Technical Report
TR-15-05
January 2015

Investigations of hydraulic and mechanical processes of the barriers embedding the silo in SFR

Laboratory tests

Lars-Erik Johannesson
Ann Dueck
Linus Andersson
Viktor Jensen

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

ISSN 1404-0344
SKB TR-15-05
ID 1484826

January 2015

Investigations of hydraulic and mechanical processes of the barriers embedding the silo in SFR

Laboratory tests

Lars-Erik Johannesson, Ann Dueck,
Linus Andersson, Viktor Jensen

Clay Technology AB

Abstract

One part of the repository for low and intermediate radioactive waste (SFR) is the so called silo repository. The objective with this study is to present results, mainly laboratory test results, to be used for the analyses of important hydro-mechanical processes in the silo.

In this study, tests have been made on GeKo/QI bentonite sampled from in-situ. Mainly swelling pressure and hydraulic conductivity tests, oedometer tests and self-sealing ability tests have been performed. The consequences of an ion exchange on swelling pressure and hydraulic conductivity has also been studied where the GeKo/QI bentonite was ion exchanged to become Ca^{2+} dominated. In addition, some tests have been made to characterize the material by determination of liquid limit, free swelling, particle density and retention curve.

Results from the laboratory tests show logical values of the swelling pressure and hydraulic conductivity. The hydraulic conductivity for a dry density of 1,000 kg/m^3 seems to be lower than 5E–11 m/s and the corresponding value for the swelling pressure is about 100 kPa. It was also observed that equilibrium was not reached in all tests in spite of long test time. This was for example observed for measured swelling pressures. The explanation of this is not clear.

Some recommendations for further tests are given for the bentonite as well as for the sand and the bentonite/sand filling of the silo repository.

Sammanfattning

En del av slutförvaret för låg och medelaktivt avfall (SFR) är det så kallade siloförvaret. Syftet med denna studie är att presentera laboratorieresultat som ska användas för analys av viktiga hydromekaniska processer för silon.

I studien har material från det befintliga förvaret (GeKO/QI) använts. Ödometerförsök, svälltrycks- och hydraulisk konduktivitetstester samt försök för att studera materialets självläkningsegenskaper har gjorts. Effekten av jonbyte på svälltryck och hydraulisk konduktivitet har också undersökts. Dessutom har materialet karakteriserats med bestämning av flytgräns, fri svällning, partikeldensitet och vattenhållningskurva.

Resultat från laboratorieförsöken visar logiska värden vad gäller hydraulisk konduktivitet och svälltryck. Vid en torrdensitet av 1 000 kg/m^3 uppmättes svälltrycket till ca 100 kPa och den hydrauliska konduktiviteten till värden lägre än 5E–11 m/s. I försöken observerades också att jämvikt var svårt att uppnå bland annat i utvecklingen av svälltryck. Orsaken till detta är oklart.

I resultaten ges också rekommendationer för fortsatta tester på bentoniten så väl som på sanden och sand/bentonitfyllningen, vilka alla ingår i siloförvaret.

Contents

1 Introduction

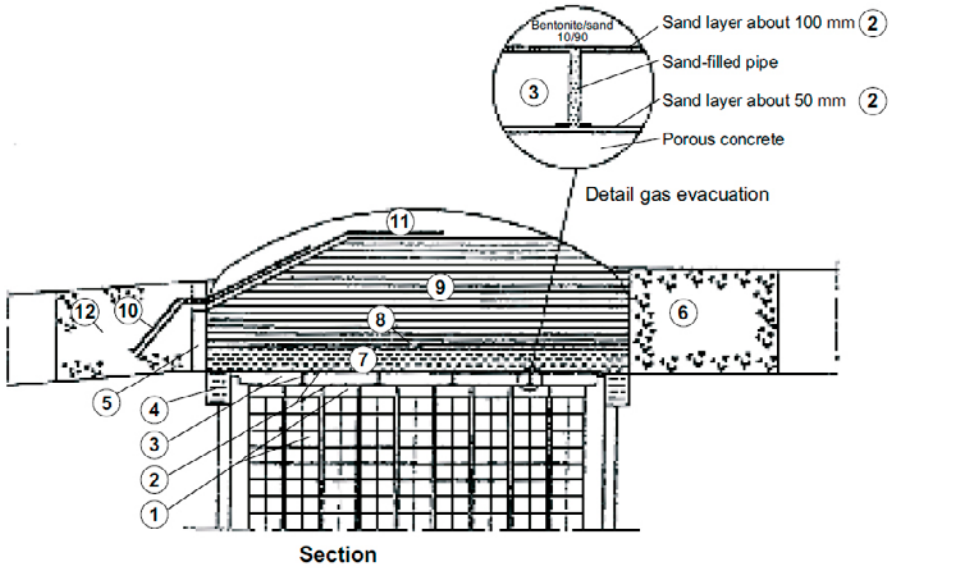
One part of the repository for low and intermediate radioactive waste (SFR) is the so called silo repository. The objective with this study is to present results, mainly laboratory test results, to be used for the analyses of important hydro-mechanical processes in the silo. The bentonite used is of the type GeKo/QI which originally is a calcium dominated bentonite. It has been converted to a sodium dominated bentonite before delivery in order to improve its swelling properties. The cases dealt with and the performed tests are summarized in Table 1-1. A schematic drawing of the upper part of the silo is shown in Figure 1-1.

Table 1-1. Cases dealt with and performed tests.

Case	Title	Description of the test types	Type of water	Accomplished according to original plans
Case 0	Characterization	Determination of normalized free swelling.		Yes
		Determination of particle density.		Yes
		Determination of liquid limit.		Yes
		Determination of grain size distribution.		No*)
Case 1	Analysis of ion-exchange of the bentonite.	Determination of swelling pressure and hydraulic conductivity before and after ion exchange of GeKo/QI.	de-ionized and 0.1M $CaCl_2$	Yes
		Oedometer tests on GeKo/QI.	de-ionized	Yes
		Oedometer tests on ion-exchanged GeKo/QI.	de-ionized	Yes
Case 2	Erosion and piping.	See Section 2-4		
Case 3	Self-sealing ability of the bentonite.	Determination of sealing properties of drilled holes in GEKO/QI specimens.	SFR water**)	Yes
		Determination of sealing properties of drilled holes of ion-exchanged GeKo/QI specimens.		No*)
Case 4	Modelling of the water uptake, laboratory tests.	Determination of water retention curve of GeKO/QI with initial w = 13%.		Yes
		Additional retention curve.		No*)
		Determination of water retention properties with psychrometers.		Yes
		Water uptake tests with GeKo/QI.	SFR water**)	Yes
		Additional water uptake tests with GeKo/QI.		No*)
		Determination of swelling pressure and hydraulic conductivity.	SFR water**)	Yes
		Unconfined compression tests.	SFR water**)	Yes
Case 8	Analyses of the settlement of the packed sand fill of the silo top.	Proctor tests, CRS tests etc.		No*)
Case 9	Analyses of the hydro-mechanical behavior of the bentonite/sand silo top.	Determination of swelling pressure and hydraulic conductivity and oedometer tests.		No*)
Case 10	Analyses of what happened with the bentonite/sand bottom bed and the hydro-mechanical evolution.	Determination of swelling pressure and hydraulic conductivity and oedometer tests.		No*)

*) Laboratory tests excluded from test plan.
**) Water prepared to simulate the ground water at the SFR repository.

The results from tests on the GeKo/QI bentonite in this study have in some cases been compared with data from tests on the sodium dominated and more common Wyoming bentonite MX-80 (from American Coll. Co.). In the beginning of this study test results on MX-80 were also used for the design of a suitable test matrix and equipment for the tests on GeKo/QI.



1 Grouted waste packages
2 Pressure-distributing sand layer
3 Reinforced concrete pad with gas evacuation pipes
4 Compacted fill of bentonite/sand 30/70
5 Compaction support of concrete
6 Concrete plug
7 Compacted fill of bentonite/sand 10/90
8 Unreinforced concrete pad
9 Compacted fill (friction material)
10 Pipe system for loading-in of sand in silo cupola
11 Cement-stabilized sand
12 Concrete plug – Cast after sand filling

Figure 1-1. *Overview of the components in the top part of the closed silo repository (SKB 2008).*

2 Laboratory tests and results

2.1 General

The results concerning cases 0–4 and 8–10 are presented in this Chapter. For each case, a short presentation is given followed by a description of the test types used and compiled data from the present investigation and in some cases also from previous studies.

The water content is defined as the ratio of the mass of water to the dry mass where the dry mass was determined after drying at 105˚C for 24h. The bulk density is defined as the total mass of a sample and the volume determined by weighing the sample above and submerged in paraffin oil. The dry density was then calculated from the bulk density and the water content.

The so called SFR water is artificial water prepared to simulate the ground water at the SFR repository and containing NaCl, $CaCl_2$ and $MgCl_2$ to a total salt content of 6 g/l, see also Section 2.4.1.3.

2.2 Case 0: Characterization

Characterization of the GeKo/QI bentonite is an important part of the laboratory testing programme. The normalised free swelling, the particle density and the liquid limit were chosen as suitable parameters for the characterization.

The normalized free swelling and the liquid limit have been determined on candidate backfill materials by Johannesson and Nilsson (2006). In Table 2-1 the results are shown for the Na-dominated Wyoming bentonite MX-80 and the Ca-dominated Greek bentonite Deponit Ca-N.

Table 2-1. Characterization of two materials presented based on Johannesson and Nilsson (2006).

Clay type	Initial water content (%)	Normalized free swelling (ml/g)	Liquid limit (%)	Swelling minerals (%)
Deponit CA-N	16.3	5.3	157	80–85
MX-80	8.8	20.8	524	80–85

The particle densities of MX-80 and Deponit Ca-N are ρ_s = 2,780 kg/m^3 and ρ_s = 2,750 kg/m^3, respectively according to Karnland et al. (2006).

The resulting normalized free swellings and liquid limits from the present study are given in Table 2-2. In addition to the ordinary determination done with de-ionized water the normalized free swelling was also determined with the so called SFR water (see Section 2.4.1.3). Furthermore, the liquid limit and free swelling were also determined on GeKo/QI ion exchanged to be Ca^{+2} dominated (GeKo/QI Ca). Totally five determinations of the particle density have been done with the mean value and standard deviation of 2,806 kg/m^3 and 34 kg/m^3, respectively.

At sampling the water content was higher than 35% and the material was therefore dried at laboratory room climate. After drying a couple of days the average water content was between 12% and 14% which was the initial water content used in the laboratory tests.

Table 2-2. Results from free swelling and liquid limit tests.

Type of clay	Type of water	Normalized free swelling (ml/g)	Liquid limit (%)
GeKo/QI	SFR	5.4	–
GeKo/QI	de-ionized	9.4	365
GeKo/QI Ca	de-ionized	3.2	135

2.3 Case 1: Analysis of the effect of ion-exchange of the bentonite

An ion-exchange of the GeKo/QI bentonite cannot be excluded over the life time of the SFR facility. In this study an ion-exchange from Na^{+} to Ca^{2+} has been considered. The consequences on the silo were studied by determination of swelling pressure and hydraulic conductivity before and after the ion-exchange, see Section 2.3.1. The effect of ion-exchange on GeKo/QI was also studied by oedometer tests where the compressibility is measured, see Section 2.3.2.

2.3.1 Swelling pressure and hydraulic conductivity tests

From studies on MX-80 by Karnland et al. (2008) the swelling pressure at a dry density of 1,000 kg/m^3 was determined to approximately 150 kPa. The water used for the determinations was a solution with low ionic strength or de-ionized water. The hydraulic conductivity of MX-80 was approximately 1E–11 m/s. These values were interpolated between measured values.

Swelling pressure and hydraulic conductivity of purified and ion-exchanged MX-80, ion-exchanged to be more sodium or calcium dominated, were measured by Karnland et al. (2006). Estimated at a dry density of 1,200 kg/m^3 the calcium dominated bentonite had approximately half of the swelling pressure compared to the sodium dominated bentonite and the hydraulic conductivity of the calcium dominated bentonite was approximately 2 times higher compared to the sodium dominated bentonite. According to the study, the effect of the dominating ion can be expected to be larger at lower densities.

In the present study the swelling pressure and hydraulic conductivity were measured in a combined test with the set-up shown in Figure 2-1. The method has previously been used by e.g. Dueck et al. (2011). The specimens were saturated from filters placed at the bottom and top of the samples. A piston was placed on top of the specimen in order to keep its volume constant and the swelling pressure was continuously monitored by a load cell installed at the top of the piston.

After saturation, a pore pressure gradient was applied across the specimen and the volume of the out-flowing water measured until stable rate of flow was established. The hydraulic conductivity was then calculated according to Darcy's law. No backpressure was used, i.e. the pore pressure on the outlet side was atmospheric. The measurements of the outflow were made over a period of hours.

Specimens were compacted to a suitable density and de-ionized water was added after evacuation of air from tubes and filters surrounding the specimen. When equilibrium was considered the final value of the swelling pressure was registered and measurement of hydraulic conductivity was made. The subsequent ion-exchange was achieved by change of the fluid from de-ionized water to a 0.1M $CaCl_2$ solution as described by Karnland et al. (2006) and Dueck et al. (2010).

Samples with a diameter of 50 mm and a height of 10 mm were compacted to the target densities between 950 and 1,050 kg/m^3. The results from the measurements of the tests made with de-ionized water are presented in Table 2-3. Increase in swelling pressure was seen during the measuring period and thus two swelling pressures were evaluated and presented in the table.

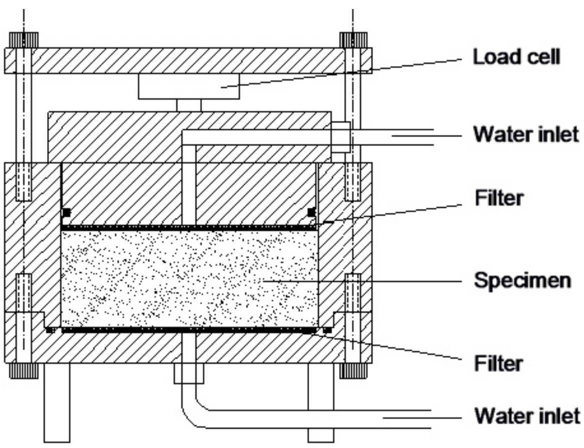


Figure 2-1. A schematic drawing of the device used for determining swelling pressure and hydraulic conductivity (Dueck et al. 2011).

Table 2-3. Test results from determination of swelling pressure and hydraulic conductivity of three specimens with de-ionized water before ion exchange.

Sample No	Dry density (kg/m³)	Swelling pressure (kPa)	(kPa)	Applied pressure difference (kPa)	Pressure gradient (m/m)	Hydr. cond. (m/s)
SFR_Pk1_1	990	94*)	151**)	23	234	8.55E–12
SFR_Pk1_2	959	90*)	133**)	23	234	9.30E–12
SFR_Pk1_3	1,038	160*)	203**)	23	234	4.13E–12

*) Swelling pressure evaluated just before the hydraulic conductivity was determined 2014-04-11.
**) Swelling pressure evaluated just before the $CaCl_2$ solution was applied 2014-05-23.

The measurement of the swelling pressure continued while the 0.1 M $CaCl_2$ solution was applied to the samples, see Figure 2-2. The figure is indicating a drop in swelling pressure of approximately half to one third of the initial value after introducing the salt solution. The hydraulic conductivities were determined after equilibrium with subsequent determinations of water content and density of the specimens. The results from these determinations are shown in Table 2-4. Comparison of the hydraulic conductivity determined before (see Table 2-3) and after the salt solution was introduced (see Table 2-4) indicates an increase with a factor of about 2.

Table 2-4. Test results from determination of swelling pressure and hydraulic conductivity of three specimens after ion exchange.

Sample No	Dry density (kg/m³)	Swelling pressure (kPa)	Applied pressure difference (kPa)	Pressure gradient (m/m)	Hydr. cond. (m/s)
SFR_Pk1_1	990	37	13	132	2.36E–11*)
SFR_Pk1_2	959	46	13	132	2.00E–11*)
SFR_Pk1_3	1,038	93	13	132	8.83E–12*)

*) Hydraulic conductivity determined with 0.1M $CalCl_2$ solution.

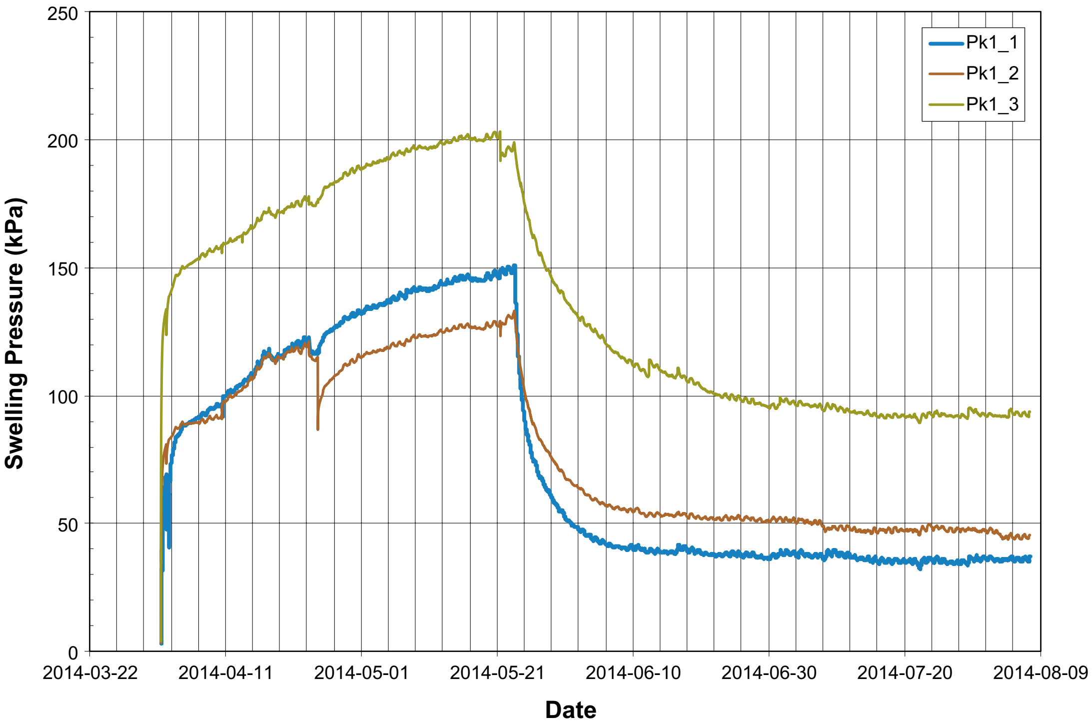


Figure 2-2. The swelling pressure as function of date before and after introducing 0.1M $CaCl_2$ on 2014-05-23.

2.3.2 Oedometer tests

For the oedometer tests the specimens placed in a rigid ring are set to saturation at a constant vertical stress. After equilibrium stepwise loading and unloading are made at continuous measurement of deformation and stress.

The tests were made on the original GeKo/QI bentonite and on ion-exchanged GeKo/QI. The ion-exchanged material was prepared by a method similar to the one introduced and described by Karnland et al. (2006). Ground material was dispersed in de-ionized water and $CaCl_2$ was added to a concentration of 1M. The material was left to settle and the supernatant was removed. The procedure was repeated three times. The remaining material was transferred to dialysis membranes and placed in plastic tanks with de-ionized water. The de-ionized water was changed 12 times until low electrical conductivity was measured. The material was dried in 40°C and then used in the oedometer tests after crushing.

Two specimens of the original material and two specimens with ion exchanged material were prepared with a diameter of 35 mm. Two of the specimens were subjected to two steps of loading (SFR_OE1_1 and SFR_OE1_3) and two of them to two steps of unloading (SFR_OE1_2 and SFR_OE1_4). The tests were running with de-ionized water. The results from each step are presented in Table 2-5 and Figure 2-3 and details can be found in Appendix 1.

The results from the oedometer tests show that the relation between the density and pressure for the two types of material (see Figure 2-3), not ion-exchanged and ion-exchanged, are similar. However, according to the results presented in Figure 2-2 a lower value of the swelling pressure from the ion-exchanged would be expected. Plausible explanations for the difference might be:

- differences in the test methods,
- differences in the methods for ion-exchanging the material,
- two different density intervals were investigated. The density of the samples for the oedometer tests were higher compared to other tests in this study.

Table 2-5. The vertical stress and the dry density at the end of each load step of the completed oedometer tests.

Sample No	Final vertical pressure (kPa)	Dry density (kg/m^3)	Ion exchanged material
SFR_OE1_1	305	1,125	No
SFR_OE1_1	766	1,189	No
SFR_OE1_1	1,199	1,236	No
SFR_OE1_2	301	1,125	No
SFR_OE1_2	150	1,106	No
SFR_OE1_2	78	1,057	No
SFR_OE1_3	297	1,089	Yes
SFR_OE1_3	629	1,129	Yes
SFR_OE1_3	1,353	1,225	Yes
SFR_OE1_4	326	1,087	Yes
SFR_OE1_4	140	1,065	Yes
SFR_OE1_4	66	1,047	Yes

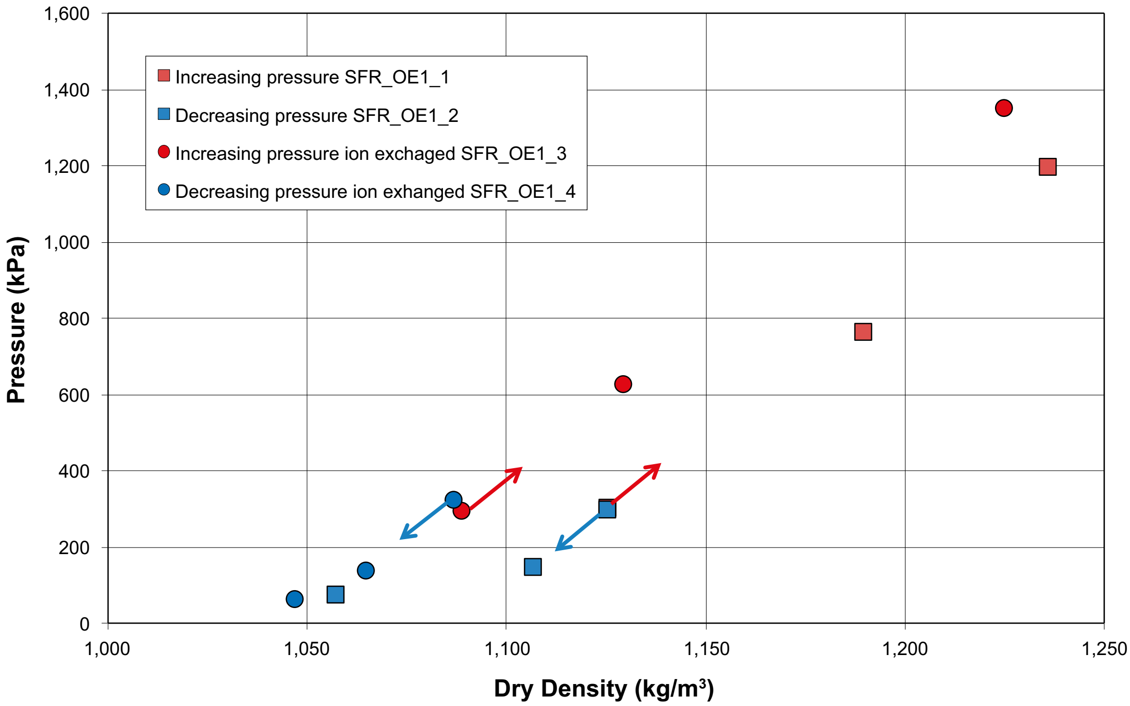


Figure 2-3. *The applied pressure as function of the dry density of the samples at the end of each load step for the completed oedometer tests. The arrows are indicating the start and the stress path from the initial state of each test.*

2.4 Case 2 Erosion tests

2.4.1 Test information

2.4.1.1 General

A series of erosion tests were performed on the GEKO/QI bentonite from the SFR silo to determine the erosion properties of the material. A total of four tests were performed and the only parameter that was varied was the water flow rate.

1.4.1.2 Material

The tests were performed on bentonite sampled from the top of the SFR silo wall. The current water content in the sample was about 35–40%. This is high compared to the water content at the time of installation in 1987, which was about 15%. Therefore the material was dried to about 15% water content before used in the tests.

2.4.1.3 Water

The water used in these tests was composed according to the estimated ground water composition in SFR. The recipe was deduced from data received from report R-13-16 (Auqué et al. 2013). The total salinity is 0.61%, primarily from sodium chloride but also some calcium chloride and a small amount of magnesium chloride. The exact recipe is presented in Table 2-6.

Table 2-6. Recipe representing the proposed composition of penetrating ground water at SFR.

Tap water (l)	NaCl (g)	$CaCl_2$ (g)	$MgCl_2$ (g)
100	385	166	59

2.4.1.4 Test equipment

A transparent tube with inner diameter 100 mm and length 250 mm was used in all tests. The tube was placed lying down making the flow direction horizontal. A Grundfos dosing pump was used to apply a constant water flow rate to the equipment inlet. Figure 2-4 shows the fully rigged test equipment.

2.4.1.5 Test plan

Four tests were performed at three different water flow rates. The test with the highest flow rate (0.1 l/min) was duplicated. Only one test was performed at 0.05 and 0.01 l/min. Table 2-7 shows the full test plan.

Table 2-7. All the performed tests.

Flow rate (l/min)	0.1	0.05	0.01
Number of tests	2	1	1

2.4.2 Method

2.4.2.1 Sample preparation

Since the material was in granular form it was necessary to establish the flow channel artificially to prevent direct sealing/clogging at the start up. This was done by placing a 4 mm thick stick in the center of the tube while filling it with the bentonite sample. An example of sample preparation is shown in Figure 2-5. When the tests were started the 4 mm stick was pulled out slowly as the water progressed through the artificially made channel.

Figure 2-4. The fully rigged test equipment. A transparent tube with inner diameter 100 mm and length 250 mm was used in all tests.

Figure 2-5. Sample preparation with a 4 mm stick to artificially create a flow channel.

2.4.2.2 Test performance and outflow sampling

The performance followed the same routine for all four tests.

- A constant flow of water was applied to the inlet.
- All tests were run to an accumulated outflow of about 250–300 liters.
- Water pressure was registered to detect pressure build ups.
- Photos were taken continuously to document any significant visual observations.
- Samples were taken from the outflow at specific time intervals to determine the bentonite concentration of the outflow.
- A sediment trap was used to collect the eroded material in the outflow that was not sampled.
- The flow channels were exposed and documented with photos at dismantling.

The sampling was performed in glass jars holding samples of 0.9–1.0 liters. The sampling was done at a higher frequency in the beginning of the test and at a lower frequency by the end of the test. Approximately 25 samples were planned to be taken in each test. The first 6–10 liters were sampled in all tests and then the sampling frequency was gradually reduced and by the end of each test every 10^{th} to 15^{th} liter was sampled (except night time when larger gaps occurred, especially in the 0.1 l/min tests).

2.4.2.3 Determination of eroded material

The amount of eroded material in the outflow was determined through the following routine;

- A reference sample was taken from the water reservoir to determine the exact salinity of the water by evaporating the water in a ventilated oven at 105°C.
- All glass jars were weighed carefully before sampling.
- The jars with outflow samples were weighed and then placed in a ventilated oven at 105°C.
- When all water was evaporated from the sample the jar was once more weighed. The amount of eroded bentonite could be determined by subtracting the amount of salt corresponding to the water evaporated from the sample.
- After the test the mass of the material in the sediment trap was determined the same way.

2.4.3 Results

Sample mass of the tests ranged between 2,062–2,138 g and the water content of the material was between 14.7–15.4%. With a sample volume determined from the equipment diameter 100 mm and length 250 mm the dry densities ranged from 0.916–0.947 g/cm^3. This is in average approximately 5% less than the assumed dry density of the SFR-silo bentonite, which is about 0.980 g/cm^3.

2.4.3.1 Bentonite concentrations in outflow

The determined bentonite concentrations in the outflow are shown in Figure 2-6. Initially the bentonite concentrations in the outflow range from 1–10 g/l. As the tests progress the concentrations in the outflow are reduced and after 50 liters accumulated outflow all samples except one (Test 3, 0.05 l/min) contain less than 1 g/l bentonite.

By interpolating the bentonite concentration of each sample over the corresponding time period the total amount of eroded material can be estimated. This interpretation is shown in Figure 2-7 where the accumulated eroded material is plotted as a function of the accumulated outflow. The straight black lines in the figure show a model that describes the expected maximum and minimum accumulated eroded material (Sandén and Börgesson 2010). The dashed grey line describes a suggested new upper limit of the model.

The water pressures from all performed tests are presented in Figure 2-8. No significant water pressure build-ups are registered in the tests. However, there are some quick water pressure peaks at the start-up of test 1 and test 2. These are related to the artificial formation of the flow channel.

The amount of eroded material in the sediment trap was added to the total amount of material determined in the outflow samples for each test. This amount could then be compared to the total estimated eroded material displayed in Figure 2-7. Table 2-8 shows a comparison of these two methods. It is seen that the total material mass from samples and sediment amounts to 59.7–104.4% of the estimated total eroded material. The average percent samples + sediments of the estimated total erosion for all four tests is 78.1%.

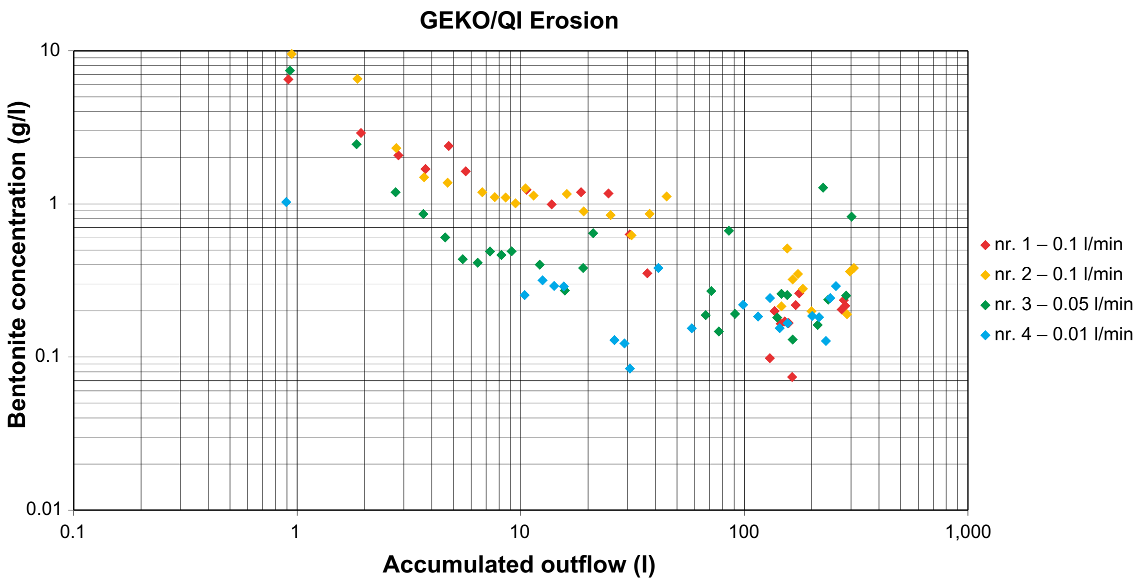


Figure 2-6. *Bentonite concentrations in the outflow for all four tests.*

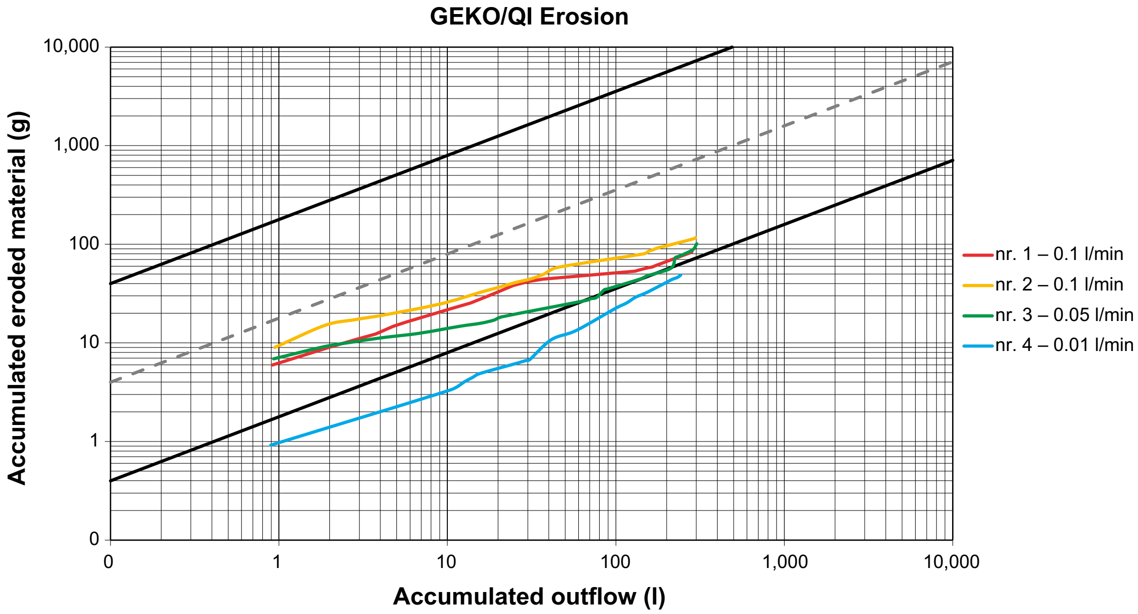


Figure 2-7. *Accumulated eroded material as a function of accumulated outflow. The straight black lines describe a model of expected maximum and minimum accumulated eroded material (Sandén and Börgesson 2010). The dashed grey line describes a suggested new upper limit of the model.*

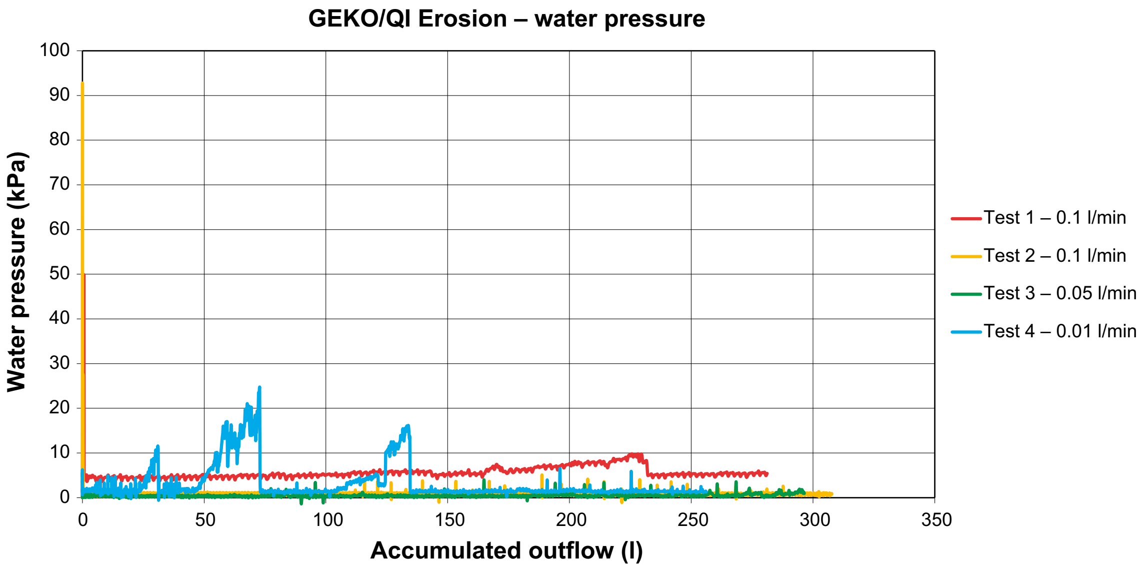


Figure 2-8. *Registered water pressure from all performed tests.*

Table 2-8. Comparison of the total amount of eroded material in the samples and sediment trap with the estimated total erosion.

Test ID	1	2	3	4
Sediment mass (g)	25.32	91.48	65.41	25.02
Tot. samples mass (g)	28.20	35.13	20.07	6.58
Samples + sediment mass (g)	53.52	126.61	85.49	31.60
Estimated tot. erosion (g)	83.69	121.29	101.46	52.97
Part samples + sediments of estimated tot. erosion (%)	64.0	104.4	84.3	59.7

2.4.4 Discussion and conclusions

As seen in Figure 2-6 the bentonite concentrations in the outflow decreases as the test progresses and by 50 liters accumulated outflow the concentration is less than 1 g/l in all samples but one (test 3, 0.05 l/min). The results are similar to previously performed pellet erosion studies within the EVA and ÅSKAR projects (Börgesson et al. 2015a, Andersson and Sandén 2012) where general trend is that the outflow concentrations are 1 g/l or less after about 100 liters accumulated outflow.

When the accumulated erosion is estimated from the determined outflow concentrations it is seen that tests 1, 2 and 3 is within the expected range of the updated model. For test 4 the total estimated erosion is actually less than the minimum expected erosion. Thereby the model seems valid also for horizontal erosion of the GEKO/QI bentonite granules.

Table 2-8 in the previous section compares the total material mass in the samples and sediment trap to the estimated total erosion of each test. The average value is 78.1%, which means that the general trend seems to be that the interpretation in Figure 2-7 gives a slight overestimation of the eroded material. It is likely that the sediment trap fails to capture a significant amount of fines and therefore the "Samples + sediment mass" fraction in fact should be larger. The comparison shows that the estimation of accumulated eroded material seems to be in the right order of magnitude, with a slight over estimation.

The conclusions from the evaluation of the tests are presented below:

- The bentonite concentration in the outflow ranges from 1–10 g/l initially. By 50 liters accumulated outflow the concentrations are 1 g/l or less (exception: one sample in test 3, 0.05 l/min).
- The results coincide well with previous erosion studies on bentonite pellets.
- The erosion model (Sandén and Börgesson 2010) seems valid for the GEKO/QI granule bentonite. The erosion of test 4 (0.01 l/min) is actually less than the model lower limit.
- The estimation of accumulated eroded material seems to be in the right order of magnitude, with a slight overestimation.

2.5 Case 3: Study of the self-sealing ability of the bentonite (silo)

For the performance of the barrier the sealing ability of the bentonite is studied. The self-sealing tests were made on specimens where a centric hole was drilled through saturated specimens of GeKo/QI. The sealing ability was evaluated from measurements of swelling pressure and hydraulic conductivity before and after drilling the hole.

The method has previously been used by Sandén et al. (2008) where the self-sealing ability of four backfill materials was studied. In that study three specimens of MX-80 pellet with an initial density of 980 kg/m^3 were included. Cylindrical specimens with diameter 101 mm and height 85 mm were used and after measurement of swelling pressure and hydraulic conductivity a hole with diameter 5 mm (or 10 mm) were drilled in each specimen. After healing and homogenization during 3 weeks the hydraulic conductivity and swelling pressure were measured again. The results are shown in Table 2-9. The hydraulic conductivity was evaluated with Darcy's law and the water pressure difference used was 20 kPa. In the report the swelling pressure was also given. Before drilling the measured swelling pressure was between 50 kPa and 60 kPa and after drilling and 3 weeks of healing and homogenization the values were between 40 kPa and 70 kPa.

Table 2-9. Results from self-sealing ability tests presented by Sandén et al. (2008). The hydraulic conductivity is given both before and after drilling a hole through the specimens. Included in the table are also the initial and final dry densities, the type of water used and the diameter of the drilled hole.

Material	Dry density		Type of water	Hydraulic conductivity		Hole diameter
	Initial (kg/m^3)	Final (kg/m^3)		Before (m/s)	After (m/s)	(mm)
MX-80 pellet	980	930	1% salt	$2.1\cdot10^{-11}$	$7.7\cdot10^{-11}$	5
MX-80 pellet	980	930	3.5% salt	$9.6\cdot10^{-11}$	$1.3\cdot10^{-8}$	10
MX-80 pellet	980	880	3.5% salt	$1.2\cdot10^{-10}$	$5.4\cdot10^{-9}$	5

Similar tests were made on GeKo/QI material with SFR water (see Section 2.4.1.3) in this study. Three tests were prepared with an average dry density of 1,000 kg/m^3. The samples were saturated during continuous measurement of swelling pressure and determination of hydraulic conductivity was also made. After these determinations one hole through each of the three specimens, with diameters of 3, 5 and 10 mm, were drilled. After healing and homogenization during approximately 5 weeks the hydraulic conductivity and swelling pressure were measured again. Swelling pressure and hydraulic conductivity before and after the drilling are shown in Table 2-10.

The hydraulic conductivities determined after drilling show that sealing of the drilled holes has occurred. The relatively small differences in the hydraulic conductivities between the three specimens also indicate that sealing has occurred. However, the values before the drilling seems high compared to other test results in this study and further tests are recommended.

Table 2-10. Results from the determination of swelling pressure and hydraulic conductivity made both after and before the drilling of holes. The tests were made with SFR water. The pressure difference at the hydraulic conductivity measurements was between 14 and18 kPa resulting in a pressure gradient between 19 and 22 m/m.

Sample No	Dry density	Swelling pressure		Hydraulic conductivity		Hole diameter
		Before	After	Before	After	
	(kg/m^3)	(kPa)	(kPa)	(m/s)	(m/s)	(mm)
SFR_Pk3_1	1,019*)	59	84	3.72E–10	1.73E–10	3
SFR_Pk3_2	1,028*)	65	76	4.57E–10	2.21E–10	5
SFR_Pk3_3	1,005*)	61	70	4.46E–10	1.91E–10	10

*) The target dry density at the preparation of the specimens was 1,000 kg/m^3.

2.6 Case 4: Modelling of the water uptake, laboratory tests

For modelling of the water uptake the water retention curve, swelling pressure and hydraulic conductivity are properties that need to be known. In order to verify water uptake properties, results from water uptake tests are also preferable. These test types and unconfined compression tests were made.

2.6.1 Determination of retention curve

The specific retention curve (for definition, see Dueck and Nilsson 2010) was determined on free swelling powder starting from a water content of 13.2%. Eight specimens were prepared in pans which were placed in glass jars containing salt solutions, generating constant relative humidity. The measurements were carried out at 25°C at the following different *RH* values 0%, 11%, 33%, 58%, 75%, 84%, 93% and 97%. Furthermore, additional results were obtained by psychrometer measurements on specimens with high water contents.

The result from the jar measurements are shown in Figure 2-9 together with the hydration and dehydration retention curves of MX-80 (Dueck and Nilsson 2010). The results are also shown in Table 2-11.

Table 2-11. Retention curve determined after equilibrium in salt solutions.

Relative humidity RH (%)	Water content w (%)
0.0	0.2
11.3	8.0
32.8	10.8
57.6	15.2
75.3	20.1
84.4	23.0
93.1	26.8
97.3	34.2

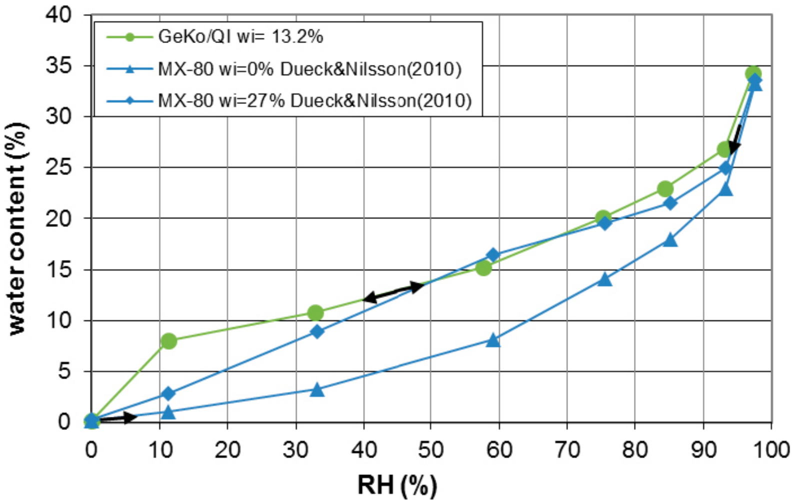


Figure 2-9. *Specific retention curve of GeKo/QI with results of hydration and dehydration retention curves of MX-80. The results were achieved from equilibrium with salt solutions at 25°C.*

To achieve results at higher relative humidity the water potential was measured by soil psychrometers (Wescor®) on GeKo/QI bentonite mixed with SFR water (see Section 2.4.1.3) and de-ionized water (to water contents about 35%, 48%, 56% and 67%). The results are shown in Figure 2-10 plotted together with parts of the retention curve shown in Figure 2-9. From the relative humidity, defined according to Equation 2-1, the corresponding water portential ψ (kPa) can be determined according to the thermodynamic equation, Equation 2-2, given by e.g. Fredlund and Rahardjo (1993, Chapter 4).

$$RH = 100 \cdot \frac{p}{p_s} \tag{2-1}$$

where

p = partial pressure of pore-water vapour (kPa)

p_s = saturation pressure of water vapour over a flat surface of pure water at the same temperature (kPa)

$$\psi = -\frac{R \cdot T}{v_{w0} \cdot \omega_v} \ln\left(\frac{p}{p_s}\right) \tag{2-2}$$

where

T = absolute temperature (K)

R = universal gas constant (8.31432 J/(mol K))

v_{w0} = specific volume of water ($1/\rho_w$ m^3/kg)

ω_v = molecular mass of water vapour (18 kg/kmol)

For each RH the measurements were made with two sensors using both the dew point method and the wet bulb method. The bars at each measurement show the maximum and minimum values. The calibration of the sensors were made with salt solutions which, to give high accuracy, requires higher temperature control than was possible to achieve in the present study where the temperature control was limited to 25°C ± 0.1°C. Thus the values presented in Figure 2-10 should be used as approximate values and the results show no clear difference between measurements above bentonite mixed with de-ionized and SFR water. For comparison reason the measuring results were also evaluated from the approximate calibration factors given by the manufacturer, which are shown in Appendix 2. Except the measurements at the water content of 35% the results show a similar trend.

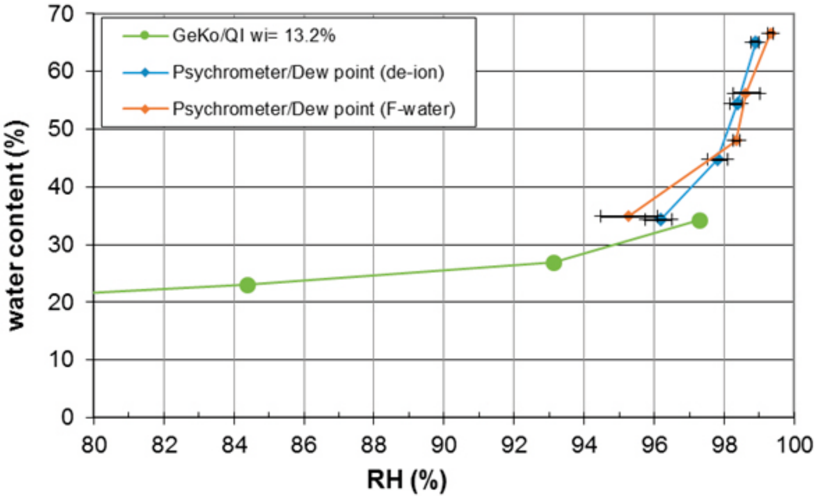


Figure 2-10. *Results from measurements of water potential with soil psychrometers on GEKO/QI bentonite at water contents about 35%, 48%, 56% and 67%. The bars mark the maximum and minimum values of relative humidity. Part of the retention curve in Figure 2-9 is also shown (green line).*

2.6.2 Water uptake tests

For the water uptake tests specimens were placed in rigid rings. The specimens had access to water from one end during specific time. After this time the tests were stopped and the water content and density were determined as a function of distance to the water inlet side.

Test results from these tests are shown in Figure 2-11 where the distribution of water content after 5 h, 1, 2 and 4 weeks are shown as a function of the distance from the water inlet. The initial dry densities of the samples were between 1,030 kg/m^3 and 1,100 kg/m^3 and the initial water content was 12.2%. The specimen diameter and height were 100 mm and 50 mm respectively and SFR water (see Section 2.4.1.3) was used for the tests.

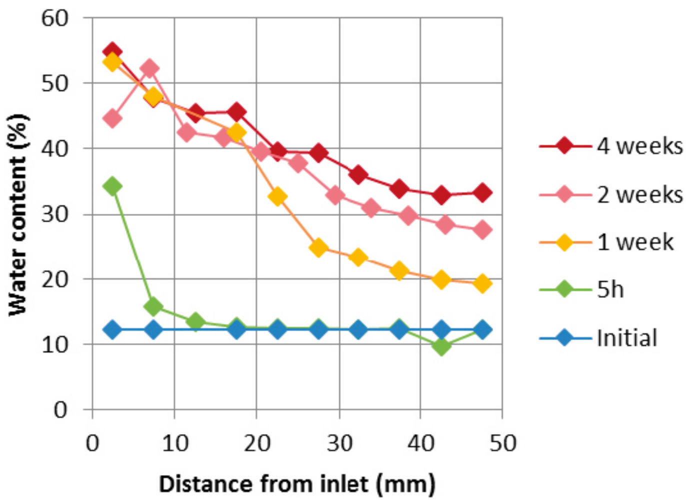


Figure 2-11. *Distribution of water content from water uptake tests on GeKo/QI samples with an initial dry density between 1,030 and 1,100 kg/m^3 and 50 mm height. The tests were interrupted after 5h, 1, 2 and 4 weeks. SFR water was used.*

2.6.3 Swelling pressure and hydraulic conductivity tests

The test procedure for this type of test is described in Section 2.3.1. The test referred to were made with de-ionized water while the tests described in this section were made with SFR water (see Section 2.4.1.3).

Specimens were compacted to a suitable density and SFR water was added after evacuation of air from tubes and filters surrounding the specimens. The swelling pressure was measured continuously during the saturation phase and when equilibrium was considered measurement of hydraulic conductivity was made.

Samples with a diameter of 50 mm and a height of approximately 15 mm were compacted to densities between 750 and 1,070 kg/m^3. The results from the measurements are presented in Table 2-12.

The measured swelling pressures are plotted as a function of the dry density together with other determinations of swelling pressure made within this project, see Figure 2-12. The yellow dots are measurements of swelling pressure made on the samples used for evaluation of self sealing ability, see Section 2.5, and where SFR water was used. The blue triangles represent measurements where de-ionized water was used (see Section 2.3.1) and thus show higher values than measurements where SFR water was used. The green dots represent measurements on GeKo/QI ion-exchanged to be Ca^{2+}dominated and consequently these values are lower than all other values.

Table 2-12. Test results from completed swelling pressure and hydraulic conductivity tests. The tests were made with SFR water.

Sample No	Dry density (kg/m^3)	Swelling pressure (kPa)	Applied pressure difference (kPa)	Pressure gradient (m/m)	Hydr. cond. (m/s)
SFR_Pk4_1	978	91.0	26	174	5.50E–11
SFR_Pk4_2	746	9.5	1	7	1.38E–05*)
SFR_Pk4_3	1,070	167.3	24	158	1.18E–11
SFR_Pk4_4	811	20.5	–	–	–
SFR_Pk4_5	841	33.7	–	–	–
SFR_Pk4_6	880	64.6	–	–	–

*) Uncertain value.

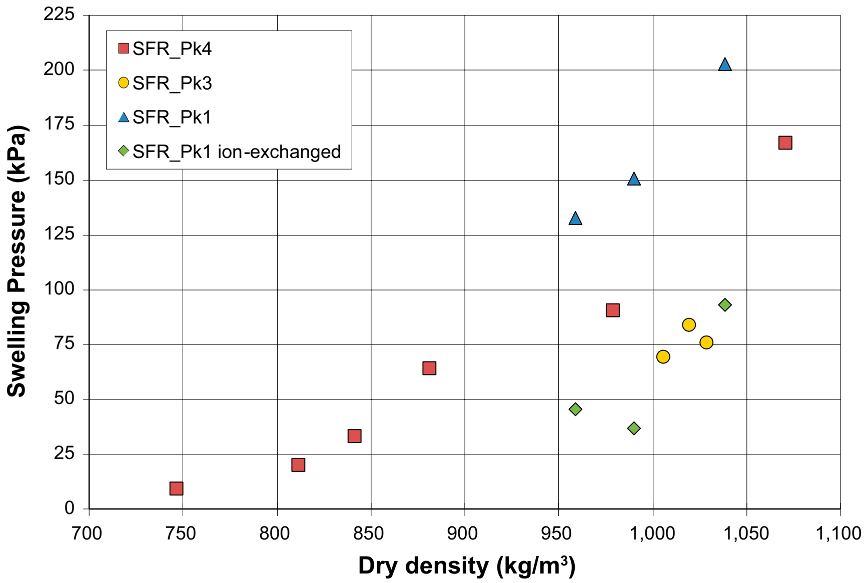


Figure 2-12. The swelling pressure as function of dry density for different water types, test types and dominating ion. The red squares are taken from Table 2-12. The yellow dots are taken from Table 2-10. The blue triangles are taken from Table 2-3 and the green diamonds are taken from Table 2-4.

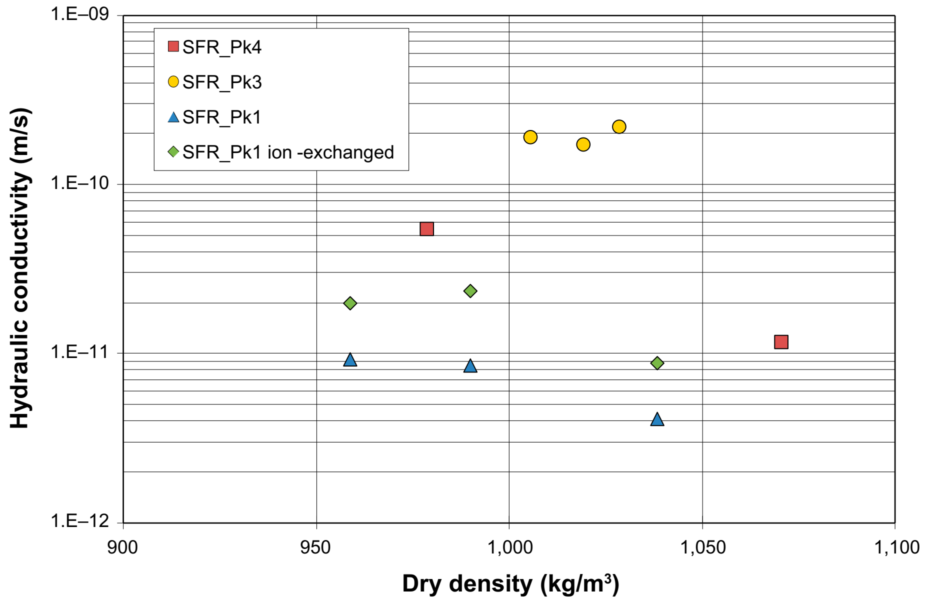


Figure 2-13. *The hydraulic conductivity as a function of dry density for different water type, test types and dominating ion. The red squares are taken from Table 2-12. The yellow dots are taken from Table 2-10. The blue triangles are taken from Table 2-3 and the green diamonds are taken from Table 2-4.*

The hydraulic conductivities measured within this project are plotted as a function of the dry density in Figure 2-13. The lowest value of hydraulic conductivity was measured with de-ionized water. The highest values were measured on the samples were the sealing ability was studied. These specimens also showed low swelling pressure.

The values of the swelling pressure and hydraulic conductivity are logical. The hydraulic conductivity for a dry density of 1,000 kg/m^3 seems to be lower than 5E–11 m/s. Corresponding value for the swelling pressure is about 100 kPa.

2.6.4 Unconfined compression tests

The unconfined compression test is an experimentally simple method where a cylindrical specimen is compressed axially under a constant rate of strain with no radial confinement or external radial stress. The maximum deviator stress during shearing is used as measure of the shear strength. The method is described in detail by e.g. Dueck et al. (2011).

Cylindrical specimens with diameter 25 mm and height 50 mm were prepared by compaction of material with different water contents to dry densities between 980 kg/m^3 and 1,450 kg/m^3. The different water contents were prepared by mixing GeKo/QI bentonite with an initial water content of 13.7% with SFR water (see Section 2.4.1.3) to the water contents of 35%, 45%, 58% and 68%. The tested specimens had a degree of saturation between 95 to 100%.

The specimens were placed in the mechanical press and the compression was run at a constant strain rate of 0.8%/min which corresponds to 0.4 mm/min for the actual specimens. During compression the specimens were surrounded by a thin plastic film to minimize evaporation of water. After failure the water content and density were determined. The results are shown as maximum deviator stress as a function of dry density in Figure 2-14. More details from the tests are shown in Appendix 3.

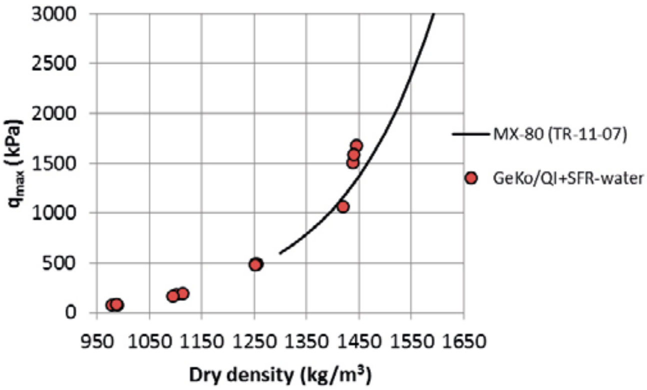


Figure 2-14. *The maximum deviator stress as a function of dry density from the unconfined compression tests. Results from GeKO/QI bentonite are compared with corresponding results from MX-80.*

2.7 Case 8: Analyses of the settlement of the packed sand fill of the silo top

A filling of sand on top of the silo (above the filling of a mixture of sand and bentonite, see Section 2.8) will probably be used at the closure and this filling will be compacted in situ. The most upper part of the filling close to the ceiling cannot be compacted properly and thus this part will have a low initial density.

Sand at low density can when it is disturbed change its density by settlement (resulting in a higher density) by several processes as:

1. Saturation
2. Creep (time dependent settlement)
3. Vibration

An optimum design of the filling requires that the effects of these processes for the chosen sand are known together with its compressibility and hydraulic conductivity. The density of a filling of sand and other friction materials compacted in situ is also dependent on the water content of the material at the installation. The maximum density of the filling is reached at specific water content. This water content and corresponding density are also important to know, in order to get an optimum filling. This is investigated with a so called Proctor test.

Sands of different types have been investigated in previous made investigations i.e. for the plug project at Äspö (Börgesson et al. 2015b). In this investigation three types of sands were tested. The results from the Proctor test are summarized in Table 2-13. This table includes also the lowest measured density of the material achieved when the material was carefully poured into a test cylinder.

At the testing of the hydraulic conductivity of the three materials at low densities two of them (Naural sand/gravel and MakPak® 0–5) showed a significant settlement at saturation. In Table 2-14 the hydraulic conductivity of the three investigated sands, determined at about 93–97% of the maximum density according to the Proctor test are shown. The results show high hydraulic conductivity values for all three materials.

Table 2-13. The maximum dry densities and the optimal water contents from the modified Proctor compaction tests performed by PEAB AB together with the lowest densities achieved when the material was carefully poured into a test cylinder (Börgesson et al. 2015b).

Material	Optimal water content	Max. dry density	Lowest dry density
Natural sand/gravel 0–4 mm	14–15%	1.74 g/cm^3	1.49 g/cm^3
MakPak® 0–5 mm	11–12%	1.96 g/cm^3	1.62 g/cm^3
Macadam 2–4 mm	1.5%	1.77 g/cm^3	1.38 g/cm^3

Table 2-14. The measured hydraulic conductivity of the three investigated sands for the plug project (Börgesson et al. 2015b).

Material	Dry density	Hydraulic cond.
Natural sand/gravel 0–4 mm	1.65 g/cm^3	2.49E–05 m/s
MakPak® 0–5 mm	1.92 g/cm^3	6.50E–06 m/s
Macadam 2–4 mm	1.66 g/cm^3	1.24E–04 m/s

The compressibility for the three investigated sands were determined with a so called CRS-test where the samples are placed in a rigid ring and a constant vertical deformation rate is applied to the sample during continuous measurement of the deformation and applied load, see Figure 2-15.

The results from the CRS-test are shown in Figure 2-16. The initial dry density for *MakPak® 0–5 mm* and for the *Natural sand/gravel 0–4 mm* was 1.59 g/cm^3 and 1.56 g/cm^3 respectively. The *Macadam 2–4 mm* was investigated at two different initial dry densities, 1.35 and 1.60 g/cm^3 respectively.

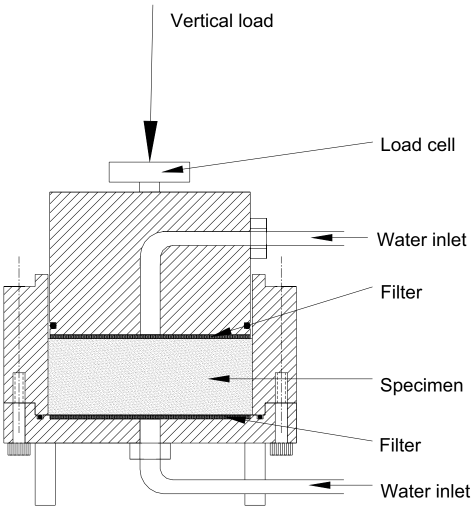


***Figure 2-15.** Schematic sketch of the CRS-test.*

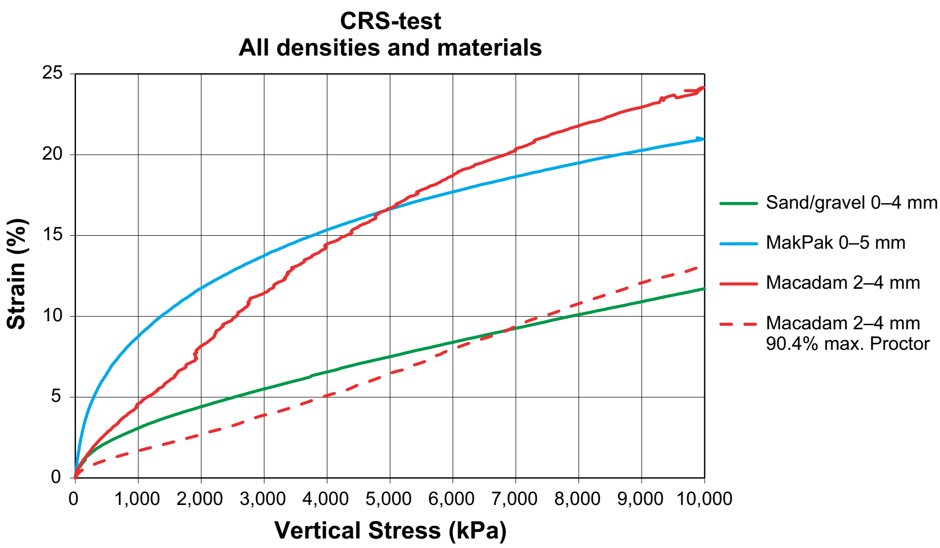


***Figure 2-16.** The compression strain plotted as a function of the vertical stress compared for all performed tests.*

Based on the given values of the described materials, the most suitable properties for the filling are achieved for the *Macadam 2–4 mm* compacted to 90% of max. Proctor. With a maximum height of the sand filling on top of the silo of about 10 m the expected and conservative maximum deformation of the sand itself will be less than 20 cm. This figure does not include the deformation of the bottom bed and the 10% bentonite and 90% sand filling on top. Furthermore, the expected deformation will be developed during the installation phase and thus can be compensated for at the emplacement. However, there might be practical problems at the installation of this high density filling (90% of max. Proctor) close to the ceiling of the silo which must be further investigated.

2.8 Case 9: Analyses of the hydro-mechanical behaviour of the bentonite/sand silo top

On the lid of the silo a filling with a mixture of bentonite and sand will probably be used, see Figure 1-1. This filling will be compacted in situ. In order to be able to select a suitable filling material the following parameters must be investigated:

1. Compaction properties.
2. Hydraulic conductivity.
3. Swelling pressure.
4. Compressibility.

Mixtures of bentonite and crushed rock have been used as backfill material both in the Backfill and Plug Test and in the Prototype Repository (30% MX-80 bentonite and 70% crushed rock). At the selection of the backfill material for these tests also 10/90 mixtures was investigated (Börgesson 2001, Chapter 6). The investigation of the compaction properties (Proctor tests) showed that the mixture of 10% bentonite and 90% crushed rock had a maximum dry density of about 2.16 g/cm^3 at a water content of about 8%. The hydraulic conductivity for this mixture at the dry density of 2.00 g/cm^3 was determined to be between 1E–11 and 1E–10 m/s. The compressibility for this mixture expressed as a compression module (M) was evaluated to about 50–70 MPa. No direct measurement of the swelling pressure was made, but data from oedometer test indicates that the swelling pressure at a density of about 2.00 g/cm^3 was about 200 kPa.

2.9 Case 10: Analyses of what happened with the bentonite/sand bottom bed and the hydro-mechanical evolution

At the installation of the bottom bed with an approximate height of 1.5 m a mixture of 10% GeKo/QI bentonite and 90% sand was used as filling material. The filling was compacted in layers of 0.2 m to an average dry density of 2,170 kg/m^3 (Pusch 2003). No sensors were installed in the bottom bed (sensors for measuring total pressure and water pressure were installed in the surrounding slot). After the installation of the silo the deformation of the silo top were measured in totally four positions. Furthermore, the total weight (including the weight of the silo and deposited waste) was noted. From this data, the strain and the vertical stress on the bottom plate of the silo can be calculated, see Figure 2-17. The diagram is indicating that after an initial relatively large deformation the strain of the bottom filling is proportional to the applied vertical stress on the bottom plate. The evaluated modulus ($M = \Delta\sigma/\Delta\varepsilon$) from the diagram is calculated to 34 MPa.

The final deformation will depend on the evolution of the filling of the silo (the maximum applied load on the bottom plate of the silo) but also on the behavior of the material when it will be further saturated. The degree of saturation of the bottom filling is unknown at this stage.

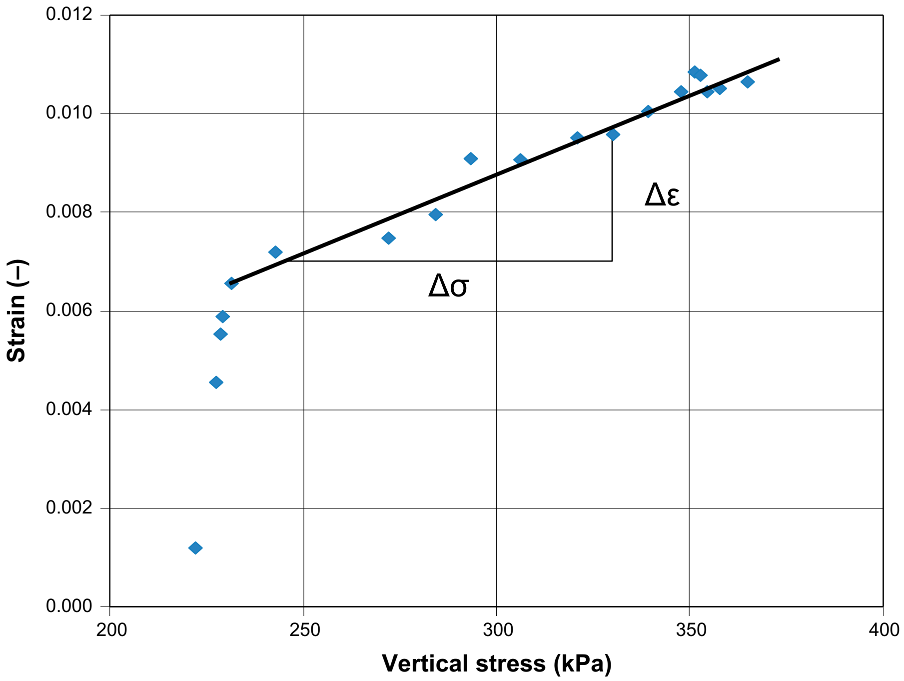


Figure 2-17. The strain of the bottom filling as function of the applied vertical stress on the plate of the silo.

3 Conclusions and discussion

The main part of the results in this report is presented to be used for the analyses of important hydro-mechanical processes in the silo repository. Based on the results of these tests the following observations, comments and recommendations are given.

The following observations could be made:

- An effect of the ion-exchange, making the bentonite Ca-dominated, was seen on the determined variables; swelling pressure, hydraulic conductivity, liquid limit and free swelling.
- The values of the swelling pressure and hydraulic conductivity are logical. The hydraulic conductivity for a dry density of 1,000 kg/m^3, measured with SFR-water, seems to be approximately 5E–11 m/s. Corresponding value for the swelling pressure is about 100 kPa.
- The swelling pressures measured on the original material are somewhat lower than expected compared to measurements on MX-80 bentonite with the same density. The effect of ion exchange to Ca^{2+} was also less than expected. The hydraulic conductivity measured on the GeKo/QI bentonite was somewhat higher compared to expected values measured on MX-80 bentonite with the same density.
- The erosion tests resulted in a measured erosion rates that is within the erosion limits proposed by Sandén and Börgesson (2010).
- The sealing tests indicate that the bentonite has potential to seal erosion channels but more tests are recommended.

The following comments are important for the interpretation and further use of the results:

- The equipment and methodology used in this study are usually used in a higher range of densities and thus higher pressures. This means that some of the test results suffer from an error which due to the low pressures measured in the present study becomes relatively large. However, in the tests where the relation between density and pressure were the main task, arrangements were taken to minimize these effects by for example use of special pistons of low weight material (peek) and by use of a special type of calibration.
- Equilibrium was not always achieved at termination of the tests. This was for example seen in the measured swelling pressure. It is not clear if this is an effect of the methodology, the solutions used or if it can be considered as a material property.

The following studies are recommended for further analyses:

- Since the material used for the present laboratory study was sampled in-situ, further tests on the chemical-mineralogical properties are suggested.
- In order to decrease the statistical uncertainty, more tests on the hydraulic conductivity and swelling pressure are recommended.
- Some further oedometer tests with loading and unloading are desirable. These tests should be made in a lower range of density compared to those already made. In addition to tests on GeKo/QI bentonite oedometer tests on ion-exchanged GeKo/QI bentonite being ion exchanged during the ongoing tests are suggested.
- Further tests are also recommended concerning the self sealing ability of the bentonite.
- Laboratory tests on the bentonite/sand filling materials are suggested especially to determine the behavior after saturation.

References

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

Andersson L, Sandén T, 2012. Optimization of backfill pellets properties. ÅSKAR DP2. Laboratory tests. SKB R-12-18, Svensk Kärnbränslehantering AB.

Auqué L F, Gimeno M, Acero P, Gómez J, 2013. Compositions of groundwater for SFR and its extention, during different climatic cases, SR-PSU. SKB R-13-16, Svensk Kärnbränslehantering AB.

Börgesson L, 2001. Äspö Hard Rock Laboratory, Compilation of laboratory data for buffer and backfill materials in the Prototype Repository. SKB IPR-01-34, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, Dueck A, Andersson L, Jensen V, Nilsson U, Olsson S, Åkesson M, Kristensson O, Svensson U, 2015a. Consequences of water inflow and early water uptake in deposition holes – EVA-project. SKB TR-14-22, Svensk Kärnbränslehantering AB.

Börgesson L, Sandén T, Andersson L, Johannesson L-E, Goudarzi R, Åkesson M, 2015b. System design of Dome Plug. Preparatory modelling and tests of the sealing and draining components. SKB R-14-25, Svensk Kärnbränslehantering AB.

Dueck A, Nilsson U, 2010. Thermo-hydro-mechanical properties of MX-80. Results from advanced laboratory tests. SKB TR-10-55, Svensk Kärnbränslehantering AB.

Dueck A, Börgesson L, Johannesson L-E, 2010. Stress-strain relation of bentonite at undrained shear. Laboratory tests to investigate the influence of material composition and test technique. SKB TR-10-32, Svensk Kärnbränslehantering AB.

Dueck A, Johannesson L-E, Kristensson O, Olsson S, 2011. Report on hydro-mechanical and chemical-mineralogical analyses of the bentonite buffer in Canister Retrieval Test. SKB TR-11-07, Svensk Kärnbränslehantering AB.

Fredlund D G, Rahardjo H, 1993. Soil mechanics for unsaturated soils. New York: Wiley.

Johannesson L-E, Nilsson U, 2006. Deep repository – engineered barrier systems. Geotechnical behaviour of candidate backfill materials. Laboratory tests and calculations for determining performance of the backfill. SKB R-06-73, Svensk Kärnbränslehantering AB.

Karnland O, Olsson S, Nilsson U, 2006. Mineralogy and sealing properties of various bentonites and smectite-rich clay minerals. SKB TR-06-30, Svensk Kärnbränslehantering AB.

Karnland O, Nilsson U, Weber H, Wersin P, 2008. Sealing ability of Wyoming bentonite pellets foreseen as buffer material – Laboratory results. Physics and Chemistry of the Earth 33, S472–S475.

Pusch R, 2003. Design, construction and performance of the clay-based isolation of the SFR silo. SKB R-03-30, Svensk Kärnbränslehantering AB.

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

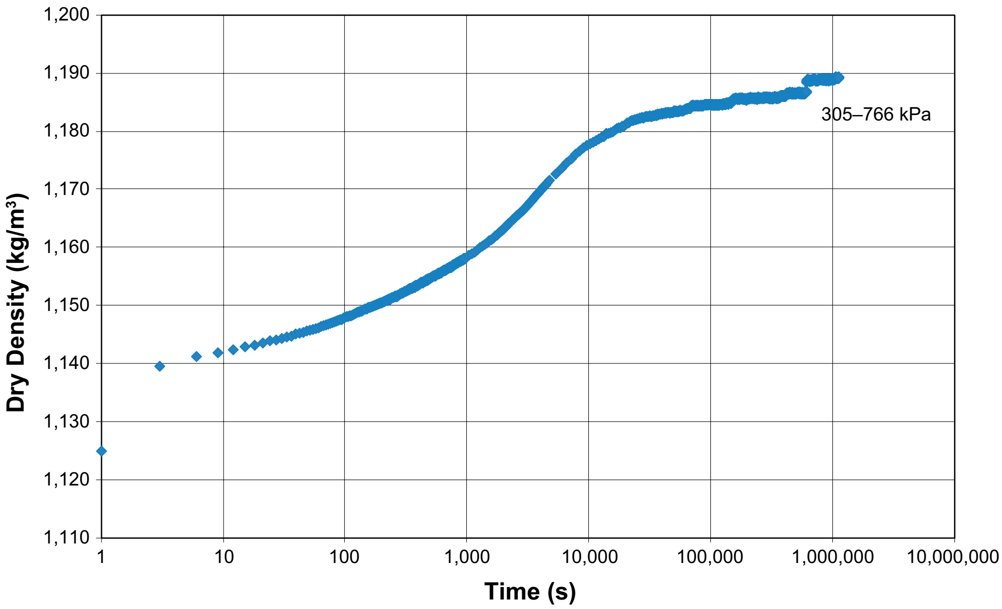
Sandén T, Börgesson L, Dueck A, Goudarzi R, Lönnqvist M, 2008. Deep repository – Engineered barrier system. Erosion and sealing processes in tunnel backfill materials investigated in laboratory. SKB R-08-135, Svensk Kärnbränslehantering AB.

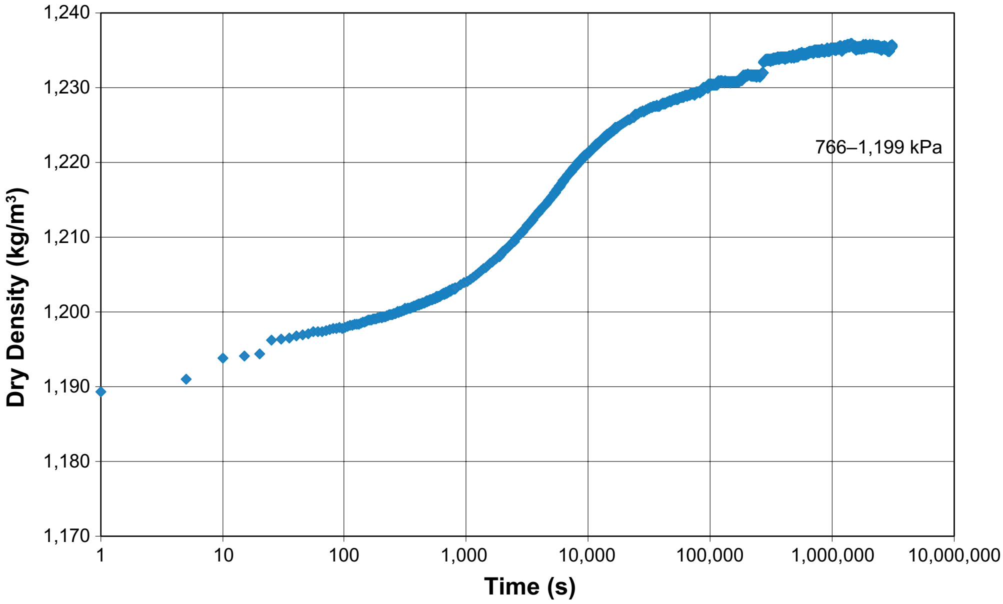
SKB, 2008. Safety analysis SFR 1. Long-term safety. SKB R-08-130, Svensk Kärnbränslehantering AB.

Appendix 1

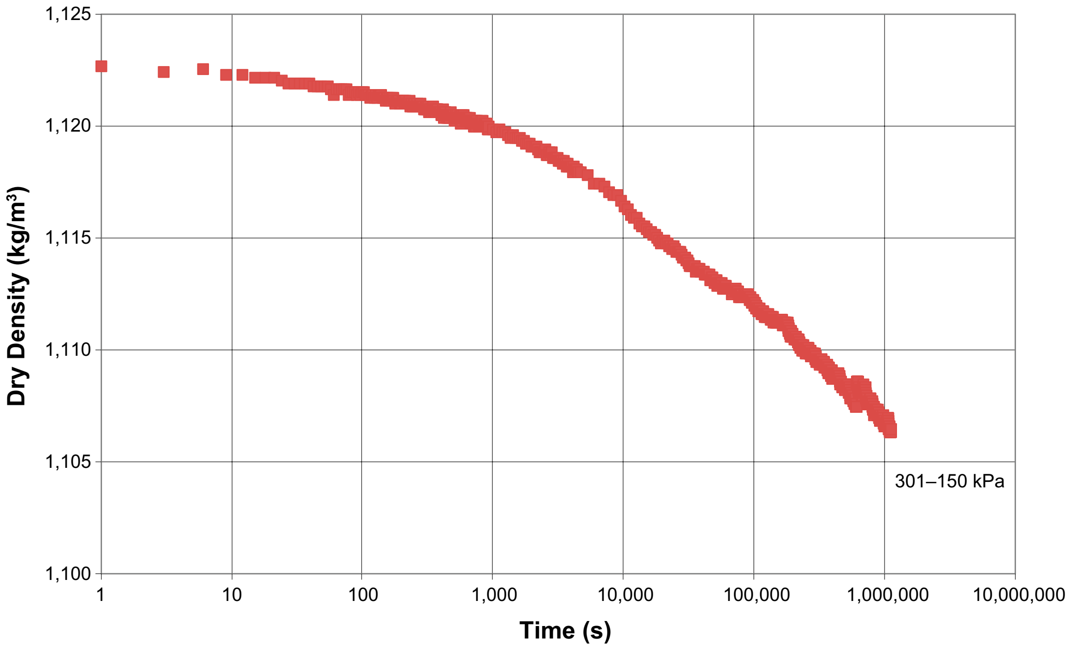
Results from oedometer tests

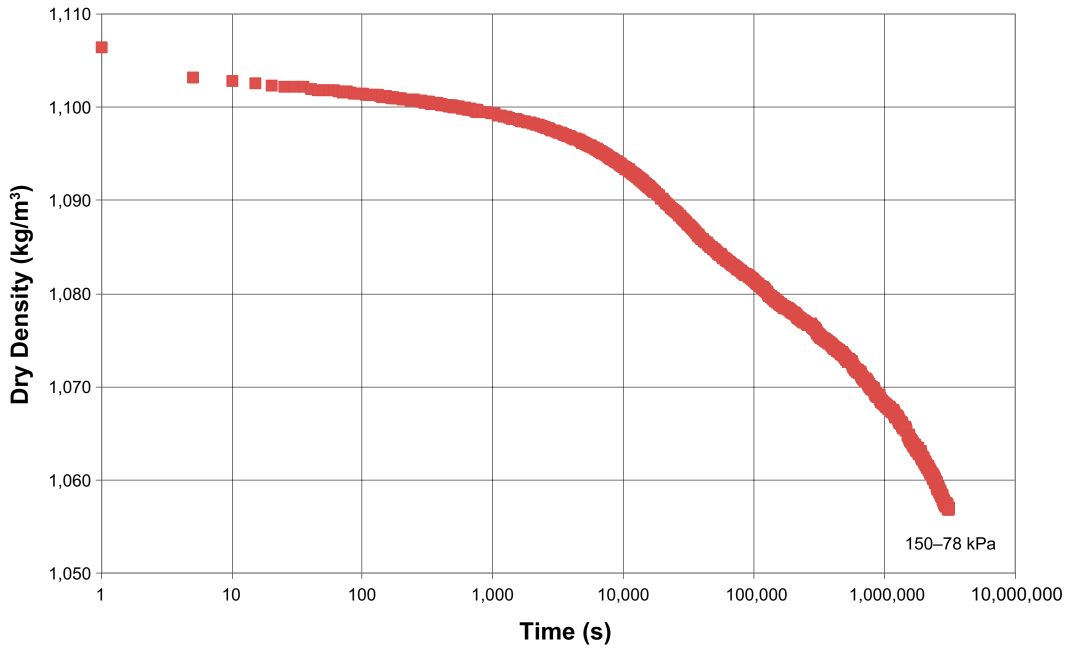
Results from oedometer test No SFR_OE1_1. The dry density of the samples as function of time for the two loading steps.



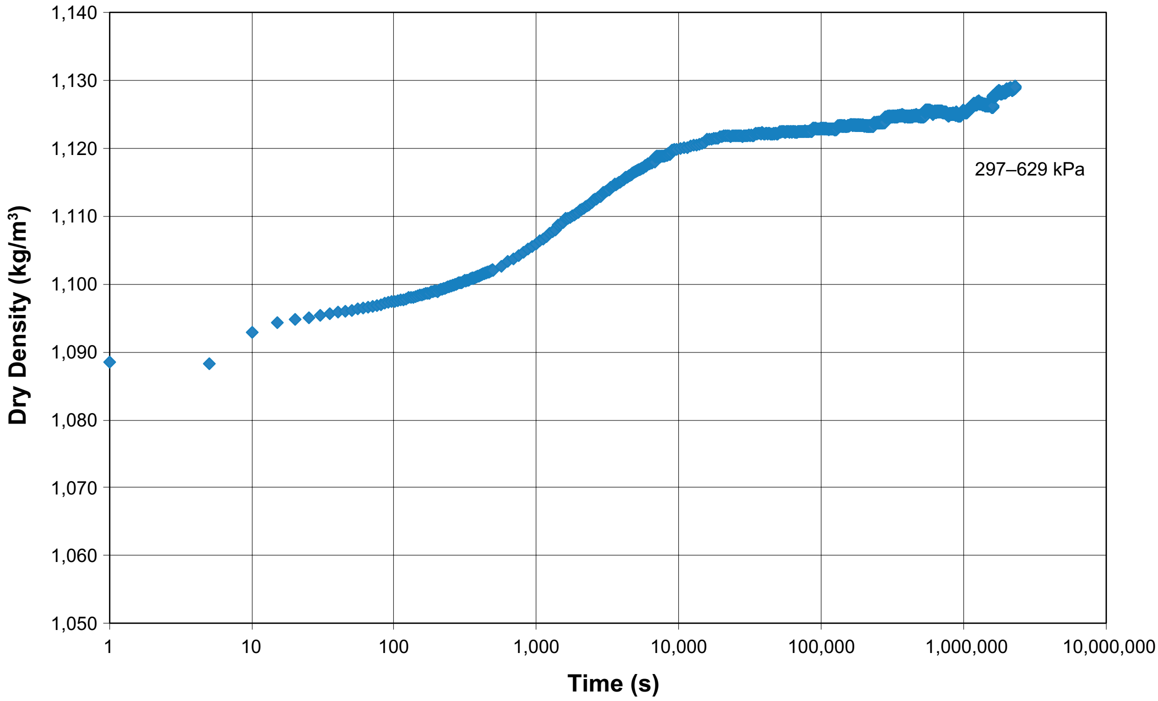


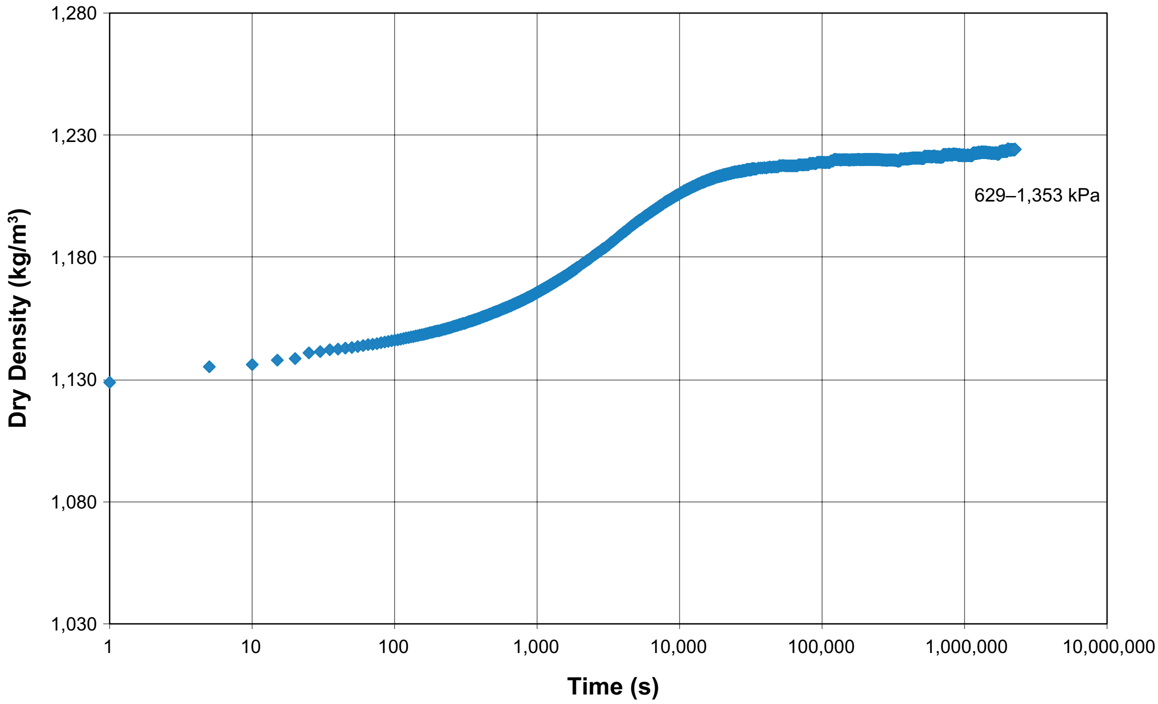
Results from oedometer test No SFR_OE1_2. The dry density of the samples as function of time for the two steps of unloading.



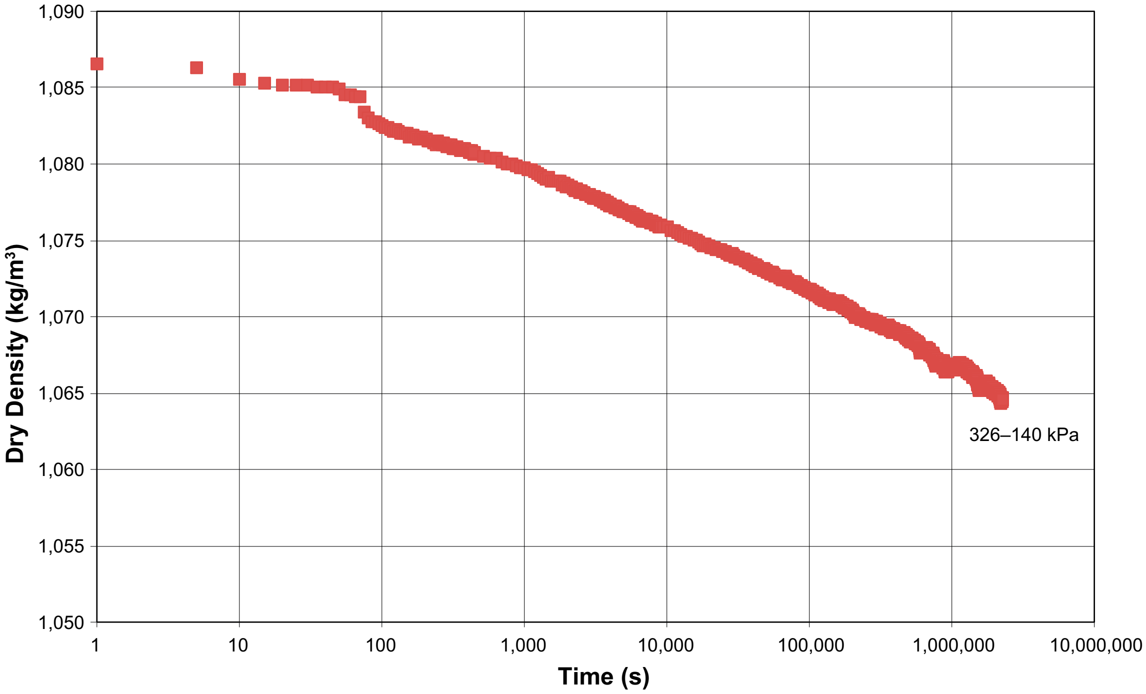


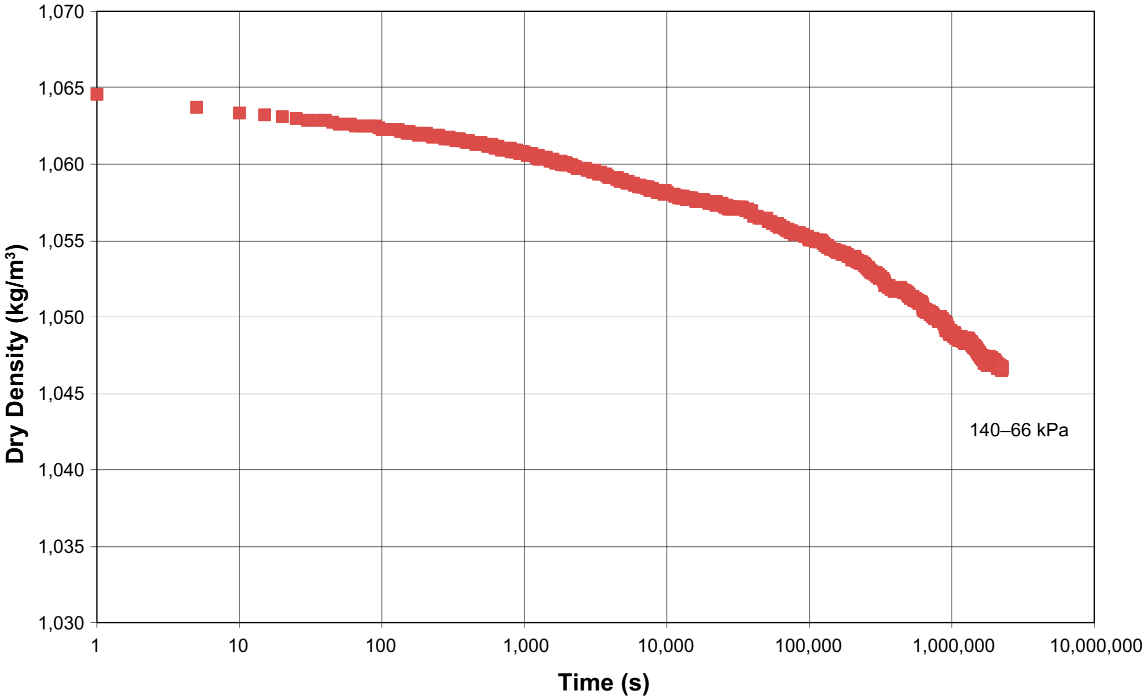
Results from oedometer test No SFR_OE1_3. The dry density of the samples as function of time for the two steps of unloading.





Results from oedometer test No SFR_OE1_4. The dry density of the samples as function of time for the two steps of unloading.

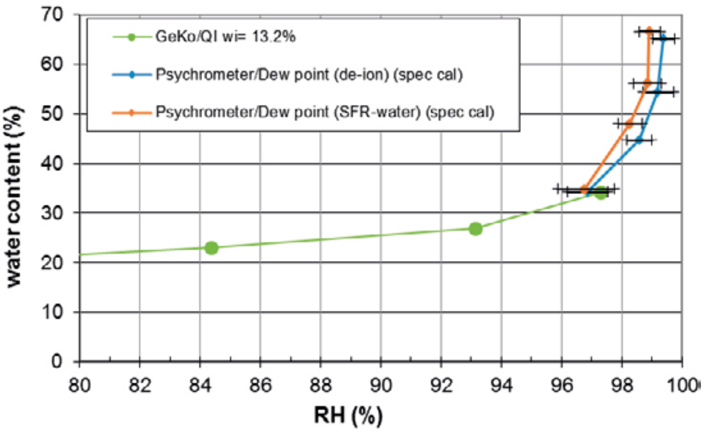




Appendix 2

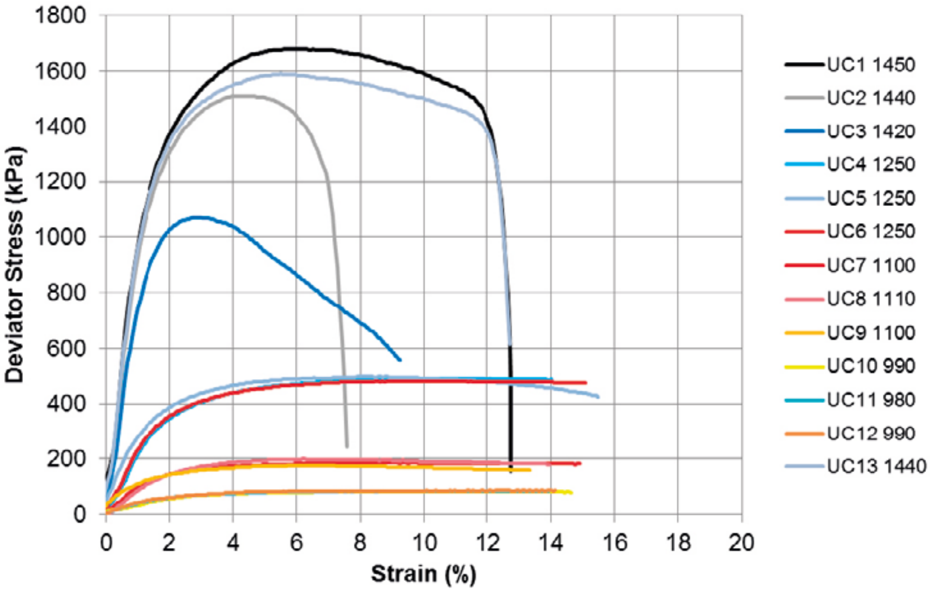
Additional evaluation of measured water potential

Measurements of water potential were made with soil psychrometers according to Section 2.6.1. As a complement to that evaluation made by use of calibrations made within the project (Figure 2-10) the evaluation was also made by use of the approximate calibration values given by the manufacturer, see below.



Results from unconfined compression tests

Results from unconfined compression tests. The deviator stress is plotted as a function of strain and the dry densities are presented in the legend. In addition, the resulting water contents, dry density, maximum deviator stress and corresponding strain are show in the table below.



Water content w (%)	Dry density ρ_d (kg/m³)	Maximum deviator stress q_{max} (kPa)	Strain at qmax ε (%)
33.4	1,445	1,680	6.0
33.3	1,437	1,510	4.3
33.3	1,418	1,070	2.9
44.5	1,252	490	11.2
44.4	1,254	500	8.1
44.8	1,251	480	10.2
55.3	1,102	180	9.0
54.2	1,113	200	6.3
55.7	1,094	180	6.3
65.3	989	80	9.6
66.4	978	80	11.4
65.6	987	90	11.9
33.8	1,440	1,590	5.5

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

skb.se

Arkitektkopia AB, Bromma, 2015