOWMO_19	LOWMO_29	CEMEU_02	CEMEU_15
CC16_28	ASH_42	CS_06	CS_05	SS_30	SS_31
CC16_29	ASH_10	ASHFE_04	ASHFE_05	CEM_08	CEM_37
CC16_30	ASH_03	LOWSR_06	LOWSR_12	ASHNI_05	ASHNI_04

*Each specimen was prepared individually and given a unique denomination. Data on the specimens are stored in the database SICADA.

Table G-2. The bentonite blocks in experiment 17*.

Block #	Bentonite block	Specimen N	Specimen S	Specimen E	Specimen W
CC17_01	WYO_03	SS_36	SS_41	CS_25	CS_01
CC17_02	WYO_08	CEMFE_11	CEMFE_06	CEMCR_01	CEMCR_23
CC17_03	WYO_05	CEMCS_08	CEMCS_27	CEMSR_22	CEMSR_25
CC17_04	WYO_33	CEMNI_14	CEMNI_23	CEMMO_03	CEMMO_18
CC17_05	WYO_47	WUOEU_03	WUOEU_02	LOWCS_07	LOWCS_16
CC17_06	WYO_06	LOWNI_14	LOWNI_15	CEMFE_32	CEMFE_41
CC17_07	WYO_11	LOWCR_14	LOWCR_18	LOW_14	LOW_13
CC17_08	WYO_04	CEM_01	CEM_36	LOWFE_01	LOWFE_07
CC17_09	WYO_36	WYOMO_05	WYOMO_02	WYOCS_03	WYOCS_02
CC17_10	WYO_46	WYOCR_02	WYOCR_03	WYOSR_05	WYOSR_03
CC17_11	WYO_45	LOWMO_20	LOWMO_24	CEMEU_24	CEMEU_17
CC17_12	WYO_13	CS_17	CS_11	SS_07	SS_08
CC17_13	WYO_44	WYOFE_04	WYOFE_03	CEM_22	CEM_07
CC17_14	WYO_29	LOWSR_13	LOWSR_03	WYONI_02	WYONI_04
CC17_15	WYO_15	–	–	–	–
CC17_16	ASH_34	–	–	–	–
CC17_17	ASH_16	SS_29	SS_26	CS_12	CS_04
CC17_18	ASH_38	CEMFE_20	CEMFE_09	CEMCR_27	CEMCR_16
CC17_19	ASH_24	CEMCS_21	CEMCS_02	CEMSR_20	CEMSR_08
CC17_20	ASH_19	CEMNI_18	CEMNI_08	CEMMO_17	CEMMO_11
CC17_21	ASH_44	ASHEU_04	ASHEU_03	LOWCS_01	LOWCS_05
CC17_22	ASH_22	LOWNI_03	LOWNI_11	CEMFE_19	CEMFE_07
CC17_23	ASH_20	LOWCR_03	LOWCR_16	LOW_07	LOW_06
CC17_24	ASH_18	CEM_28	CEM_02	LOWFE_12	LOWFE_10
CC17_25	ASH_43	ASHMO_03	ASHMO_02	ASHCS_01	ASHCS_03
CC17_26	ASH_17	ASHCR_05	ASHCR_02	ASHSR_05	ASHSR_04
CC17_27	ASH_25	LOWMO_27	LOWMO_22	CEMEU_09	CEMEU_03
CC17_28	ASH_23	CS_03	CS_20	SS_01	SS_22
CC17_29	ASH_46	ASHFE_03	ASHFE_02	CEM_19	CEM_33
CC17_30	ASH_47	LOWSR_01	LOWSR_05	ASHNI_03	ASHNI_02

*Each specimen was prepared individually and given a unique denomination. Data on the specimens are stored in the database SICADA.

Table G-3. The bentonite blocks in experiment 18*.

Block #	Bentonite block	Specimen N	Specimen S	Specimen E	Specimen W
CC18_01	FEB_03	SS_20	SS_19	CS_37	CS_16
CC18_02	FEB_22	CEMFE_03	CEMFE_12	CEMCR_21	CEMCR_07
CC18_03	FEB_24	CEMCS_13	CEMCS_04	CEMSR_13	CEMSR_26
CC18_04	FEB_16	CEMNI_04	CEMNI_09	CEMMO_26	CEMMO_28
CC18_05	FEB_15	FEBEU_03	FEBEU_05	LOWCS_14	LOWCS_09
CC18_06	FEB_21	LOWNI_21	LOWNI_09	CEMFE_30	CEMFE_22
CC18_07	FEB_12	LOWCR_26	LOWCR_24	LOW_18	LOW_17
CC18_08	FEB_18	CEM_18	CEM_15	LOWFE_18	LOWFE_09
CC18_09	FEB_19	FEBMO_05	FEBMO_04	FEBCS_04	FEBCS_05
CC18_10	FEB_17	FEBCR_04	FEBCR_05	FEBSR_04	FEBSR_05
CC18_11	FEB_20	LOWMO_09	LOWMO_18	CEMEU_21	CEMEU_05
CC18_12	FEB_14	CS_38	CS_23	SS_17	SS_18
CC18_13	FEB_09	FEBFE_05	FEBFE_04	CEM_21	CEM_30
CC18_14	FEB_36	LOWSR_07	LOWSR_10	FEBNI_02	FEBNI_01
CC18_15	FEB_13	–	–	–	–
CC18_16	IBE_21	–	–	–	–
CC18_17	IBE_02	SS_06	SS_16	CS_22	CS_34
CC18_18	IBE_23	CEMFE_24	CEMFE_08	CEMCR_11	CEMCR_14
CC18_19	IBE_11	CEMCS_05	CEMCS_12	CEMSR_02	CEMSR_07
CC18_20	IBE_07	CEMNI_13	CEMNI_11	CEMMO_23	CEMMO_27
CC18_21	IBE_01	IBEEU_05	IBEEU_02	LOWCS_13	LOWCS_17
CC18_22	IBE_24	LOWNI_06	LOWNI_07	CEMFE_35	CEMFE_15
CC18_23	IBE_04	LOWCR_15	LOWCR_22	LOW_12	LOW_15
CC18_24	IBE_03	CEM_16	CEM_12	LOWFE_04	LOWFE_14
CC18_25	IBE_44	IBEMO_04	IBEMO_05	IBECS_05	IBECS_04
CC18_26	IBE_08	IBECR_01	IBECR_02	IBESR_04	IBESR_05
CC18_27	IBE_41	LOWMO_05	LOWMO_06	CEMEU_28	CEMEU_20
CC18_28	IBE_06	CS_32	CS_31	SS_21	SS_09
CC18_29	IBE_45	IBEFE_03	IBEFE_04	CEM_11	CEM_32
CC18_30	IBE_47	LOWSR_08	LOWSR_14	IBENI_03	IBENI_05

* Each specimen was prepared individually and given a unique denomination. Data on the specimens are stored in the database SICADA.

Table G-4. The bentonite blocks in experiment 19*.

Block #	Bentonite block	Specimen N	Specimen S	Specimen E	Specimen W
CC19_01	FEB_28	SS_40	SS_32	CS_36	CS_28
CC19_02	FEB_26	CEMFE_31	CEMFE_39	CEMCR_13	CEMCR_19
CC19_03	FEB_35	CEMCS_07	CEMCS_06	CEMSR_12	CEMSR_05
CC19_04	FEB_11	CEMNI_02	CEMNI_01	CEMMO_22	CEMMO_29
CC19_05	FEB_39	FEBEU_04	FEBEU_02	LOWCS_11	LOWCS_03
CC19_06	FEB_37	LOWNI_25	LOWNI_02	CEMFE_29	CEMFE_16
CC19_07	FEB_10	LOWCR_12	LOWCR_08	LOW_05	LOW_08
CC19_08	FEB_40	CEM_40	CEM_34	LOWFE_24	LOWFE_22
CC19_09	FEB_33	FEBMO_03	FEBMO_02	FEBCS_03	FEBCS_02
CC19_10	FEB_38	FEBCR_02	FEBCR_03	FEBSR_02	FEBSR_01
CC19_11	FEB_34	LOWMO_01	LOWMO_02	CEMEU_01	CEMEU_11
CC19_12	FEB_27	CS_21	CS_40	SS_02	SS_03
CC19_13	FEB_32	FEBFE_02	FEBFE_03	CEM_27	CEM_35
CC19_14	FEB_30	LOWSR_15	LOWSR_09	FEBNI_04	FEBNI_05
CC19_15	FEB_29	–	–	–	–
CC19_16	IBE_42	–	–	–	–
CC19_17	IBE_05	SS_11	SS_09	CS_33	CS_39
CC19_18	IBE_46	CEMFE_01	CEMFE_25	CEMCR_06	CEMCR_08
CC19_19	IBE_31	CEMCS_15	CEMCS_11	CEMSR_10	CEMSR_15
CC19_20	IBE_38	CEMNI_07	CEMNI_05	CEMMO_10	CEMMO_25
CC19_21	IBE_27	IBEEU_04	IBEEU_03	LOWCS_04	LOWCS_12
CC19_22	IBE_28	LOWNI_10	LOWNI_17	CEMFE_10	CEMFE_27
CC19_23	IBE_30	LOWCR_25	LOWCR_06	LOW_16	LOW_01
CC19_24	IBE_40	CEM_09	CEM_39	LOWFE_26	LOWFE_02
CC19_25	IBE_29	IBEMO_03	IBEMO_02	IBECS_03	IBECS_02
CC19_26	IBE_39	IBECR_04	IBECR_05	IBESR_01	IBESR_03
CC19_27	IBE_26	LOWMO_28	LOWMO_23	CEMEU_18	CEMEU_07
CC19_28	IBE_28	CS_29	CS_10	SS_14	SS_39
CC19_29	IBE_37	IBEFE_05	IBEFE_01	CEM_41	CEM_20
CC19_30	IBE_32	LOWSR_16	LOWSR_04	IBENI_04	IBENI_02

* Each specimen was prepared individually and given a unique denomination. Data on the specimens are stored in the database SICADA.

Table G-5. The composition of the bentonite blocks in experiment 20*.

Block #	Bentonite block	Specimen N	Specimen S	Specimen E	Specimen W
CC20_01	FEB_01	CEMFE_40	CEMFE_36	CEMMO_21	CEMMO_09
CC20_02	FEB_05	CEMCR_12	CEMCR_17	CEMNI_20	CEMNI_24
CC20_03	FEB_08	SS_13	SS_27	CS_27	CS_30
CC20_04	FEB_02	CEMSR_27	CEMSR_21	CEM_24	CEM_29
CC20_05	FEB_06	CEMEU_06	CEMEU_27	CEMCS_16	CEMCS_22
CC20_06	FEB_04	LOWFE_06	LOWFE_03	LOWMO_03	LOWMO_13
CC20_07	FEB_07	LOWCR_11	LOWCR_17	LOWNI_12	LOWNI_24
CC20_08	IBE_14	CEMFE_13	CEMFE_28	CEMMO_16	CEMMO_05
CC20_09	IBE_15	CEMCR_25	CEMCR_10	CEMNI_03	CEMNI_22
CC20_10	IBE_16	SS_15	SS_37	CS_35	CS_24
CC20_11	IBE_12	CEMSR_16	CEMSR_01	CEM_17	CEM_25
CC20_12	IBE_13	CEMEU_30	CEMEU_12	CEMCS_22	CEMCS_24
CC20_13	IBE_09	LOWFE_16	LOWFE_23	LOWMO_26	LOWMO_25
CC20_14	IBE_10	LOWCR_07	LOWCR_20	LOWNI_08	LOWNI_27
CC20_15	WYO_25	–	–	–	–
CC20_16	WYO_28	CEMFE_04	CEMFE_17	CEMMO_30	CEMMO_02
CC20_17	WYO_23	CEMCR_22	CEMCR_24	CEMNI_15	CEMNI_27
CC20_18	WYO_14	SS_04	SS_05	CS_08	CS_02
CC20_19	WYO_12	CEMSR_06	CEMSR_14	CEM_31	CEM_23
CC20_20	WYO_10	CEMEU_08	CEMEU_14	CEMCS_20	CEMCS_10
CC20_21	WYO_24	LOWFE_17	LOWFE_05	LOWMO_31	LOWMO_16
CC20_22	WYO_22	LOWCR_01	LOWCR_05	LOWNI_16	LOWNI_18
CC20_23	WYO_19	–	–	–	–
CC20_24	ASH_11	CEMFE_34	CEMFE_33	CEMMO_15	CEMMO_07
CC20_25	ASH_39	CEMCR_09	CEMCR_08	CEMNI_17	CEMNI_26
CC20_26	ASH_09	SS_28	SS_25	CS_19	CS_26
CC20_27	ASH_26	CEMSR_23	CEMSR_19	CEM_10	CEM_04
CC20_28	ASH_07	CEMEU_29	CEMEU_19	CEMCS_19	CEMCS_01
CC20_29	ASH_06	LOWFE_21	LOWFE_20	LOWMO_21	LOWMO_15
CC20_30	ASH_04	LOWCR_27	LOWCR_09	LOWNI_01	LOWNI_23

*Each specimen was prepared individually and given a unique denomination. Data on the specimens are stored in the database SICADA.

SKB is tasked with managing Swedish nuclear and radioactive waste in a safe way.

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Arkitektkopia AB, Bromma, januari 2015