R-06-73

Deep repository – engineered barrier systems

Geotechnical behaviour of candidate backfill materials

Laboratory tests and calculations for determining performance of the backfill

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Clay Technology AB

November 2006

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Executative summary

SKB in Sweden and Posiva in Finland are developing and implementing similar disposal concepts for the final disposal of spent nuclear fuel. A co-operation and joint development work between Posiva and SKB with the overall objective to develop backfill concepts and techniques for sealing and closure of the repository have been going on for several years. There are two main reasons to perform more research and development concerning the backfilling concept. 1) The location of the deep repository will be in a rock formation were ground water with salinity higher than 1% may occur and this influences the function of the previously considered backfill materials in a negative way (a ground water salt content of 3.5% will be used as design basis in this study) and 2) The need to develop backfilling concepts for other excavations (caverns, transport tunnels, shafts and ramps) of the repository. There are also other reasons such as developing the installation procedures so that the long time requirements can be fulfilled.

In this report 5 natural clays and 7 different mixtures of ballast and clay have been investigated in the laboratory. All the investigated materials are potential backfill materials. The objective of the investigation is to find the density of the materials required to fulfil certain requirements. Furthermore static compaction tests on some of the materials have also been made. The purpose with these tests is to find out the expected densities of pre-compacted blocks of the materials and how the density is depending on the water ratio of the materials and the compaction stress.

The requirements on the investigated materials used in this report are as follows:

- The swelling pressure of the backfill should not be smaller than 200 kPa.
- The hydraulic conductivity of the backfill should be lower than 1E–10 m/s.
- The compression of the backfill caused by the swelling of the buffer in the deposition hole should not be so large that the density of the buffer at the top of the canister is lower than 1,950 kg/m^3.

These requirements are based on the function indicators stated in SR-Can, see for example /1-2/. The requirement on swelling pressure was increased to 200 kPa from the 100 kPa stated as function indicator. The main reason for this was that relative influence of the friction in the oedometer is less at higher swelling pressure resulting in a more accurate measurement.

The function indicators are valid after the backfill has homogenised and been fully saturated. How high the safety margin needs to be to ensure sufficient homogenisation, account for long time degradation etc is not addressed.

The densities for the different investigated backfill materials in order to fulfil the requirements are listed in Table 1.

The main conclusion from Table 1 is that, except for the 30/70 mixtures, the highest density needed to fulfil the requirements are concerning compression. For the 30/70 mixtures the highest density is needed to ensure that the hydraulic conductivity of 1E–10 m/s and swelling pressure of 200 kPa are maintained.

Table 1. The dry densities for the different investigated backfill materials in order to fulfil the requirements together with the reachable dry densities.

Material-types	Required dry densities (kg/m^3) based on: Hydraulic conductivity	Swelling pressure	Deformation properties
Asha 230	1,120	1,050	1,160
Milos bf	1,090	1,060	1,240
DJP	1,220	1,240	1,400
Friedland	1,400	1,350	1,510
30/70 mixtures	1,700–1,890*	1,730–1,800	1,690
50/50 mixture	1,280	1,450	1,560

* For this interval the extrapolated densities from Table 4-1 are excluded.

Contents

1 Introduction

SKB in Sweden and Posiva in Finland are developing and implementing similar disposal concepts for the final disposal of spent nuclear fuel. A co-operation and joint development work between Posiva and SKB with the overall objective to develop backfill concepts and techniques for sealing and closure of the repository have been going on for several years. There are two main reasons to perform more research and development concerning the backfilling concept. 1) The location of the deep repository will be in a rock formation were ground water with salinity higher than 1% may occur and this influences the function of the previously considered backfill materials in a negative way (a ground water salt content of 3.5% will be used as design basis in this study) and 2) The need to develop backfilling concepts for other excavations (caverns, transport tunnels, shafts and ramps) of the repository. There are also other reasons such as developing the installation procedures so that the long time requirements can be fulfilled.

Other problem areas that have been identified in the previous work are backfilling tunnels with high water inflow and to achieve a high efficiency in the backfilling operation.

The work is divided into 4 phases:

1. The first phase of the work has already been performed and reported, and consisted of desk studies to identify options and select preferred concepts for further studies /1-1/. One outcome from the work done in phase 1 was the choice of three concepts for further studies in phase 2.
2. In phase 2, preliminary experiments and more profound analysis of the chosen concepts will be done in order to be able to select very few main alternatives. For the different concepts several types of clays and mixtures of clays and ballast are considered. This report deals with laboratory tests made on the chosen types of backfill materials.
3. In phase 3 pilot tests will be made for verifying engineering feasibility of the main alternatives of backfill
4. In phase 4 large field tests will be performed.

The requirements on the investigated materials used in this report are as follows:

- The swelling pressure of the backfill should not be smaller than 200 kPa.
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These requirements are based on the function indicators stated in SR-Can, see for example /1-2/. The requirement on swelling pressure was increased to 200 kPa from the 100 kPa stated as function indicator. The main reason for this was that relative influence of the friction in the oedometer is less at higher swelling pressure resulting in a more accurate measurement.

The function indicator for the compression properties of the backfill stated in SR-Can is M > 10 MPa. In this report a more advanced method of calculating the change in buffer density as an effect of backfill deformation is applied. The requirement used in this report is that the buffer must stay above the density limit 1,950 kg/m^3 at the top of the canister.

The function indicators are valid after the backfill has homogenised and been fully saturated. How high the safety margin needs to be to ensure sufficient homogenisation, account for long time degradation etc is not addressed in this report.

The investigated backfill materials can be divided into two main groups, natural clays and mixtures of clays and ballast. The following types of natural clays have been investigated:

1. Indian bentonite (from Ashapura) named **Asha 230.**
2. Greek bentonite named **Milos Bf.**
3. Czech bentonite named **Dnesice-Plzensko Jih (DPJ).**
4. German bentonite named **Friedland.**

The characterisations of these clays are described in Section 2.

For the tests made with mixtures the following bentonites have been used:

1. Wyoming bentonite (natural Na-bentonite) named **MX-80.**
2. Wyoming bentonite (natural Na-bentonite) named **SPV200.**
3. Greek bentonite (natural Ca-bentonite) named **IBECO Deponit-CA-N.**

Also these clays are described in Section 2.

The ballast materials that were used for (see Section 2.2) the mixtures are the following:

1) Sand named **Ballast A.**
2) Crushed rock, with maximum grain size 5 mm and with no fine soil, named **Ballast B.**
3) Crushed rock, with maximum grain size 5 mm and with about 10–15% content of fine soil, named **Ballast C.**

The ballast materials used in the tests were also studied in a parallel work package (WP2) in Finland /1-3/. The aim of this work was to study the effect of ballast material properties (e.g. grain size distribution, amount of fine fraction, grain shape etc) on the compactibility of the bentonite/ballast mixture. Therefore, three different type of crushed rock were produced from Olkiluoto mica-gneiss: ballasts OL1, OL2 and OL3. The main differences between these three materials were the grain size distribution and the maximum grain size. The crushed rock used as ballast material in this particular study was named as ballast OL2a which corresponds to ballast C in this study and OL2b which corresponds to ballast B. The sand (ballast A) was also the same in both studies.

Previous performed tests on bentonite and backfill materials indicate that their properties (swelling pressure, hydraulic conductivity etc) are very much affected by the salinity of the pore water. In the performed tests, the backfill materials have been mixed and saturated with water with different salinity in order to investigate its influence on the tests results. The water types used are described in Section 2.3.

The backfill can be placed in the tunnel in principal in two ways, compacted in situ in the tunnel or by placing blocks of backfill material in the tunnel. The second technique must be combined with filling of the space between the rock surface and the blocks with pellets of bentonite in order ensure full contact between the backfill and the tunnel. Independent of the installation technique it is important that the saturated and homogenised backfill has sufficiently low hydraulic conductivity. The new tests for evaluating the hydraulic conductivity together with previous performed tests are described in Section 4. It is also important to make sure that the density of the backfill is high enough to get a swelling pressure against the tunnel wall. If the swelling pressure of the backfill is too low there is a risk that contact between the backfill and the tunnel might be to poor. Based on the performance requirements, the required swelling pressure is 100 kPa, but in order to study the robustness of the system, swelling pressure of 200 kPa was used as a target value in this study. This value was assumed to have sufficient safety margin in order to reach the required 100 kPa swelling pressure also in the long-term, e.g. despite of minor mineralogical changes. The results from the measurements of the swelling pressure of the investigated backfill materials together with previous performed tests are described in Section 3. It is also of great importance that the backfill materials can withstand a high pressure from the swelling buffer material without large compression. The compressibility of the backfill materials are investigated by oedometer tests. The tests together with the results are described in Section 5. Tests for evaluating the possibility to make blocks of the investigated backfill materials are described in Section 6. The materials are compacted with two compaction pressures (25 and 50 MPa) and at different water ratios. The results from the oedometer tests together with assumptions about the achievable densities of the backfilling are used for calculating expected displacement of the backfill and corresponding swelling of the buffer in a deposition hole. The results from such calculations are described in Section 7.

2 Characterisation of tested materials

2.1 Clay types

A characterization of the used clays was made before the actual tests on the backfill materials started. The characterization involved determination of following "parameters"; water ratio, normalized free swelling and liquid limit. In Table 2-1 the parameters are listed for all the clay types used in this project.

The initial water content defined as the weight of the water in the sample divided with the weight of the solid particles varied between 6–17%.

For determination of the normalized free swelling, 1.1 g clay was carefully poured in a measuring glass filled with 100 ml de-ionized water. After 24 hours the volume of the clay gel was determined and normalized with respect to the weight of solid particles. The expected value for MX-80 is about 15–20 ml. The value for SPV200 should be in the same range since it is the same type of clay but with another granule size distribution. The free swelling volume of the rest of the clays is significant lower than for the Wyoming bentonite (see Table 2-1).

The definition of the liquid limit (w_L) of a soil is the water content where the soil transforms from plastic to liquid state. This parameter is for a bentonite correlated to parameters as swelling pressure and hydraulic conductivity. The liquid limit was determined with the fall-cone method. The method is described by the Swedish Geotechnical Society (SGF) /2-1/. The expected liquid limit for MX-80 is 450–550%. The liquid limit for the rest of the clays is significantly lower (Table 2-1).

The content of the swelling minerals in the clays are also listed in the table. The figures are preliminary.

Table 2-1. Parameters determined on the used clays.

Clay type	Initial water ratio (%)	Normalised free swelling (ml)	Liquid limit (%)	Swelling minerals* (%)
Asha 230	15.6	8.4	180	60–65
Milos backfill	10.7	5.0	150	50–60
DPJ	6.1	4.8	109	35–45
Friedland	6.4	7.7	109	25–35
Deponit CA-N	16.3	5.3	157	80–85
MX-80	8.8	20.8	524	80–85
SPV200	9.0	16.8	552	80–85

* Preliminary data from Clay Technology /2-2/.

2.2 Ballast

Three types of ballast were used in the tests. They were delivered by Posiva and are further described in /1-3/. The ballast materials used for the mixtures were the following:

1) Sand named **Ballast A.**
2) Crushed rock, with maximum grain size 5 mm and with no fine soil, named **Ballast B.**
3) Crushed rock, with maximum grain size 5 mm and with about 10–15% content of fine soil, named **Ballast C.**

The gain size distribution for two of the ballast materials are shown in Figure 2-1. Ballast A is a sand with a grain size between 0.5 and 1.2 mm. The amount of bentonite in the mixtures varied between 30–50%.

2.3 Water

The performed tests were made with the following water; distilled water, water with salinity of 3.5% (50/50 $NaCl/CaCl_2$) and water with 7% salinity. The water types are named **Water I**, **Water II** and **Water III** in this report. The different types of water were used both at the saturation of the samples and when water was percolated trough the samples at the tests done for determining the hydraulic conductivity.

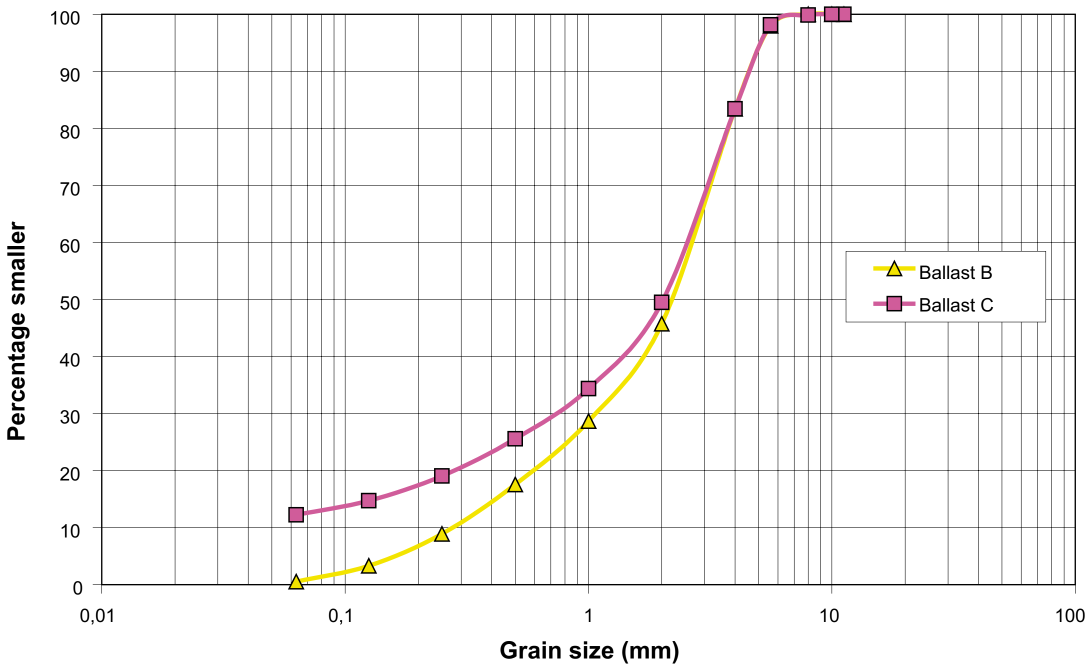

***Figure 2-1.** Grain size distribution for the used ballast materials.*

2.4 Natural clays

The four clays Asha 230, Milos I, DPJ and Friedland were investigated without addition of ballast material. The water was added to the samples after the material had been placed in the oedometers. In Table 2-2 the investigation matrix for the different clays is shown. The swelling pressure and the hydraulic conductivity were measured (see Section 3 and 4) on all 28 samples in the matrix, while oedometer tests were performed on samples marked with red cells in the table (see Section 5). Compaction tests were performed on samples having yellow cells in Table 2-2 (see Section 6).

2.5 Mixtures

Some of the clays (MX-80, SPV200 and Deponit CA-N) were mixed with the three types of ballast material to yield a backfill material. The clays and the ballast material had their natural water ratio during the mixing and the water was added to the samples after the material had been placed in the oedometers. The ballast and the clays were mixed by hand. Table 2-3 shows the matrix with the different mixtures. The swelling pressure and the hydraulic conductivity were measured on all 49 mixtures (see Section 3 and 4) while also oedometer tests were made on mixtures marked with red cells in the table (see Section 5). Compaction tests were performed on the mixtures having yellow cells (see Section 6).

Table 2-2. The different "natural clays" investigated in the project.

Clay type	Water I	Water II			Water III		
	Dens 1	Dens 1	Dens 2	Dens 3	Dens 1	Dens 2	Dens 3
Asha 230	1:1	1:2	1:3	1:4	1:5	1:6	1:7
Milos I	2:1	2:2	2:3	2:4	2:5	2:6	2:7
DPJ	3:1	3:2	3:3	3:4	3:5	3:6	3:7
Friedland	4:1	4:2	4:3	4:4	4:5	4:6	4:7

Table 2-3. The different mixtures investigated in the project.

Mixture	Water I	Water II			Water III		
	Dens 1	Dens 1	Dens 2	Dens 3	Dens 1	Dens 2	Dens 3
MX-80/Ballast B, 30/70*	Mix 1:1	Mix 1:2	Mix 1:3	Mix 1:4	Mix 1:5	Mix 1:6	Mix 1:7
SPV200/Ballast B, 30/70	Mix 2:1	Mix 2:2	Mix 2:3	Mix 2:4	Mix 2:5	Mix 2:6	Mix 2:7
Deponit CA-N/Ballast B, 30/70	Mix 3:1	Mix 3:2	Mix 3:3	Mix 3:4	Mix 3:5	Mix 3:6	Mix 3:7
Deponit CA-N/Ballast B, 40/60	Mix 4:1	Mix 4:2	Mix 4:3	Mix 4:4	Mix 4:5	Mix 4:6	Mix 4:7
Deponit CA-N/Ballast B, 50/50	Mix 5:1	Mix 5:2	Mix 5:3	Mix 5:4	Mix 5:5	Mix 5:6	Mix 5:7
Deponit CA-N/Ballast A, 30/70	Mix 6:1	Mix 6:2	Mix 6:3	Mix 6:4	Mix 6:5	Mix 6:6	Mix 6:7
Deponit CA-N/Ballast C, 30/70	Mix 7:1	Mix 7:2	Mix 7:3	Mix 7:4	Mix 7:5	Mix 7:6	Mix 7:7

* 30% MX-80 and 70% Ballast B.

3 Measurements of swelling pressure

3.1 Introduction

In order to determine the swelling pressure of the clay material a sample was placed in an oedometer with constant volume and the pressure was measured while the sample was saturated. An amount of material was weighed and placed in an oedometer, (see Figure 3-1) and compacted in the oedometers. After compaction the air was evacuated before the filters were filled with water. A water pressure of 20 kPa was applied and kept constant during the saturation of the sample (without circulation). The nominal dimensions of the oedometer sample were Ø 50 mm and height 20 mm. The density of the backfill was chosen with the aim to achieve a swelling pressure (p_s) of 200 kPa. If the material was previously tested some guidance could be used, otherwise the density was estimated. The swelling pressure (p_s) was measured with a force transducer.

The same equipment and material was used to measure the hydraulic conductivity (see Section 4). After ending the measurements the oedometer was disassembled and the sample was examined. The dimensions and the mass of the sample were measured. Thereafter the sample was divided into two parts. One part was used to measure the density by immersion in liquid paraffin and the other part was oven dried (105°C for 24 h) to determine water ratio.

3.2 Test results

Figure 3-2 shows an example of how the swelling pressures (p_s) evolve over time. The first sample (Fl 01) is saturated with deionised water (water I), the three following samples (Fl 02–Fl 04) with 3.5% saline solution (water II) and the last three (Fl 05–Fl 07) with 7.0% saline solution (water III). The aim was to have some samples with swelling pressure p_s = 200 kPa. However, in most cases it was difficult to predict the density that would lead to the correct pressure. To get a comparable result for different clays and mixtures the swelling pressure (p_s) was plotted against the measured density, as in Figure 3-3. From the measured pressures a density of the materials that would have a p_s = 200 kPa could be interpolated. In some cases an extrapolation was made when the pressures for all samples exceeded 200 kPa.

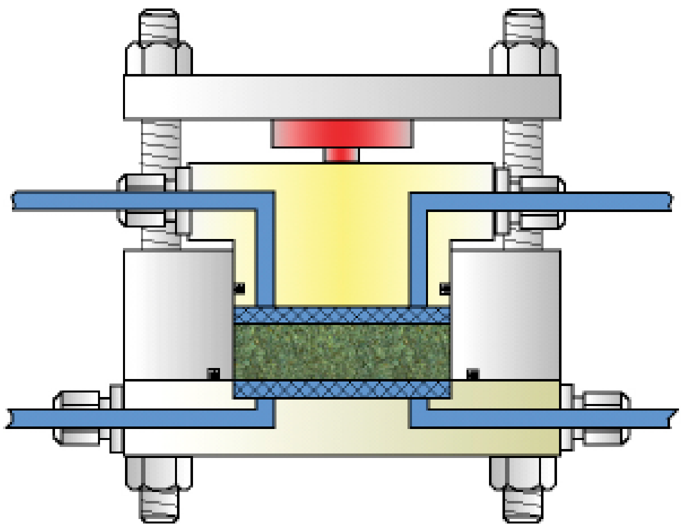

Figure 3-1. *Chematic drawing of the oedometer.*

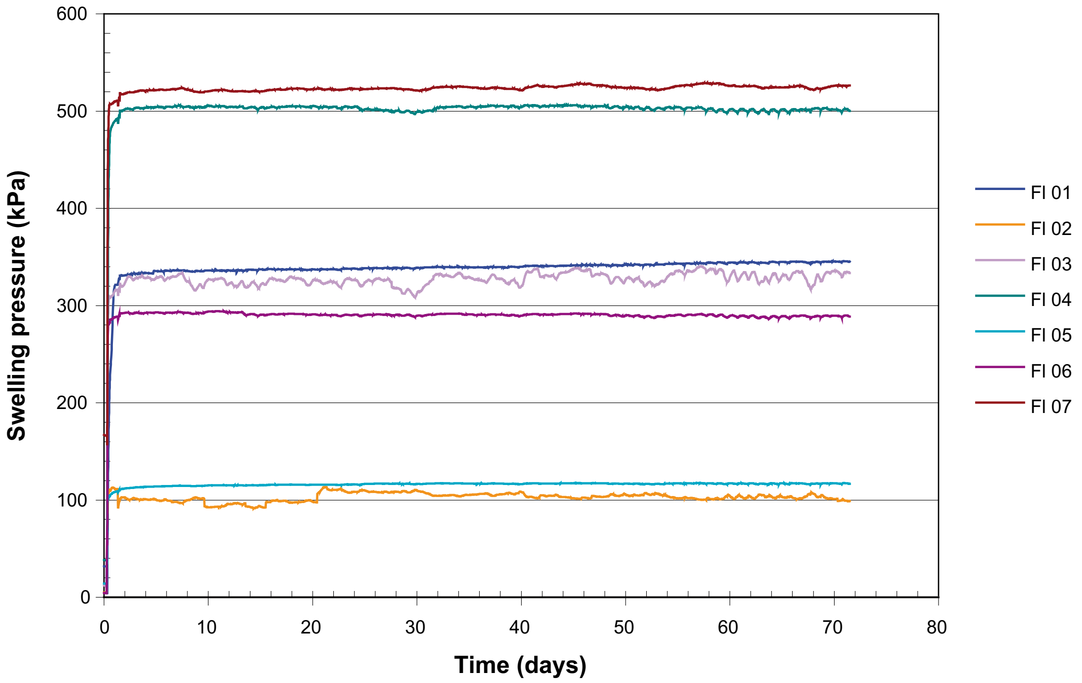

Figure 3-2. *The swelling pressure plotted as function of time for the seven tests made on Friedland clay**.** FI01 = deionized water, FI02–04 = water with a salinity of 3.5% and FI05–07 = water with a salinity of 7%.*

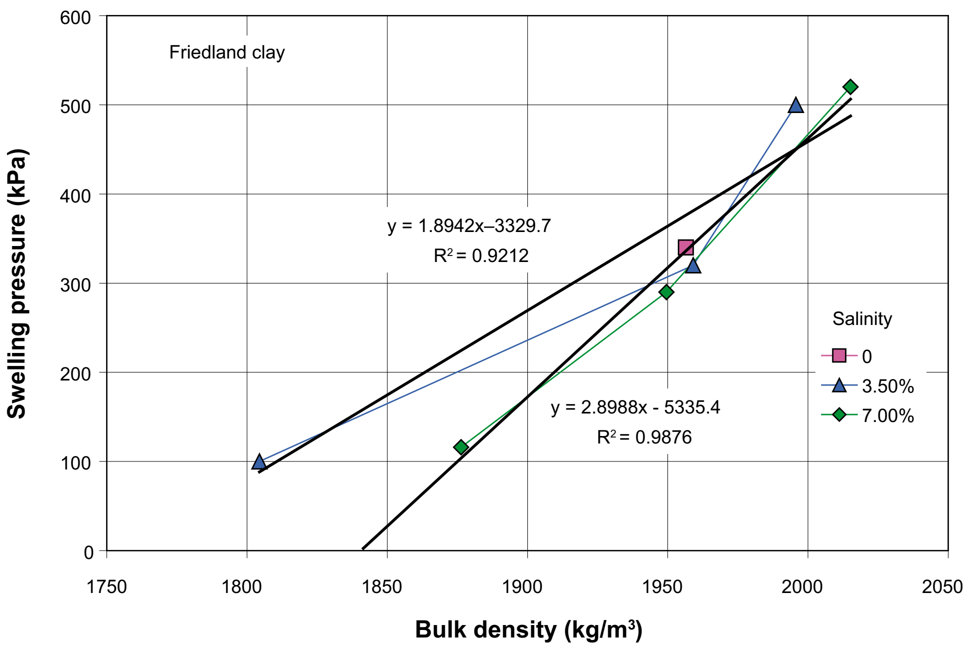

Figure 3-3. *The swelling pressure plotted as function of the bulk density for seven tests made on Friedland clay. Linear regression lines are also fitted to the results. The lines are used for interpolating the density needed to get a swelling pressure of 200 kPa**.***

These are denoted * in the summary. This was made for each investigated materials and for the two types of water. The results are summarised in Table 3-1. The measurements for all tests are presented in Appendix I and Appendix II where the figures from all tests are shown. In most cases the regression is fairly good, but in some cases (particular mix 1.2 and 7) it is poor. This can be explained either by inhomogeneous mixing or the difficulty to measure the density. This also applies to the hydraulic conductivity results presented in next section.

3.3 Analyses of data

The preliminary content of swelling minerals (see Table 2-1) together with the content of ballast material for the mixtures can be used to calculate the clay void ratio. The calculations are made with the assumption that the total voids in the sample together with the total volume of the swelling minerals yield the clay void ratio. In Figure 3-4 and Figure 3-5 the measured swelling pressure for the different natural clays and the mixtures are plotted as function of the clay void ratio.

The figures indicate that for a given swelling pressure a lower clay void ratio is required for the mixtures than for the natural clays. The figures also show that the salt content is affecting the swelling pressure and this affect is more pronounced for the natural clays expressed in change in clay void ratio in order to get a certain swelling pressure. The required clay void ratio for getting a swelling pressure of 200 kPa varies between 2.4 and 3.1 for the natural clays while corresponding values for the mixtures varies between 1.8 and 2.3. These values can be compared with the required void ratio for MX-80 to get a swelling pressure of 200 kPa, which for distilled water is about 1.5, see /3-1/.

Table 3-1. Evaluated densities (density at saturation and dry density) at a swelling pressure of 200 kPa.

No.	Material	Density at swelling pressure 200 kPa	
		Sat. dens/dry dens water II (3.5%) (kg/m^3)	Sat. dens/dry dens water III (7%) (kg/m^3)
Clay 1	Asha 230	1,670/1,050	1,690/1,080
Clay 2	Milos backfill	1,680/1,060	1,700/1,100
Clay 3	DPJ	1,790/1,240	1,830/1,300
Clay 4	Friedland	1,860/1,350	1,910/1,420
Mix 1	30/70 MX-80/B	2,090/1,730	2,090/1,730
Mix 2	30/70 SPV/B	2,120/1,780	2,130/1,790
Mix 3	30/70 CaN/B	2,130/1,800	2,150/1,830
Mix 4	40/60 CaN/B	2,100/1,740*	2,100/1,750*
Mix 5	50/50 CaN/B	1,910/1,450	2,010/1,600
Mix 6	30/70 CaN/A	2,100/1,760*	2,120/1,780*
Mix 7	30/70 CaN/C	2,090/1,740	2,090/1,740

* Denotes extrapolated values.

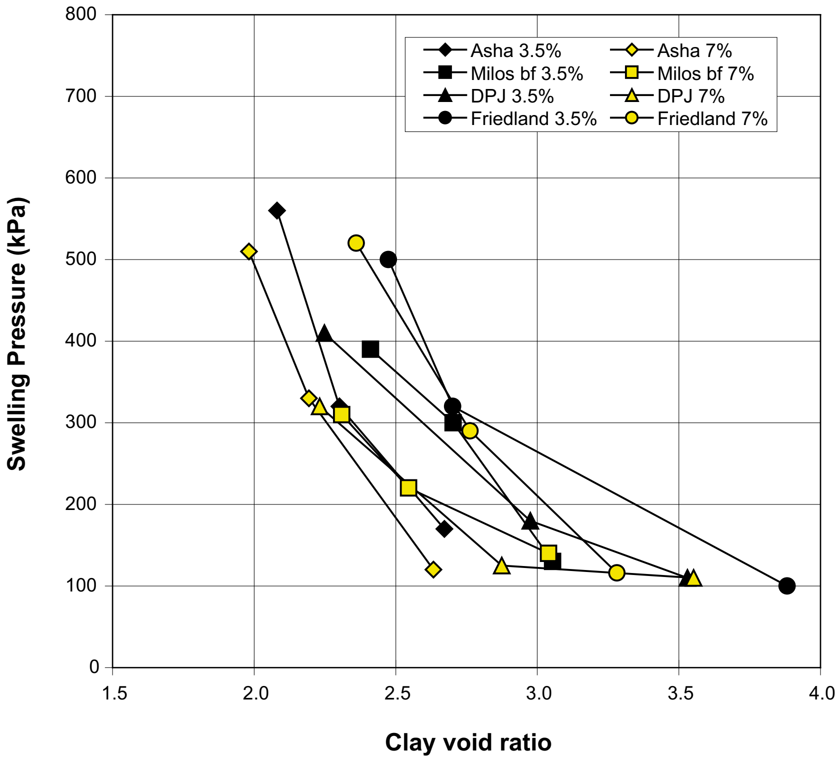

Figure 3-4. *The swelling pressure of the investigated natural clays plotted as function of the clay void ratio.*

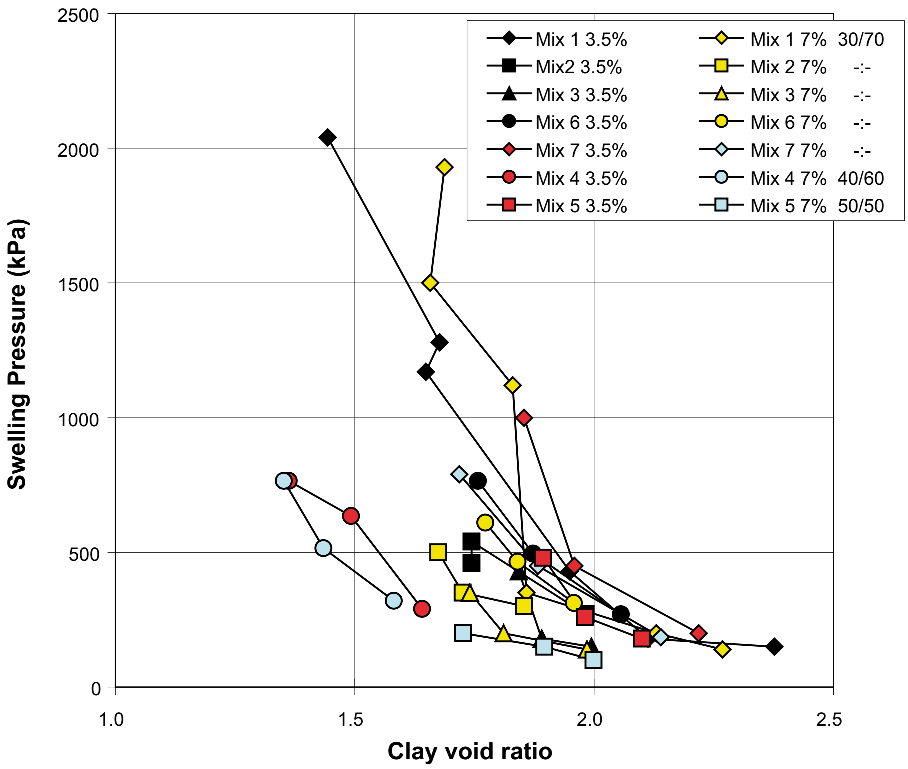

Figure 3-5. *The swelling pressure of the investigated mixtures plotted as function of the clay void ratio.*

3.4 Comparison with previously made tests

3.4.1 30/70 mixture

Laboratory tests for evaluating the swelling pressure of 30/70 mixtures were performed for the large scale projects in Äspö Hard rock Laboratory (PROTOTYPE and Backfill and Plug Test) /3-2/. The tests were made with a mixture of MX-80 and crushed rock with a maximum grain size of 20 mm and the water for saturating the samples had a salinity of 1.2%. The results from the tests are summarized in Table 3-2. Since the maximum grain size of the ballast in these tests is much larger compare to the ballast used in the new tests, the oedometers had a minimum diameter of 100 mm. The results are indicating that in order to get a swelling pressure of about 200 kPa a dry density of about 1,750 kg/m³ is required. This value should be compared with the 30/70 mixtures presented in Table 3-1 (Mix 1–2). The new measurements requires also a dry density of about 1,750 kg/m³ in order to get a swelling pressure of 200 kPa, although these measurements are made with a salinity in the pore water of 3.5%.

3.4.2 Friedland clay

The Friedland clay has previously been investigated at three different occasions (1997, 2000 and 2001), see /3-3/ and /3-4/. The investigations were made with three different deliveries of the clay. The results from the measurements of the swelling pressure at different salinity of the pore water are plotted in Figure 3-6. The figure shows a large variation in the measured swelling pressures. Most of this variation can be explained by the different salinity in the used water. The required densities at different salinity of the pore water in order to get a swelling pressure of about 200 kPa are listed in Table 3-3.

These results are in the same range as the new measurements made on the Friedland clay.

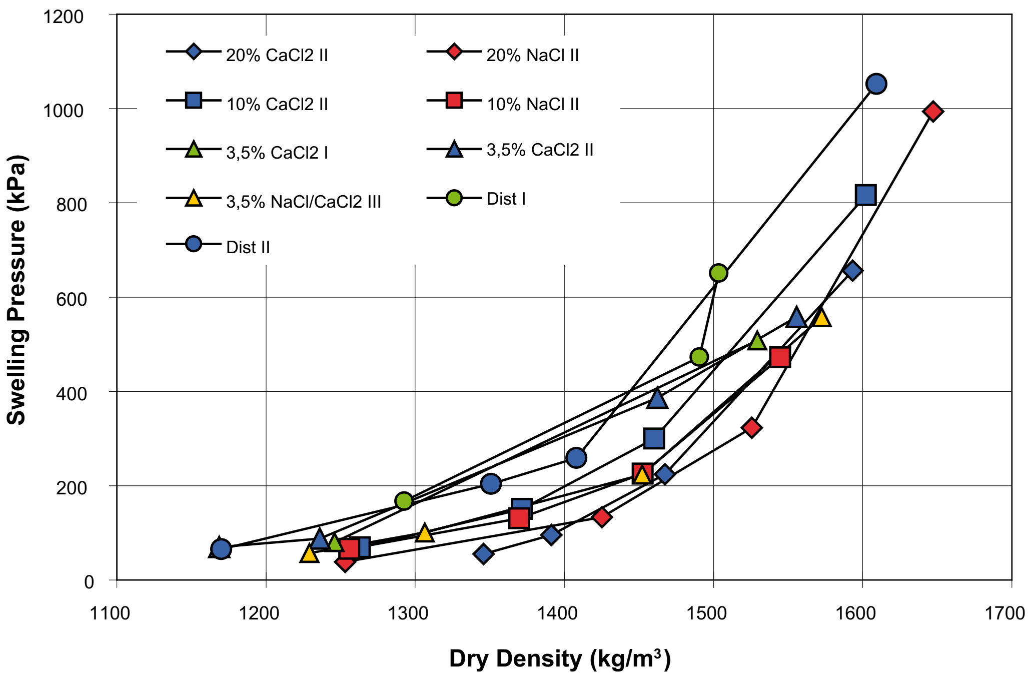

***Figure 3-6.** The swelling pressure plotted as function of the dry density for previous made tests on Friedland clay.*

Table 3-2. Swelling pressure measured on 30/70 mixture (30% MX-80 and 70% ballast of crushed rock with maximum grain size of 20 mm). The tests were made with salt water (1.2% salinity).

			Final properties					
Test no.	Clay cont. (%)	w_{ini} (%)	Proctor (%)	w (%)	ρ_d (t/m^3)	e	Sr (%)	Swelling pressure (kPa)
1	30	6.3	89	21	1,730	0.59	97	220
2	30	13.0	88	21	1,710	0.61	96	244
3	30	13.0	78	27	1,520	0.81	93	68
4	30	10.0	84	23	1,680	0.64	100	104
5	30	10.0	87	21	1,740	0.58	101	100
6	30	10.0	89	21	1,770	0.56	102	198

Table 3-3. Evaluated required dry density in order to get a swelling pressure of about 200 kPa at different salinity of the pore water from previously made tests on Friedland clay.

Salt content	Dry density (kg/m^3)
3.5% $CaCl_2$	1,330
10% $CaCl_2$	1,400
10% NaCl	1,420
20% $CaCl_2$	1,460
20% NaCl	1,420

4 Measurements of hydraulic conductivity

4.1 Introduction

After the swelling pressure had stabilized in the oedometer tests (see Section 3) the hydraulic conductivity (k) was measured by applying a water pressure gradient over the sample. The hydraulic conductivity was determined according to Darcy's law, Equation 4-1. The water inlet at the bottom of the oedometer (see Figure 3-1) was connected to a GDS digital controller that controls the water pressure and measures both water volume and pressure.

$$k = \frac{q}{A \times i} \qquad (4\text{-}1)$$

where

k = hydraulic conductivity

q = water inflow/outflow per sec

i = hydraulic gradient

A = sample area

Initial tests were made to find out how the applied gradient is affecting the evaluated hydraulic conductivity. The tests were made on a sample with a swelling pressure of 100 kPa. The results from the initial tests made on Friedland clay are shown in Figure 4-1. The figure indicates that the scatter in the evaluated hydraulic conductivity is high at low pressure (low gradient) and rather stable at a water pressure below half of the swelling pressure. A general "rule of thumb" for these materials is to not exceed a water pressure higher than half of the swelling pressure. This has been applied to all tests, although in some cases the hydraulic conductivity was so high that reduced pressure was needed to achieve reliable results.

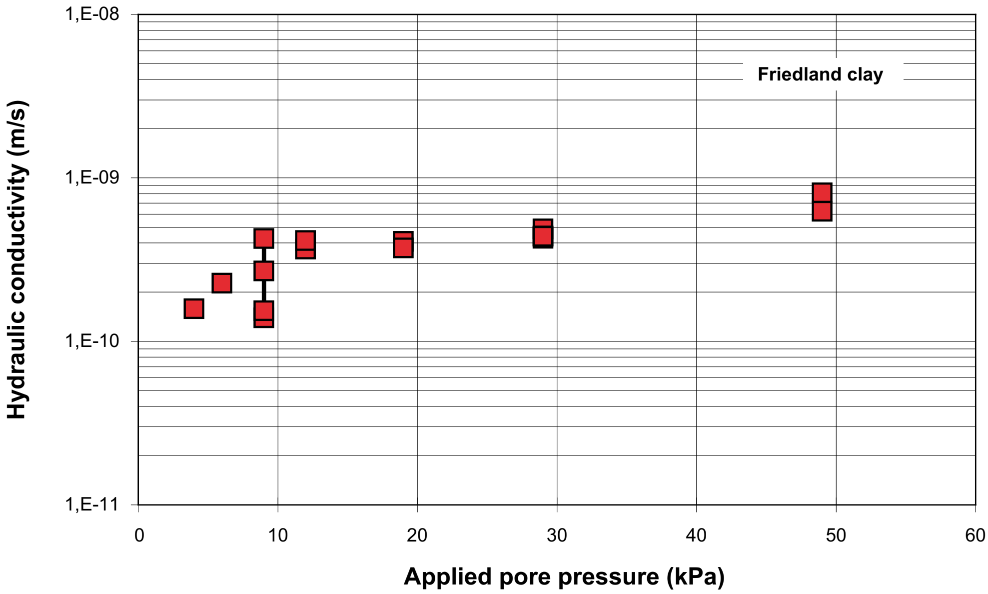

Figure 4-1. *The evaluated hydraulic conductivity plotted as function of applied pressure. The swelling pressure of the sample was about 100 kPa.*

4.2 Results

The measurements of hydraulic conductivity were continued until a stable water inflow was achieved. The evaluated hydraulic conductivity (k) was plotted as function of the measured density (see example in Figure 4-2) and as for the swelling pressure the required density to achieve a hydraulic conductivity of 1E–10 m/s was calculated in the same way. For most cases interpolation but also extrapolation was used. The results from the calculations are summarized in Table 4-1. The measured values for all tests are presented in Appendix I and the figures are presented in Appendix II.

Table 4-1. Evaluated bulk densities at a hydraulic conductivity of 1E–10 m/s for the investigated materials.

No.	Material	Density at a hydraulic cond. of 1E–10 m/s Sat. dens/dry dens water II (3.5%) (kg/m³)	Sat. dens/dry dens water III (7%) (kg/m³)
Clay 1	Asha 230	1,720/1,120	1,790/1,230
Clay 2	Milos backfill	1,700/1,090	1,720/1,120
Clay 3	DPJ	1,780/1,220	1,750/1,180
Clay 4	Friedland	1,890/1,400	1,940/1,470
Mix 1	30/70 MX-80/B	2,190/1,890	2,160/1,840
Mix 2	30/70 SPV/B	2,130/1,790*	2,110/1,760*
Mix 3	30/70 CaN/B	2,160/1,850	2,180/1,880
Mix 4	40/60 CaN/B	2,050/1,670*	2,030/1,640*
Mix 5	50/50 CaN/B	1,810/1,280*	1,910/1,440
Mix 6	30/70 CaN/A	2,000/1,590*	2,010/1,600*
Mix 7	30/70 CaN/C	2,070/1,700	2,100/1,750

* Denotes extrapolated values.

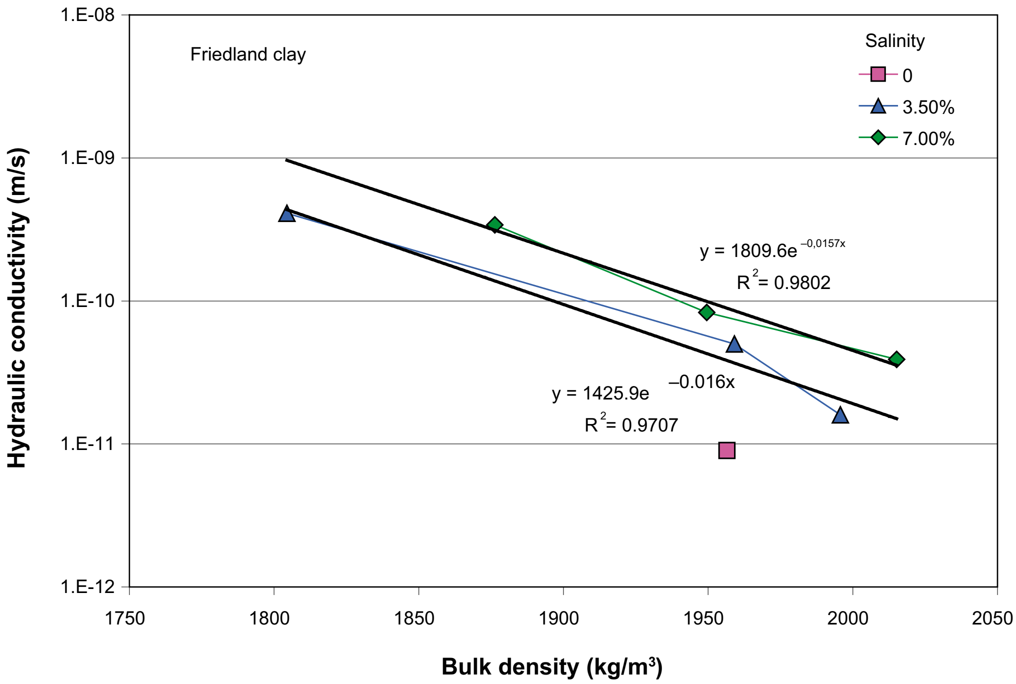

__Figure 4-2.__ The hydraulic conductivity plotted as function of the bulk density at saturation for seven tests made on Friedland clay. Exponential regression lines are also fitted to the results. The lines are used for interpolating the density needed for yielding a hydraulic conductivity of 1E–10 m/s.

When the oedometer tests were disassembled the samples were with some exception homogenous (ocular examination). The exceptions were the samples of Mix 1 (a 30/70 mixture of MX-80 and ballast B) that were subjected to water II and III. As can be seen in Figure 4-3 the clay on the top had separated from the ballast material, which probably has influenced the evaluated hydraulic conductivity.

4.3 Analyses of data

In the same way as for the swelling pressure, the hydraulic conductivity for the natural clays and the mixtures can be expressed as function of their clay void ratios. The results from these calculations are shown in Figure 4-4 and Figure 4-5.

Figure 4-3. *Pictures of the top and bottom of sample Mix 1:2 after dismantling.*

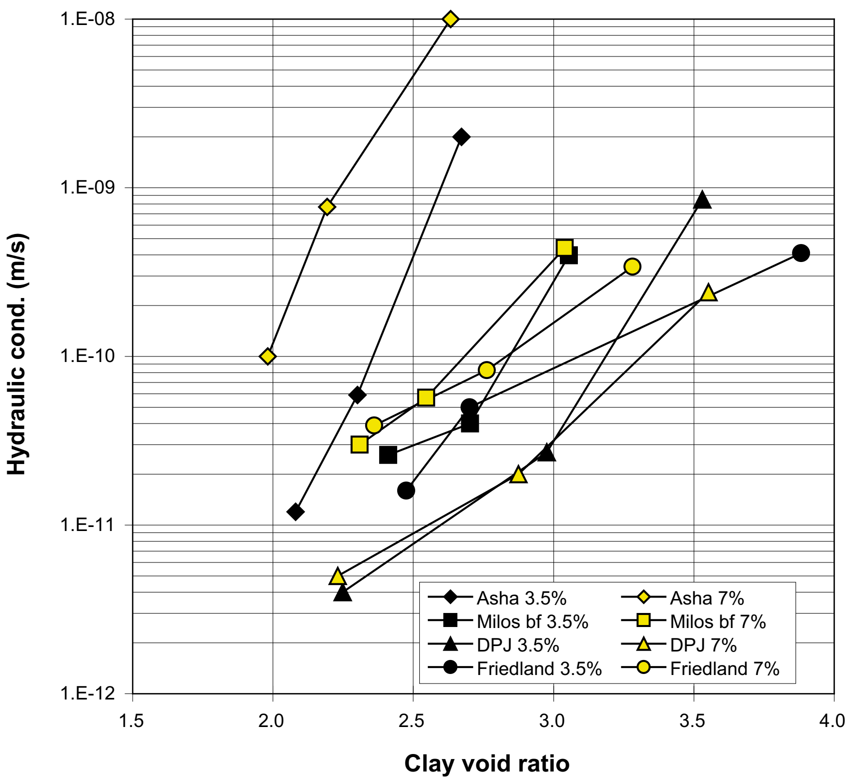

Figure 4-4. *The hydraulic conductivity for the investigated natural clays plotted as function of the clay void ratio.*

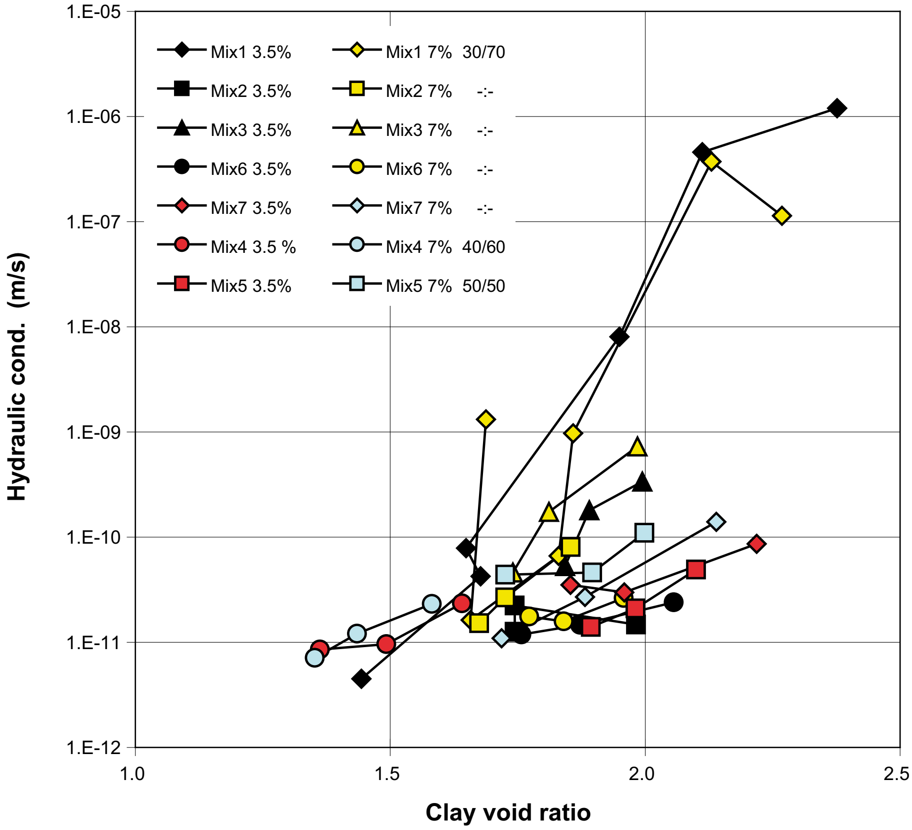

Figure 4-5. *The hydraulic conductivity for the investigated mixtures plotted as function of the clay void ratio.*

The figures indicate that, for a given hydraulic conductivity, a lower clay void ratio is required for the mixtures compared to the natural clays. The figures also show that the salt content affects the hydraulic conductivity. This affect is more pronounced for the natural clays expressed in change in clay void ratio in order to get a certain hydraulic conductivity. The required clay void ratio for getting a hydraulic conductivity of 1 E–10 m/s varies between 2.0 and 3.3 for the natural clays while corresponding values for the mixtures varies between 1.7 and 2.2. At the evaluation for the mixtures, the measurements made on Mix 1 are excluded, since at these measurements there were indications of both piping and separation of the bentonite from the ballast. The evaluated values of the clay void ratios can be compared with the required void ratio for MX-80 to get a hydraulic conductivity of 1E–10 m/s, which for distilled water is about 3, see /3-1/.

4.4 Comparison with previously made tests

4.4.1 30/70 mixture

Tests for evaluating the hydraulic conductivity on 30/70 mixtures have been performed for the large scale projects in Äspö Hard rock Laboratory (PROTOTYPE and Backfill and Plug Test) see /3-2/. The tests were made on mixtures of MX-80 and crushed rock with a maximum grain size of 20 mm. The tests were also performed with different salinity of the pore water. The results from the previous tests are summarized in Figure 4-6. Since the maximum grain size of the ballast in these tests is much larger compared to the ballast used in the new tests, the oedometers had a diameter larger than 100 mm. The salinity of the water used was about 1.2% but also deionised water was used (see Figure 4-6). The figure shows that in order to get

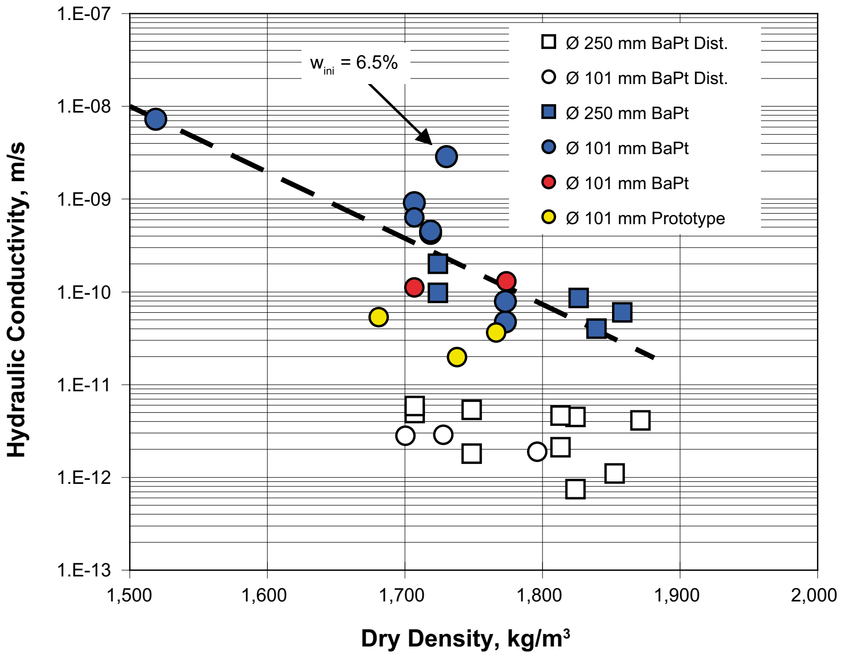

Figure 4-6. *The swelling pressure plotted as function of the dry density for previously made tests on 30/70 mixture (30% MX-80 and 70% crushed rock).*

a hydraulic conductivity of 1E–10 m/s a dry density of about 1,750 kg/m^3 is required (for 1.2% salinity in the pore water). This value is significantly lower than comparable results from the new investigation, see Table 4-1 Mix 1–2. The explanation for this can be the higher salinity in the pore water used in the new tests but also the separation of the materials in the samples observed after the dismantling of the oedometers (see Figure 4-3).

4.4.2 Friedland clay

The Friedland clay has previously been investigated at three different occasions (1997, 2000 and 2001), see /3-3/ and /3-4/. The investigations were made with three different deliveries of the clay. The results are plotted in Figure 4-7. The different salinity of the pore water might explain the variation in the measured hydraulic conductivity. In order to achieve a hydraulic conductivity of about 1E–10 m/s the dry densities presented in Table 4-2 are required. Compared to the new measurements made on this clay (see Table 4-1) these densities are somewhat higher than expected.

Table 4-2. Evaluation of the hydraulic conductivity from previous made tests on Friedland clay. The required dry density in order to get a hydraulic conductivity of about 1E–10 m/s at different salinity of the pore water.

Salt content	Dry density (kg/m^3)
3.5% $CaCl_2$	1,470
10% $CaCl_2$	1,520
10% NaCl	1,530
20% $CaCl_2$	1,600
20% NaCl	1,630

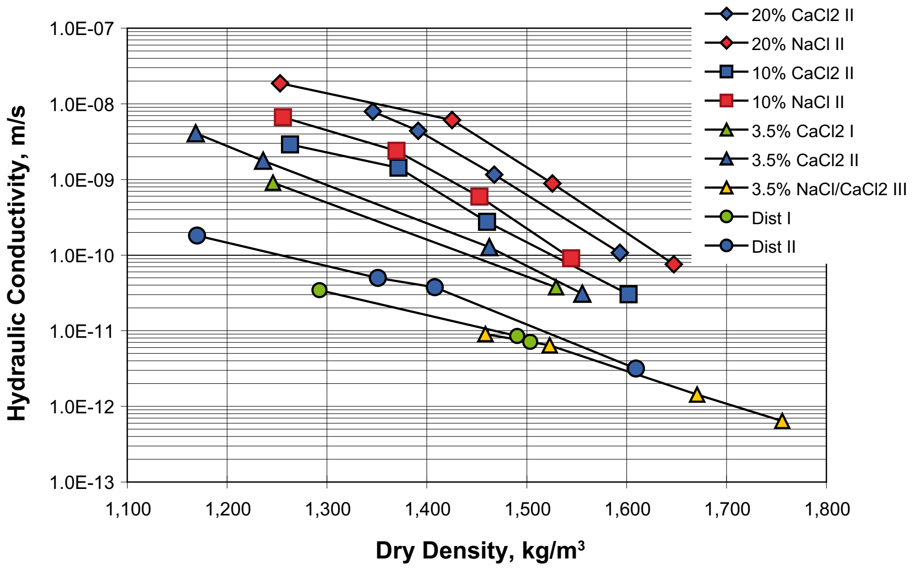

Figure 4-7. *The hydraulic conductivity plotted as function of the dry density for previous tests on Friedland clay.*

5 Oedometer tests

5.1 Introduction

The compressibility of both natural clays and some mixtures of bentonite and ballast were determined in oedometer tests. The equipment used is shown in Figure 5-1. The materials were compacted into the oedometer ring and the piston was placed on top of the samples. The sample was then saturated through the two filters at a constant vertical stress of about 200 kPa. The water used for the oedometer tests had a salinity of 3.5% (50/50 $NaCl/CaCl_2$). When the sample was saturated the vertical load was increased in steps during continuous measurement of the displacement of the sample. The following approximate load steps were used; 400, 800, 1,600 and 3,200 kPa. After the final load step, the oedometer was demounted and the density and water ratio of the sample determined. From these data void ratio, degree of saturation, dry density and density at saturation could be calculated. These data received from the tests are listed in Table 5-1. Two tests were performed on two of the materials (Asha 230 and Friedland). For three of the samples the calculated degree of saturation was much higher than 1, which indicates that either the assumed density of the solid particles is incorrect or the determined water ratio is too high. The water in the sample may also have a density higher than 1,000 kg/m^3. This item is not further discussed in this report. However, when the density of the samples at the different load steps was back calculated with use of the deformation measurements and the density the samples are assumed to have a degree of saturation $S_r = 1.00$.

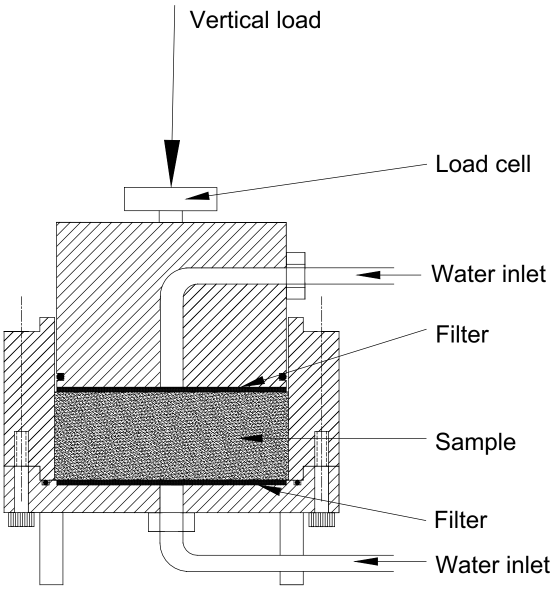

Figure 5-1. *The equipment used for the oedometer tests.*

Table 5-1. Parameters determined on the tested clays after the last load step.

Clay type	Final stress (kPa)	Dens solid (kg/m^3)	Bulk density (kg/m^3)	Void ratio	Water ratio	Dens at sat. (kg/m^3)	Dry density (kg/m^3)	Degr of sat.
Asha 230 I	3,250	2,780	1,880	1.074	0.401	1,860	1,340	1.04
Asha 230 II	3,461	2,780	1,900	1.055	0.407	1,870	1,350	1.07
Milos Backfill	3,066	2,780	1,920	0.938	0.340	1,920	1,430	1.01
DPJ	3,361	2,780	2,030	0.713	0.253	2,040	1,620	0.98
Friedland I	3,260	2,780	2,130	0.576	0.205	2,130	1,760	0.99
Friedland II	3,240	2,780	2,130	0.567	0.203	2,140	1,770	0.99
Mix 3	3,187	2,688	2,220	0.400	0.157	2,210	1,920	1.06
Mix 5	3,450	2,713	2,110	0.542	0.198	2,110	1,760	0.99
Mix 7	3,197	2,688	2,210	0.397	0.148	2,210	1,920	1.00

5.2 Determination of compressibility

An example of measured data from the load steps of one of the materials in the oedometer is shown in Figure 5-2. The void ratio as function of time is plotted for the four load steps made on mixture 5. The corresponding curves for the rest of the materials are shown in Appendix IV. The curves have a typical shape for this type of tests made on clays. The first part of the curve can be interpreted as a small elastic deformation of the material (instant and small). Part II of the curve represents the consolidation of the material. The consolidation is time dependent and is normally representing a large part of the deformation of the material. The rate of consolidation is a function of the hydraulic conductivity and the bulk modulus of the material. The third part of the deformation is representing the creep of the sample (creep in the particle skeleton). This deformation is also time-depending, but compared with the consolidation much smaller.

The final densities at the different load steps are plotted as function of the vertical stress for the different natural clays in Figure 5-3. Corresponding curve for the mixtures are shown in Appendix IV. The void ratio of the samples can also be plotted as function of the vertical stress (see Figure 5-4 for the natural clays). To these data a line can be fitted according to Equation 5-1. The lines together with the evaluated parameters A and B for the natural clays are also shown in Figure 5-4.

$$e = A + B\log_{10}(\sigma) \quad (5\text{-}1)$$

where

e = void ratio of the sample

σ = the effective stress on the sample (kPa)

The fitted curves can be used to determine the settlement of the backfill caused by the swelling of the buffer in the deposition hole (see Section 7).

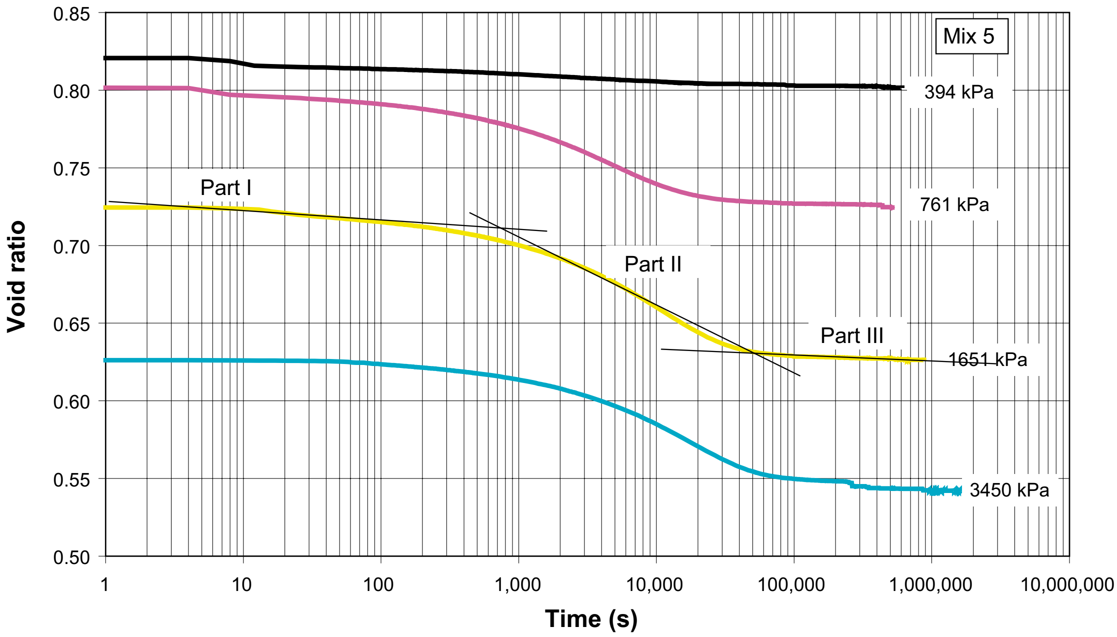

Figure 5-2. Void ratio as function of time for the four load steps made on mixture 5 in an oedometer test.

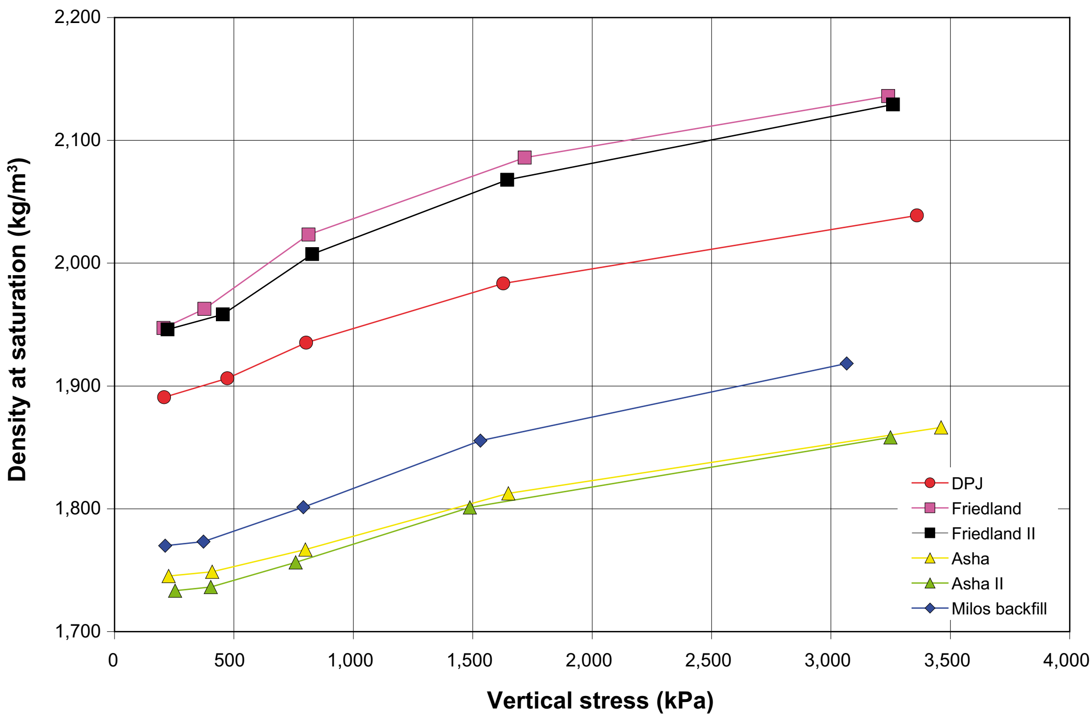

Figure 5-3. Density at saturation plotted as function of the vertical stress for the natural clays.

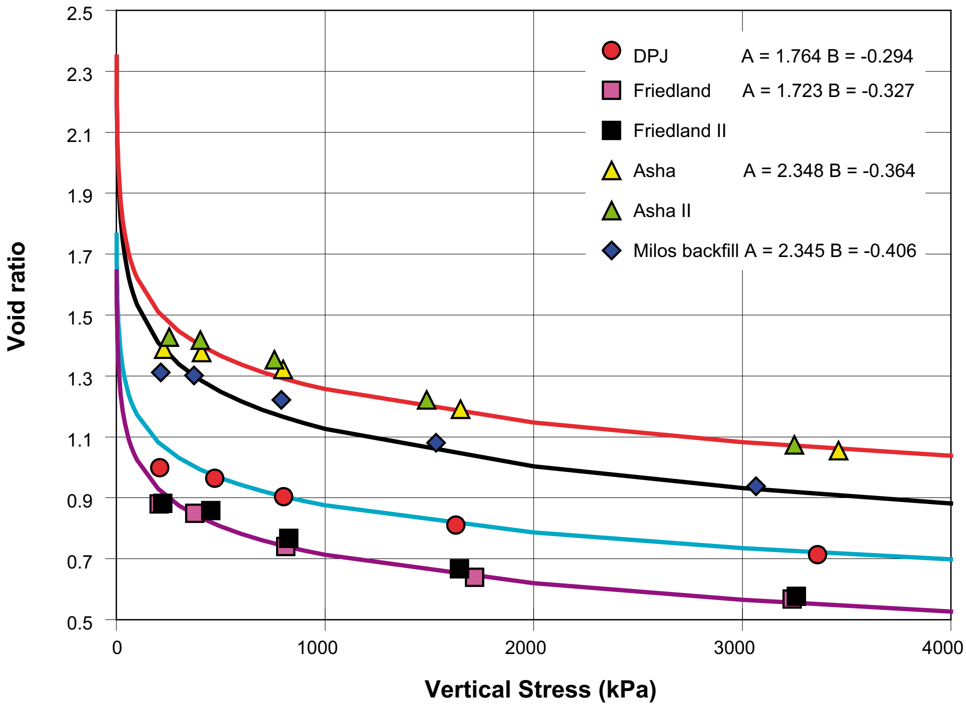

Figure 5-4. *The void ratio plotted as function of vertical effective stress for the investigated natural clays.*

5.3 Comparison with previous test results

5.3.1 Friedland clay

The results from previously performed oedometer tests on Friedland clay are plotted in Figure 5-5 together with the new results. Some of the older tests are made at very low vertical stress compared to the new tests. However, the older results at higher vertical stress fit well with the new test results. The older tests are made with the same salinity in the water as the new tests (3.5%).

5.3.2 30/70 mixtures

The results from previously performed oedometer tests on 30/70 mixture of bentonite and ballast are plotted in Figure 5-6 together with the new results. The older tests are made with MX-80, which is a Na-bentonite, while the bentonite used in the new tests (IBECO CAN) is a Ca-bentonite. Furthermore the ballast in the old tests has a maximum grain size of 20 mm. Due to the relatively large maximum grain size the old oedometer tests were made in a large Rowe oedometer. The salinity in the old tests was also much lower (between 0 and 1.2%). These circumstances can explain the differences in the results compared to the new tests (see Figure 5-6).

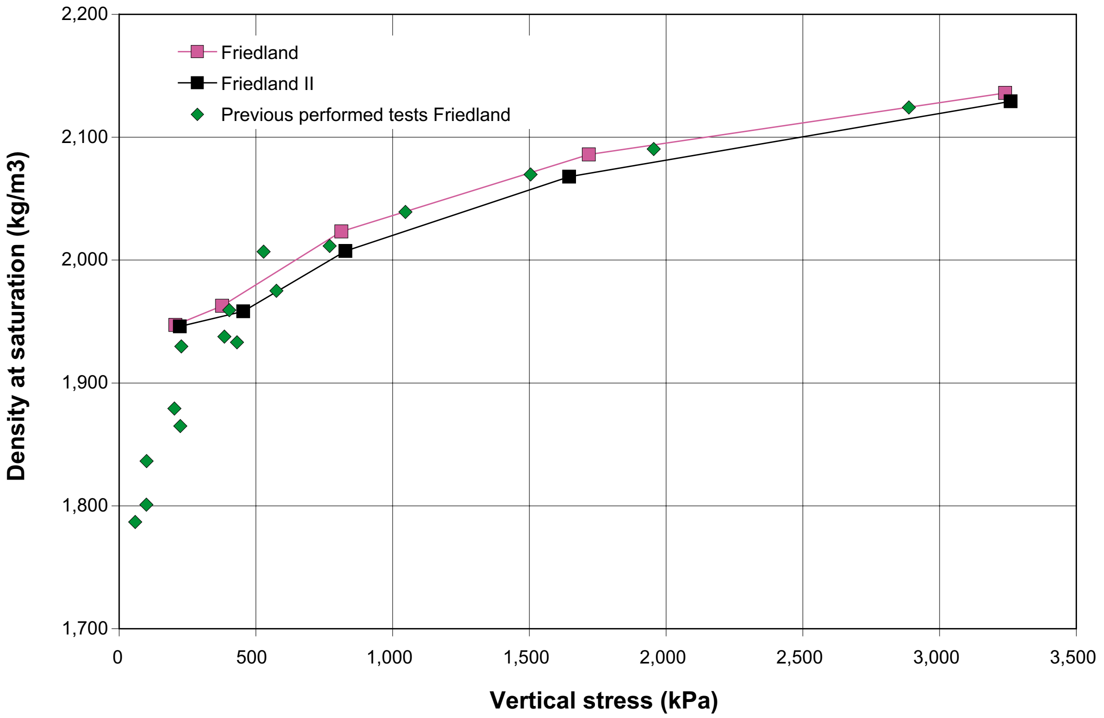

Figure 5-5. *Density at saturation plotted as function of the vertical stress for Friedland clay (both new and old tests).*

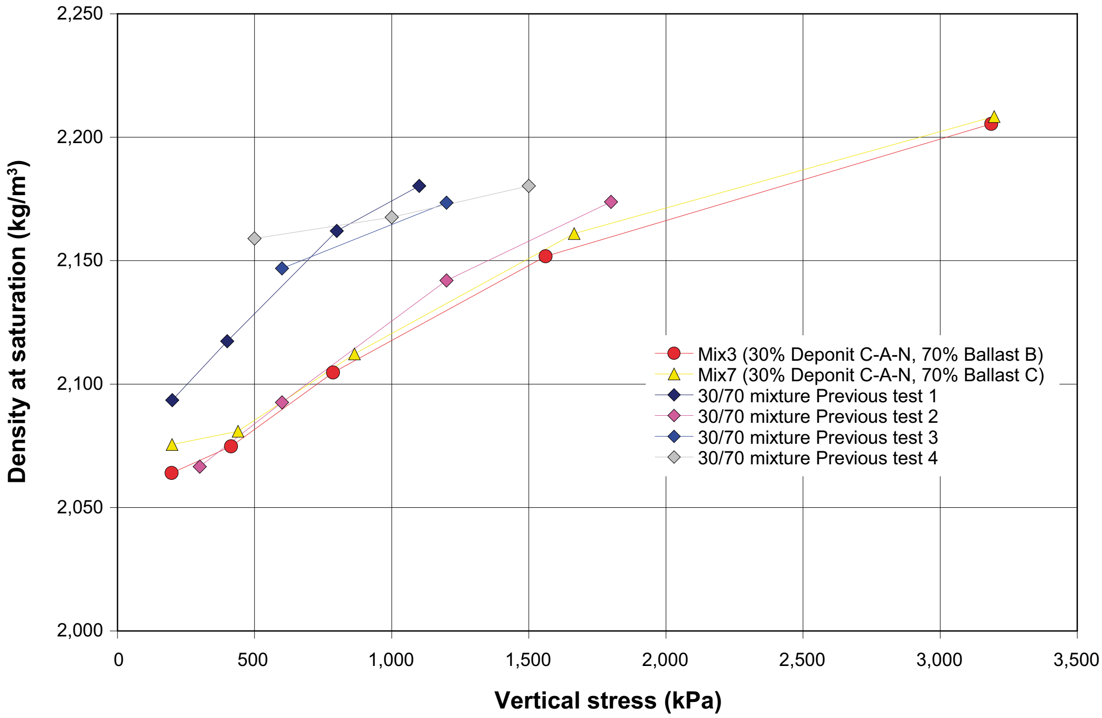

Figure 5-6. *Density at saturation plotted as function of the vertical stress of different 30/70 mixtures.*

5.4 Determination of hydraulic conductivity from the oedometer test

The hydraulic conductivity for the investigated materials was measured by applying a hydraulic gradient over the sample. Both the inflow and the outflow from the sample can be used for the calculation of the hydraulic conductivity with Equation 4-1. The data from this type of determination is described in Section 4. However the hydraulic conductivity can also be determined from the deformation/time relation at each load step from the oedometer tests with the following Equation 5-2 (oedometer technique):

$$k = \frac{T_v \times h^2 \times g \times \rho_w}{M \times t} \qquad (5\text{-}2)$$

where

k = hydraulic conductivity

T_v = time factor (in this case = 0.848)

h = half the height of the sample

M = Compression modulus

g = gravity acceleration (= 9.8 m/s^2)

ρ_w = density of pore water (normally = 1,000 kg/m^3)

t = time at 90% consolidation

The hydraulic conductivity of the natural clays calculated with these two methods is plotted in Figure 5-7 as function of the dry density of the samples. The calculations are made by using the compression modulus determined over the entire load step as a tangent modulus ($M = \Delta\sigma/\Delta\varepsilon$ where $\Delta\sigma$ = the change in vertical stress and $\Delta\varepsilon$ = the change in the vertical strain). Corresponding plot for the mixtures is shown in Figure 5-8.

The figures are indicating that the two ways of determining the hydraulic conductivity are giving similar results with one exception, Mix 3. The reason for why the determined hydraulic conductivity for this material varies between the methods might be caused by inhomogeneity of the material. When the hydraulic conductivity is determined by applying a hydraulic gradient over the sample (Darcy's law) there is a tendency for water to flow trough passages of lower density or voids in the sample, resulting in a high determined hydraulic conductivity. On the other hand when the hydraulic conductivity is determined from an oedometer test (Equation 5-2) the hydraulic conductivity is governed by parameters which are representing average properties of the sample (e.g. the modulus of the sample and the time for reaching 90% consolidation). Thus this hydraulic conductivity is more an average parameter. Both of the evaluated hydraulic conductivity might be interesting for the backfill material. The higher hydraulic conductivity (Darcy's law) is probably more relevant for determining the water flow trough the backfill while the lower hydraulic conductivity is useful when the saturation phase of the backfill is calculated.

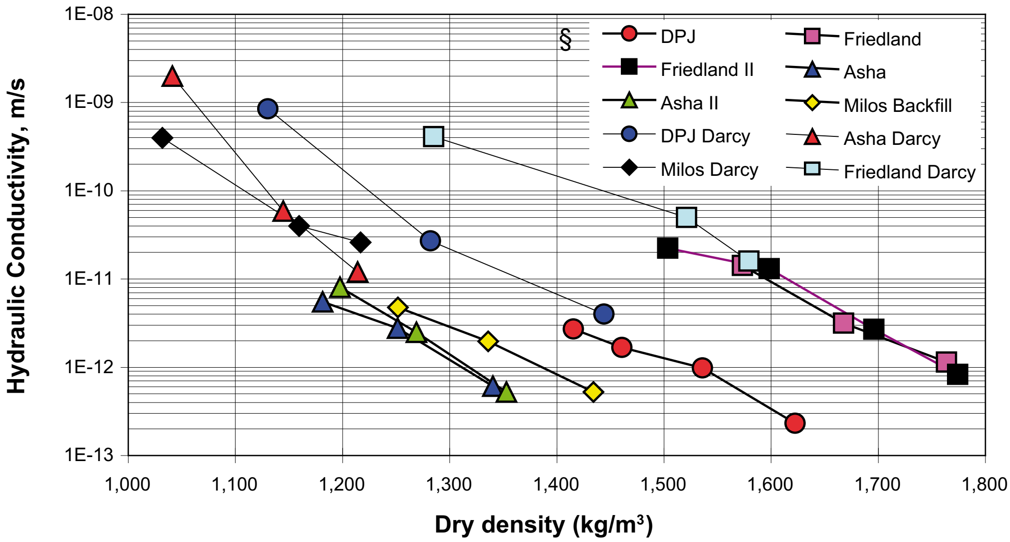

Figure 5-7. *Hydraulic conductivity of the natural clays evaluated from the oedometer tests together with tests results from other determinations of hydraulic conductivity plotted as function of the dry density of the samples.*

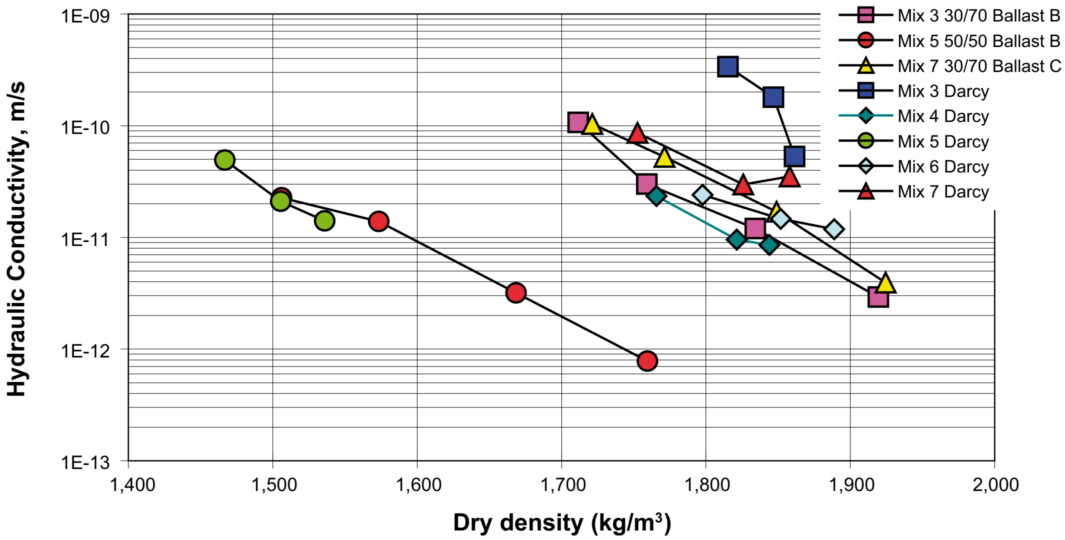

Figure 5-8. *Hydraulic conductivity of the investigated mixtures evaluated from the oedometer tests together with tests results from other determinations of hydraulic conductivity plotted as function of the dry density of the samples.*

6 Compaction tests

In order to investigate the expected density of blocks of the natural clays and some of the mixtures after uniaxial compaction, tests with small samples compacted in the laboratory were performed. The test were prepared and made in the following steps:

- The material was mixed to different water ratio (approximately 10 different water ratio for each type of material, except for DPJ which was mixed to only two different water ratios).
- The material was placed in a rigid form with a diameter of 50 mm.
- The material was compacted with two different maximum compaction stresses (25 MPa and 50 MPa).
- After compaction the density and water ratio of the samples were determined and the dry density and the void ratio calculated.

The results from the measurements are shown in Figure 6-1 and Figure 6-2 for the natural clays. The dry density and the void ratio are plotted as function of the water ratio for the compacted samples. Corresponding plots for test made on mixtures are shown in Figure 6-3 and Figure 6-4. Regarding the composition of the mixtures, see Table 2-3. The black lines in the figures (marked S_r = 100%) correspond to the dry density or void ratio at full saturation for a certain water ratio. The maximum dry densities (or minimum void ratios) and corresponding water ratios can thus be evaluated from the diagrams. These are listed in Table 6-1.

Table 6-1. Parameters determined from all compaction tests.

Material	Comp pressure (MPa)	w at max density	e at max density	Dens of solid part (kg/m^3)	Maximum dry density (kg/m^3)
Asha 230	25	0.173	0.640	2,780	1,700
Asha 230	50	0.176	0.550	2,780	1,790
Milos backfill	25	0.190	0.610	2,780	1,730
Milos backfill	50	0.140	0.500	2,780	1,850
DPJ	25	0.151	0.496	2,780	1,860
DPJ	50	0.104	0.441	2,780	1,930
Friedland	25	0.110	0.390	2,780	2,000
Friedland	50	0.070	0.330	2,780	2,090
Mix 3	25	0.072	0.243	2,688	2,160
Mix 3	50	0.065	0.202	2,688	2,240
Mix 5	25	0.110	0.360	2,713	2,000
Mix 5	50	0.100	0.330	2,713	2,040
Mix 6	25	0.070	0.340	2,688	2,010
Mix 6	50	0.070	0.300	2,688	2,070
Mix 7	25	0.080	0.250	2,688	2,150
Mix 7	50	0.070	0.216	2,688	2,210

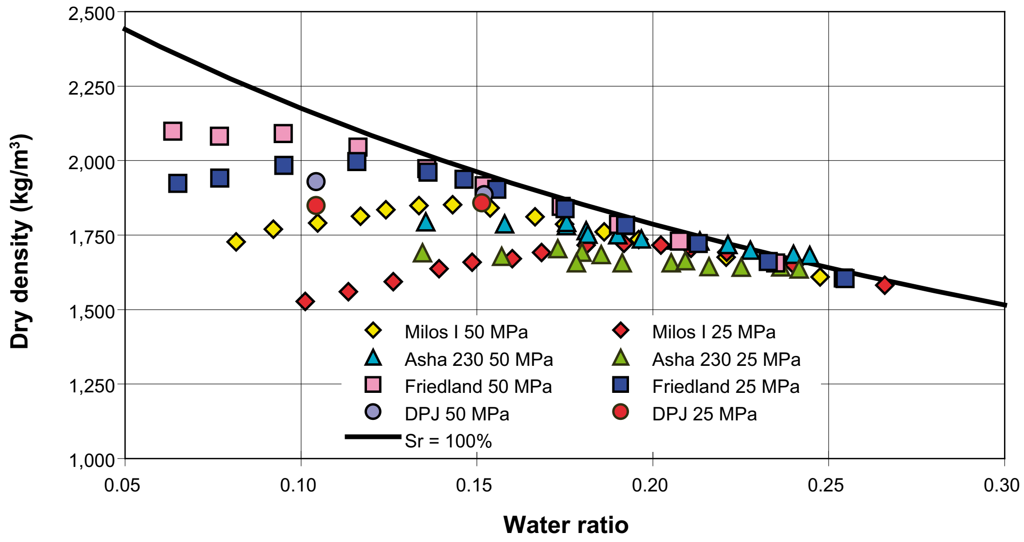

Figure 6-1. *Dry density plotted as function of water ratio for three clays compacted at two different compaction pressures (50 and 25 MPa).*

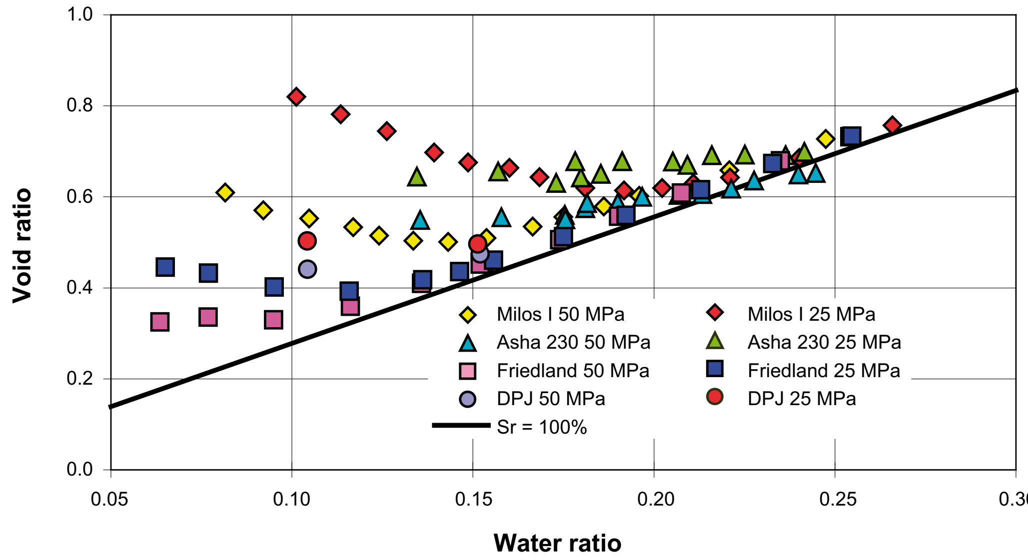

Figure 6-2. *Void ratio plotted as function of water ratio for three clays compacted with two different compaction pressures (50 and 25 MPa).*

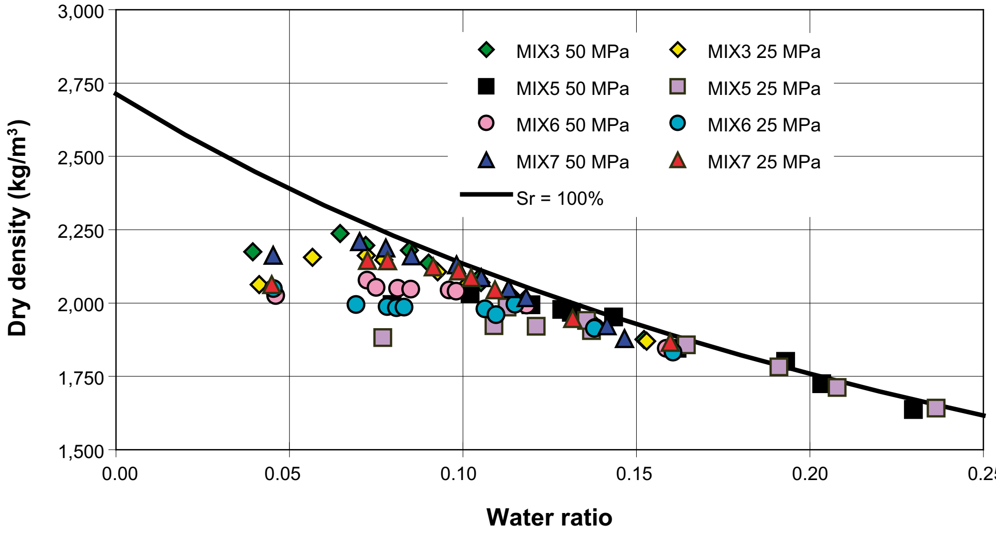

Figure 6-3. *Dry density plotted as function of water ratio for four mixtures compacted with two compaction pressures (50 and 25 MPa).*

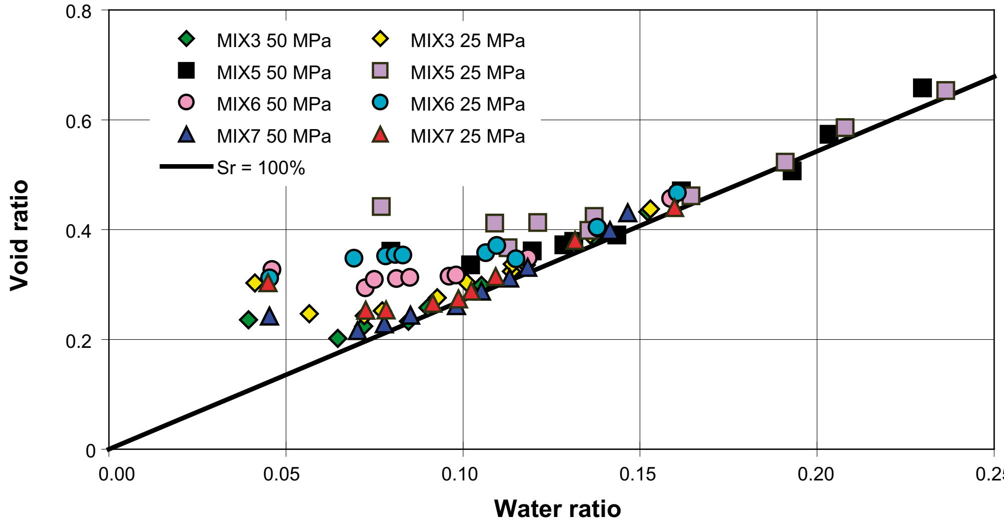

Figure 6-4. *Void ratio plotted as function of water ratio for four mixtures compacted with two compaction pressures (50 and 25 MPa).*

7 Calculations of the compression of the backfill from the swelling buffer in a deposition hole

7.1 Introduction

In Section 5 lines are fitted to the data observed from the oedometer tests. The lines have the following equation:

$$e = A + B\log_{10}(\sigma) \tag{7-1}$$

where

e = void ratio of the sample

σ = effective stress (kPa)

A simplified calculation of the compression of the backfill above a deposition hole due to the swelling of the buffer in a KBS-3 tunnel can be made (see /7-1/ about the theory). The compression of the backfill material is depending on the following factors:

1. The initial density (or void ratio) of the backfill.
2. Deformation properties of the backfill (Equation 7-1).
3. The friction between the buffer and the rock surface in the deposition hole.
4. The void ratio and the resulting swelling pressure of the buffer.
5. The stress distribution in the backfill material due to the swelling pressure of the buffer.
6. The dimensions of the deposition hole and the tunnel.

The following assumptions are made:

- The deposition hole has a radius of 0.875 m and the thickness of the buffer above the canister is 1.50 m. The thickness of the backfill inside the deposition hole is 1.00 m. The tunnel has a radius of 2.50 m.
- There is no friction between the backfill material and the rock in the deposition hole.
- The void ratio of the buffer is a function of the swelling pressure according to Equation 7-2 (see /3-2/):

$$e = e_0 \times \left[\frac{p}{p_0}\right]^{\beta} \tag{7-2}$$

where

e_0 = void ratio at the reference pressure p_0

e = void ratio at the pressure p

p_0 = reference pressure (= 1,000 kPa)

β = pressure exponent (= –0.19)

- The reduced swelling pressure at the buffer/backfill interface due to the friction between the buffer and the rock (see Figure 7-1) can be calculated according to Equation 7-3 (see /7-1/):

$$P_{sa} = P_{sb} \times e^{-\left(\frac{2z\tan(\phi)}{r}\right)} \tag{7-3}$$

where

P_{sa} = swelling pressure in the section between the buffer and the backfill

P_{sb} = initial swelling pressure of the buffer

r = radius of the deposition hole (= 0.875 m)

φ = friction angle between the buffer and the rocks surface of the deposition hole

z = vertical distance from the buffer/backfill interface

- The bentonite buffer above the canister is so thick that the buffer around the canister is not involved in the swelling.
- The vertical stress in the backfill above the buffer (in the deposition hole) is constant.
- The vertical stresses in the backfill above the deposition hole (in the tunnel) is calculated according to the theory by Boussinesq (elastic theory):

$$\Delta\sigma = q \times \left[1 - \left(\frac{1}{1+(r/y)^2}\right)^{3/2}\right] \tag{7-4}$$

where

Δσ = vertical stress in the backfill due to the swelling pressure of the buffer

q = swelling pressure of the buffer

r = radius of the deposition hole (= 0.875 m)

y = distance from tunnel floor to the position were the stress is calculated

With these equations the maximum deformation (compression) of the back fill can be calculated in the following steps:

A. The backfill above the buffer is divided in layers with defined thickness. The increase in vertical stress at the centre of each layer caused by the swelling pressure of the buffer is calculated with Equation 7-4. Knowing this increase in stress the change in void ratio can be calculated with Equation 7-1 (for the centre of each layer). By assuming that the change in void ratio at the centre of the layers is valid for the whole layer, the total compression can be calculated as the sum of the compression of all the layers. The calculation is also assuming that the initial void ratio of the backfill is known.

B. Knowing the friction angle between the buffer and the wall of the deposition hole the pressure P_{sa} (see Figure 7-1) can be calculated with Equation 7-3. (P_{sb} is assumed to be 7,000 kPa which corresponds to a saturated density of the buffer of 2,011 kg/m^3). The change in swelling pressure from Psb to Psa causes changing in void ratio of the buffer which can be calculated with Equation 7-2. With the known volume of the zone where the swelling occur and the average change in void ratio the swelling of the buffer can be calculated.

C. The final compression of the backfill can be evaluated at inter section between the deformation curve of the backfill and the swelling curve of the buffer material (see Section 7.2).

7.2 Results from made calculations

Figure 7-2 shows an example of results from a calculation. The compression of the backfill of Friedland clay and the swelling of the buffer are plotted as function of the vertical stress of the buffer and the backfill. The swelling of the buffer is plotted with four different assumption of the friction between the rock surface of the deposition hole and the buffer. Furthermore the compression of the backfill is calculated with three different initial densities (dry density). The lowest density (ρ_d = 1,480 kg/m^3) is the density achieved in compaction tests made in the field.

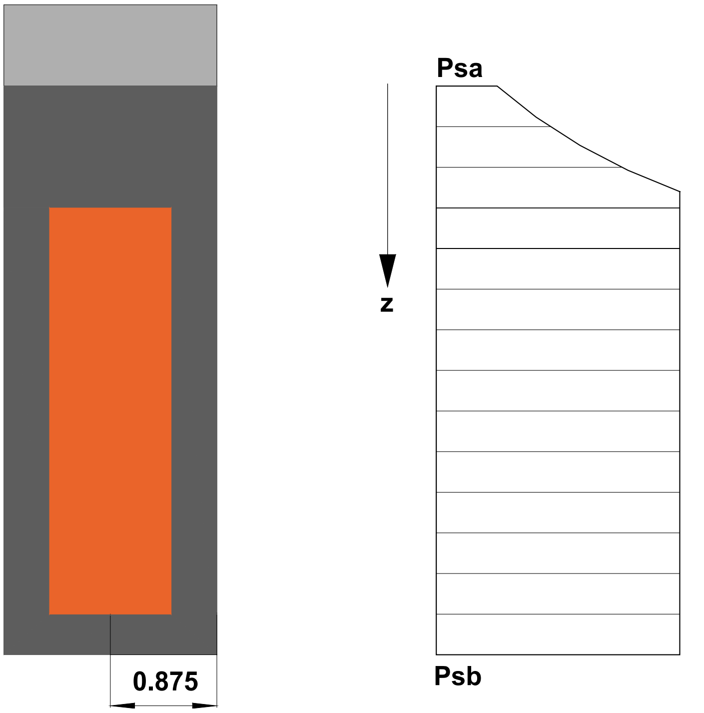

Figure 7-1. *A schematic drawing of the stresses in the buffer according to Equation 7-3.*

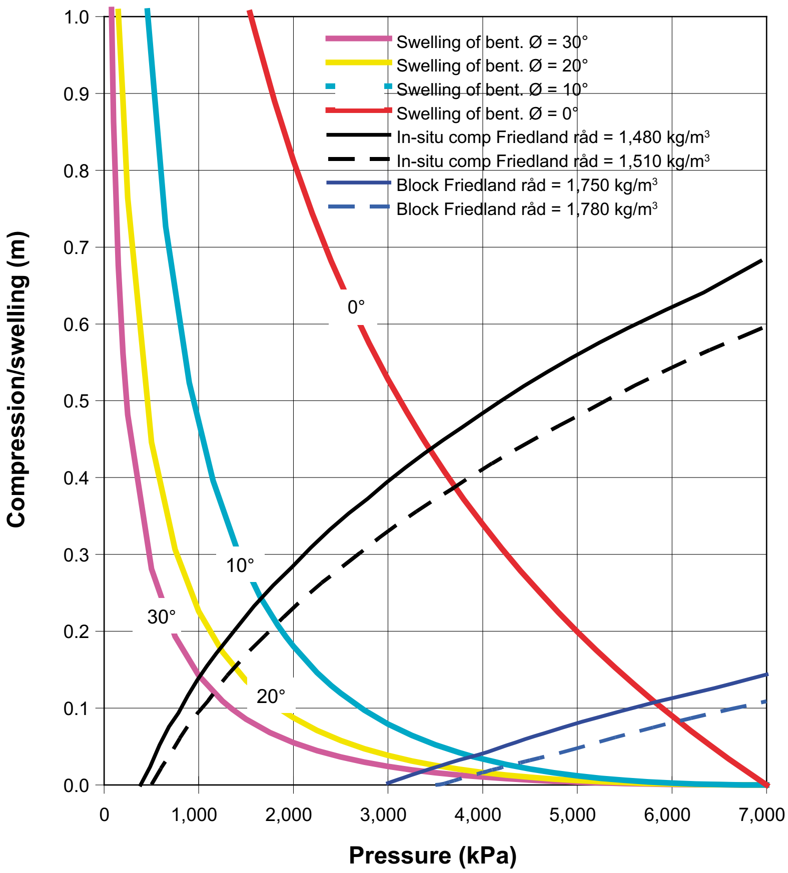

Figure 7-2. *The displacement of the interface between the compacted bentonite and the overlaying backfill (Friedland clay). The calculations are made at different angles of friction between the buffer and the surface of the deposition hole and with different assumptions about the initial density of the backfill.*

The highest density (ρ_d = 1,780 kg/m³) corresponds to the average density of the backfill built up by pre compacted blocks, slots filled with pellets and voids. The following assumptions were made at the calculation of the dry density:

- The pre compacted blocks are assumed to have the maximum achieved dry density in the laboratory tests at a compaction pressure of 25 MPa. In the case of Friedland clay this density is 2,000 kg/m³, see Table 6-1.
- The tunnel section is assumed to be filled with blocks to 78% of the total volume. 20% of the tunnel is assumed to be filled with pellets of bentonite with a dry density of 1,100 kg/m³. The rest of the tunnel section is assumed to be voids (2%).

Except for the maximum compression/swelling, the distance between the buffer/backfill interface and the level in the deposition hole where no reduction in the swelling pressure occurs is calculated (the distance z in Figure 7-1). The swelling pressure (P_{sa}) at the interface between the buffer and the backfill can also be calculated. Furthermore the density at the top of the canister is determined from the calculated swelling pressure. These parameters are shown in Table 7-1 for the case of 10° friction angle between buffer and rock surface. The distance z should according to the assumptions for the requirements be smaller than 1.5 m (the thickness of bentonite on top of the canister). This is not the case for all of the calculated concepts. For this reason calculations have also been made where the distance z is limited to just below

Table 7-1. Results from the calculations of the compression of the backfill materials. The calculations are made with the assumption of a friction angle of 10° between the buffer and the rock surface in the deposition hole.

Material	Concept	Initial dry density (kg/m³)	Compression (m)	P_{sa} (kPa)	z (m)	Sat. buffer density at top of canister (kg/m³)
Asha 230	Blocks	1,540	–	–	–	2,010
Asha 230	Blocks*	1,330	0.037	3,900	1.451	2,010
Asha 230	Blocks**	1,160	0.208	1,836	3.321	1,950
Milos bf	Blocks	1,570	–	–	–	2,010
Milos bf	Blocks*	1,440	0.037	3,900	1.451	2,010
Milos bf	Blocks**	1,240	0.208	1,836	3.321	1,950
DPJ	Blocks	1,670	0.006	5,500	0.598	2,010
DPJ	Blocks*	1,590	0.037	3,900	1.451	2,010
DPJ	Blocks**	1,400	0.208	1,836	3.321	1,950
Friedland	In situ	1,480	0.245	1,650	3.586	1,940
Friedland	In situ**	1,510	0.208	1,836	3.321	1,950
Friedland	Blocks	1,780	0.027	4,250	1.238	2,010
Friedland	Blocks*	1,750	0.037	3,900	1.451	2,010
Mix 3	In situ	1,700	0.191	1,930	3.197	1,950
Mix 3	In situ**	1,690	0.208	1,836	3.321	1,950
Mix 3	Blocks	1,910	0.065	3,250	1.904	2,000
Mix 3	Blocks*	1,950	0.037	3,900	1.451	2,010
Mix 5	Blocks	1,780	0.037	3,900	1.451	2,010
Mix 5	In situ**	1,560	0.208	1,836	3.321	1,950
Mix 7	In situ	1,700	0.191	1,935	3.190	1,950
Mix 7	In situ**	1,690	0.208	1,836	3.321	1,950
Mix 7	Blocks	1,900	0.062	3,300	1.866	2,000
Mix 7	Blocks*	1,940	0.037	3,900	1.451	2,010

* Density of the filling in order to get a z-value smaller than 1.5 m.

** Density of the filling in order to get a density at the top of the canister of minimum 1,950 kg/m³.

1.5 m (marked with * in the table below). Furthermore calculations have been made where the restriction is to minimize the density at the top of the canister to 1,950 kg/m³ which corresponds to a swelling pressure of about 3,360 kPa. These calculations are marked with ** in the table.

7.3 Detail calculations made on 30/70 mixtures and Friedland clay

The calculations presented in the previous sections are made with the assumption that the buffer has an initial swelling pressure of 7,000 kPa, corresponding to a density at saturation of 2,011 kg/m³. According to the Swedish KBS-3 concept the density at saturation of the buffer is allowed to vary between 1,950 kg/m³ and 2,050 kg/m³. In order to find out how the initial density of the buffer is affecting the compression of the backfill, additional calculations for the Friedland clay and the 30/70 mixture have been done. The results from these calculations are presented in Table 7-2. The calculations are made with three different initial density of the

Table 7-2. Results from calculations made on the compression of the two backfill materials Friedland and 30/70 mixture. The calculations are made at different initial density of the buffer and the backfill.

Material	Initial dry density backfill (kg/m³)	Initial density buffer (kg/m³)	Compression (m)	Psa (m)	z (m)	Buffer density at top of canister (kg/m³)
Friedland	1,460	1,950	0.178	1,011	2.980	1,900
Friedland	1,480	1,950	0.153	1,100	2.771	1,910
Friedland	1,630	1,950	0.042	1,840	1.494	1,950
Friedland	1,780	1,950	–	–	–	1,950
Friedland	1,480	2,000	0.224	1,540	3.415	1,940
Friedland	1,540	2,000	0.167	1,835	2.981	1,950
Friedland	1,720	2,000	0.039	3,350	1.487	2,000
Friedland	1,780	2,000	0.018	4,050	1.016	2,000
Friedland	1,430	2,050	0.376	1,841	4.480	1,950
Friedland	1,480	2,050	0.304	2,180	3.822	1,970
Friedland	1,780	2,050	0.058	5,300	1.856	2,038
Friedland	1,830	2,050	0.037	6,150	1.487	2,050
Mix 3	1,650	1,950	0.178	1,011	2.980	1,900
Mix 3	1,700	1,950	0.123	1,225	2.503	1,920
Mix 3	1,870	1,950	0.042	1,840	1.494	1,950
Mix 3	1,906	1,950	0.021	2,200	1.051	1,950
Mix 3	1,700	2,000	0.180	1,760	3.084	1,950
Mix 3	1,710	2,000	0.167	1,835	2.981	1,950
Mix 3	1,910	2,000	0.056	3,000	1.761	1,990
Mix 3	1,940	2,000	0.039	3,350	1.487	2,000
Mix 3	1,620	2,050	0.376	1,841	4.480	1,950
Mix 3	1,700	2,050	0.244	2,550	3.672	1,980
Mix 3	1,910	2,050	0.100	4,250	2.404	2,020
Mix 3	2,010	2,050	0.037	6,150	1.487	2,050

Density of the filling in order to get a density at the top of the canister of minimum 1,950 kg/m³. (1,900 kg/m³ for the initial density of the buffer of 1,950 kg/m³).

Expected density at in situ compaction of the filling.

Density of the filling in order to get a z-value smaller than 1.5 m.

Expected density when using pre compacted blocks.

buffer 1,950, 2,000 and 2,050 kg/m^3 respectively. The calculations are also made with four different assumptions on the initial dry density of the backfill. These densities are chosen in the same way as described in Section 7.2 (see also Table 7-2). The results from the calculations are arranged in the table with increasing initial dry density of the backfill.

From the table the following conclusion can be made:

- The compression of the backfill is affected much by the initial density of the buffer. This is valid for the both concept of the backfilling (in situ compaction or pre compacted blocks).
- The concept of pre-compacted blocks (marked with red in Table 7-2) is for all of the different initial buffer densities giving densities at the top of the canister higher or equal to 1,950 kg/m^3.
- The concept of in situ compaction backfill (marked with blue in Table 7-2) is for most of the different initial buffer densities giving densities at the top of the canister close to or lower than 1,950 kg/m^3.
- The compression is as expected much higher for the in situ compacted backfill.
- The maximum compression for backfill of pre compacted blocks of Friedland clay is about 0.06 m.
- The maximum compression for backfill of in situ compacted Friedland clay is about 0.30 m.
- The maximum compression for backfill of pre compacted blocks of 30/70 mixture is about 0.10 m.
- The maximum compression for backfill of in situ compacted 30/70 mixture is about 0.25 m.

8 Comments and conclusions

The requirements on the investigated backfill materials used in this report are as follows:

- The swelling pressure of the backfill should not be smaller than 200 kPa.
- The hydraulic conductivity of the backfill should be lower than 1E–10 m/s.
- The compression of the backfill caused by the swelling of the buffer in the deposition hole should not be so large that the density of the buffer at the top of the canister is smaller than 1,950 kg/m^3.

The densities for the different investigated backfill materials in order to fulfil the requirements together with the reachable densities are listed in Table 8-1. The following conclusions from the table can be drawn:

The main conclusion is that, except for the 30/70 mixtures, the highest densities are needed to fulfil the requirement concerning compression. For the 30/70 mixtures the highest density is needed to ensure that the hydraulic conductivity and swelling pressure is maintained.

Table 8-1. The dry densities for the different investigated backfill materials in order to fulfil the requirements together with the reachable dry densities.

Material types	Required dry densities (kg/m^3) based on:		
	Hydraulic conductivity	Swelling pressure	Deformation properties
Asha 230	1,120	1,050	1,160
Milos bf	1,090	1,060	1,240
DJP	1,220	1,240	1,400
Friedland	1,400	1,350	1,510
30/70 mixtures	1,700–1,890*	1,730–1,800	1,690
50/50 mixture	1,280	1,450	1,560

* For this interval the extrapolated densities from Table 4-1 are excluded.

9 Recommendations on continued work

This investigation is limited concerning the number of samples to at the most three for each type of water and material, which means that the accuracy of the determined densities in order to fulfil the requirements on the backfill materials is not possible to estimate. In order to be able to make such estimations more tests should be done.

A large scatter in the determined parameters for the mixtures can be observed. It can not be excluded that this scatter is caused by insufficient homogeneity of the material caused by poor mixing technique. This should be further investigated.

For some of the mixtures piping was observed during the measurement of the hydraulic conductivity. The risk for piping and how this is affecting the hydraulic conductivity should be further investigated.

The calculation of the compression of the backfill was made in steps where the swelling of the buffer and the compression of the backfill was set to be equal. The calculations of the deformations were made with simple methods with several assumptions. The results should be validated with other methods e.g. FE calculations.

This investigation as well as others indicates that the chemistry of the pore water is very much affecting the measured parameters. This effect should be further investigated.

The investigated parameters are measured at rather low densities compared to the density expected in a real filling, at least when pre compacted blocks are used. The investigation should be extended to higher densities in order to get relevant parameters.

To investigate the influence of the salt content of the pore water on the deformation properties more tests have to be made.

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Appendix I

The evaluated hydraulic conductivity and swelling pressure for the investigated materials

Sample	ρ_m	p_s	c_h	w	e	S_r	ρ_d	$\rho_{d\,clay}$	Clay cont.
Unit	kg/m³	kPa	m/s	%			kg/m³	kg/m³	%
As 1:1	1,730	560	1.50E–11	0.521	1.398	1.010	1,147	1,147	100
As 1:2	1,658	170	2.00E–09	0.593	1.659	0.993	1,034	1,034	100
As 1:3	1,720	320	5.90E–11	0.503	1.430	0.986	1,132	1,132	100
As 1:4	1,763	560	1.20E–11	0.452	1.294	0.982	1,199	1,199	100
As 1:5	1,664	120	1.00E–08	0.594	1.635	1.000	1,044	1,044	100
As 1:6	1,740	330	7.70E–10	0.507	1.363	1.009	1,164	1,164	100
As 1:7	1,784	510	1.00E–10	0.452	1.233	1.004	1,232	1,232	100
Mi Bf 2:1	1,729	260	3.80E–11	0.499	1.401	0.991	1,145	1,145	100
Mi Bf 2:2	1,655	130	3.97E–10	0.604	1.673	0.997	1,029	1,029	100
Mi Bf 2:3	1,705	300	4.00E–11	0.471	1.481	0.944	1,108	1,108	100
Mi Bf 2:4	1,753	390	2.60E–11	0.441	1.323	0.963	1,184	1,184	100
Mi Bf 2:5	1,657	140	4.40E–10	0.575	1.665	0.979	1,032	1,032	100
Mi Bf 2:6	1,730	220	5.69E–11	0.477	1.396	0.973	1,148	1,148	100
Mi Bf 2:7	1,772	310	3.00E–11	0.432	1.267	0.971	1,213	1,213	100
Dn 3:1	1,754	100	4.00E–11	0.455	1.321	0.977	1,185	1,185	100
Dn 3:2	1,725	110	8.50E–10	0.526	1.415	1.009	1,139	1,139	100
Dn 3:3	1,797	180	2.70E–11	0.402	1.196	0.965	1,252	1,252	100
Dn 3:4	1,917	410	4.00E–12	0.328	0.908	0.996	1,441	1,441	100
Dn 3:5	1,722	110	2.40E–10	0.491	1.424	0.978	1,135	1,135	100
Dn 3:6	1,812	125	2.00E–11	0.393	1.156	0.970	1,276	1,276	100
Dn 3:7	1,920	320	5.00E–12	0.316	0.901	0.983	1,446	1,446	100
Fl 4:1	1,956	340	9.00E–12	0.298	0.830	0.995	1,503	1,503	100
Fl 4:2	1,804	100	4.10E–10	0.404	1.175	0.975	1,264	1,264	100
Fl 4:3	1,959	320	5.00E–11	0.288	0.825	0.980	1,507	1,507	100
Fl 4:4	1,996	500	1.60E–11	0.264	0.758	0.978	1,565	1,565	100
Fl 4:5	1,876	116	3.40E–10	0.368	0.997	1.007	1,377	1,377	100
Fl 4:6	1,950	290	8.30E–11	0.284	0.843	0.963	1,492	1,492	100
Fl 4:7	2,015	520	3.90E–11	0.256	0.724	0.987	1,595	1,595	100
Mix 1:1	2,055	120	1.04E–11	0.191	0.553	0.926	1,726	951	30
Mix 1:2	2,018	150	1.20E–06	0.180	0.567	0.851	1,711	936	30
Mix 1:3	2,083	180	4.59E–07	0.169	0.504	0.899	1,782	1,001	30
Mix 1:4	2,120	430	8.04E–09	0.159	0.465	0.917	1,830	1,062	30
Mix 1:5	2,071	140	1.14E–07	0.191	0.541	0.946	1,739	965	30
Mix 1:6	2,086	200	3.74E–07	0.174	0.508	0.918	1,777	1,005	30
Mix 1:7	2,137	350	9.70E–10	0.151	0.443	0.913	1,857	1,093	30
Mix 1b:2	2,177	1,170	7.87E–11	0.132	1.345	0.899	1,924	1,173	30
Mix 1b:3	2,172	1,280	4.23E–11	0.135	1.368	0.903	1,915	1,161	30
Mix 1b:4	2,255	2,040	4.50E–12	0.131	1.177	1.022	1,994	1,263	30
Mix 1b:5	2,158	1,120	6.62E–11	0.157	1.493	0.963	1,866	1,103	30
Mix 1b:6	2,172	1,500	1.63E–11	0.131	1.352	0.888	1,921	1,169	30
Mix 1b:7	2,172	1,930	1.32E–09	0.137	1.376	0.911	1,911	1,157	30

Sample 1	water I	De-ionized water
Sample 2–4	water II	3.5% 50/50 $NaCl/CaCl_2$
Sample 5–7	water III	7.0% 50/50 $NaCl/CaCl_2$

ρ_s = 2,750 kg/m³

ρ_w = 1,000 kg/m³

Sample	ρ_m	p_s	c_h	w	e	S_r	ρ_d	$\rho_{d\ clay}$	Clay cont.
Unit	kg/m^3	kPa	m/s	%			kg/m^3	kg/m^3	%
Mix 2:1	2,114	420	2.00E–12	0.182	0.498	0.980	1,789	1,017	30
Mix 2:2	2,145	270	1.47E–11	0.179	0.473	1.015	1,820	1,051	30
Mix 2:3	2,160	540	2.24E–11	0.141	0.416	0.911	1,893	1,135	30
Mix 2:4	2,175	460	1.26E–11	0.149	0.416	0.962	1,893	1,135	30
Mix 2:5	2,140	300	8.06E–11	0.152	0.442	0.920	1,859	1,095	30
Mix 2:6	2,196	350	2.67E–11	0.157	0.411	1.021	1,899	1,142	30
Mix 2:7	2,218	500	1.52E–11	0.158	0.399	1.063	1,915	1,162	30
Mix 3:1	2,071	120	7.06E–11	0.216	0.573	1.010	1,704	929	30
Mix 3:2	2,110	150	3.37E–10	0.162	0.475	0.913	1,816	1,047	30
Mix 3:3	2,135	180	1.80E–10	0.156	0.451	0.927	1,847	1,082	30
Mix 3:4	2,176	430	5.30E–11	0.169	0.439	1.031	1,862	1,099	30
Mix 3:5	2,126	140	7.30E–10	0.169	0.473	0.957	1,819	1,050	30
Mix 3:6	2,167	200	1.74E–10	0.158	0.432	0.981	1,872	1,110	30
Mix 3:7	2,189	350	4.60E–11	0.156	0.415	1.007	1,894	1,137	30
Mix 4:1	2,119	420	1.18E–11	0.197	0.519	1.021	1,771	1,182	40
Mix 4:2	2,106	290	2.35E–11	0.193	0.523	0.992	1,766	1,176	40
Mix 4:3	2,148	635	9.58E–12	0.179	0.476	1.011	1,822	1,240	40
Mix 4:4	2,149	765	8.54E–12	0.165	0.434	1.021	1,875	1,303	40
Mix 4:5	2,118	320	2.32E–11	0.185	0.505	0.986	1,788	1,201	40
Mix 4:6	2,166	515	1.21E–11	0.174	0.458	1.023	1,846	1,267	40
Mix 4:7	2,189	765	7.10E–12	0.165	0.431	1.029	1,880	1,308	40
Mix 5:1	1,927	630	1.12E–11	0.316	0.843	1.011	1,465	1,012	50
Mix 5:2	1,902	180	4.90E–11	0.297	0.529	0.985	1,467	1,323	50
Mix 5:3	1,942	260	2.10E–11	0.290	0.481	1.003	1,506	1,388	50
Mix 5:4	2,020	480	1.40E–11	0.315	0.440	1.013	1,536	1,450	50
Mix 5:5	1,926	100	1.10E–10	0.284	0.510	0.979	1,500	1,349	50
Mix 5:6	1,964	150	4.60E–11	0.280	0.463	1.014	1,535	1,415	50
Mix 5:7	2,013	200	4.40E–11	0.261	0.436	1.020	1,597	1,455	50
Mix 6:1	2,046	160	4.46E–11	0.191	0.560	0.914	1,718	944	30
Mix 6:2	2,109	270	2.41E–11	0.173	0.490	0.946	1,798	1,027	30
Mix 6:3	2,145	495	1.47E–11	0.158	0.446	0.948	1,853	1,088	30
Mix 6:4	2,162	765	1.19E–11	0.145	0.419	0.927	1,889	1,130	30
Mix 6:5	2,128	312	2.63E–11	0.165	0.467	0.947	1,827	1,059	30
Mix 6:6	2,149	465	1.58E–11	0.154	0.439	0.940	1,863	1,100	30
Mix 6:7	2,164	610	1.75E–11	0.149	0.423	0.945	1,884	1,124	30
Mix 7:1	2,047	270	5.09E–11	0.192	0.560	0.918	1,718	943	30
Mix 7:2	2,087	200	8.62E–11	0.191	0.529	0.967	1,753	979	30
Mix 7b:3	2,124	450	2,98E–11	0.163	0.467	0.935	1,827	1,059	30
Mix 7b:4	2,148	1,000	3.52E–11	0.156	0.442	0.946	1,859	1,095	30
Mix 7:5	2,083	185	1.40E–10	0.174	0.510	0.914	1,775	1,002	30
Mix 7b:6	2,149	450	2.69E–11	0.162	0.449	0.967	1,850	1,085	30
Mix 7b:7	2,182	790	1,09E–11	0.148	0.410	0.968	1,901	1,145	30

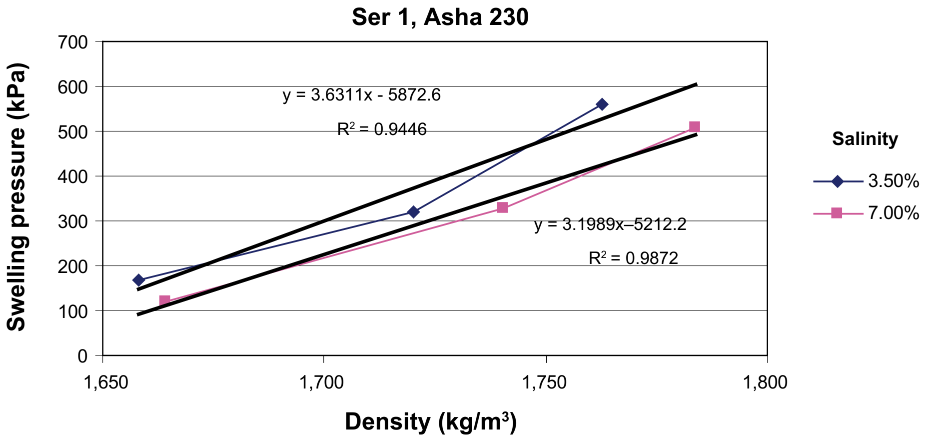
Sample 1	water I	De-ionized water
Sample 2–4	water II	3.5% 50/50 $NaCl/CaCl_2$
Sample 5–7	water III	7.0% 50/50 $NaCl/CaCl_2$

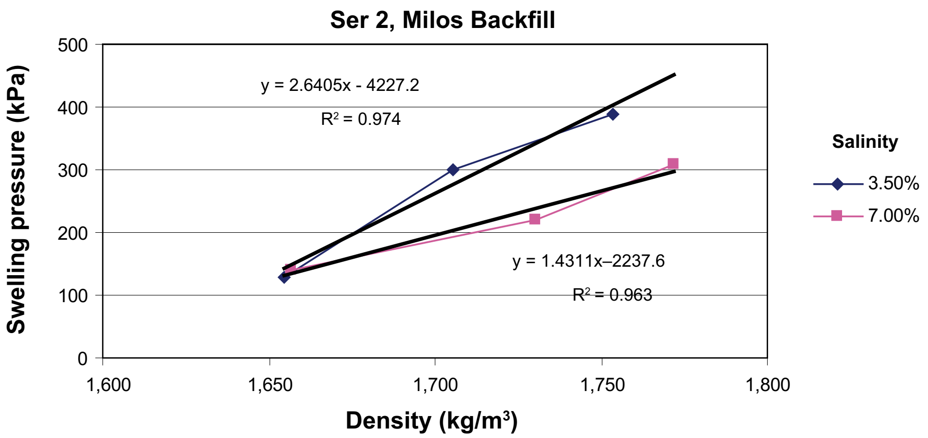
ρ_s = 2,750 kg/m^3

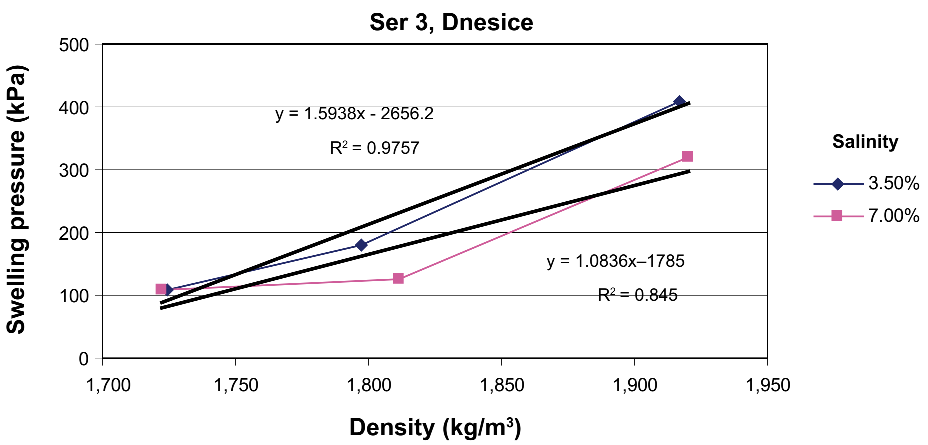
ρ_w = 1,000 kg/m^3

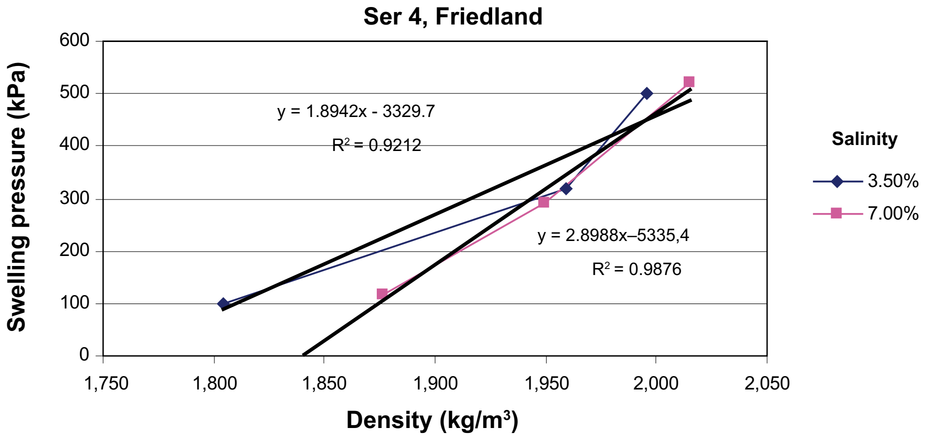
Appendix II

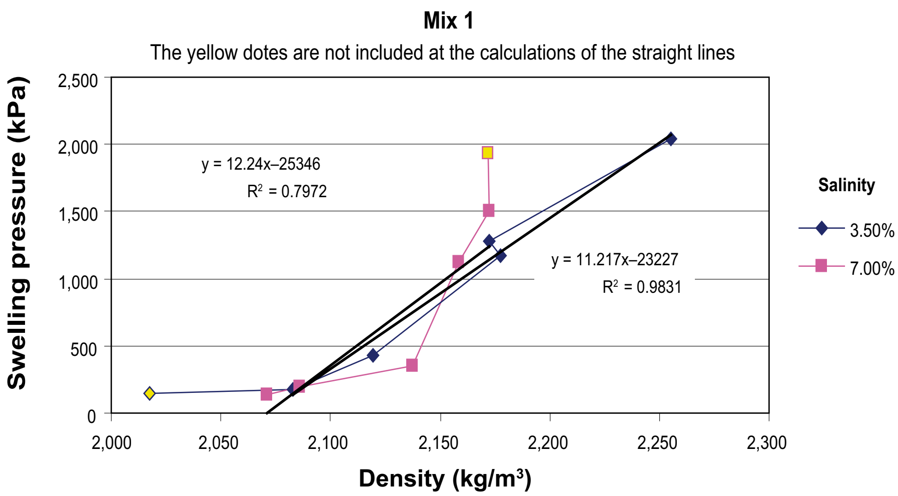
Measured swelling pressure plotted as function of saturated density for the investigated materials

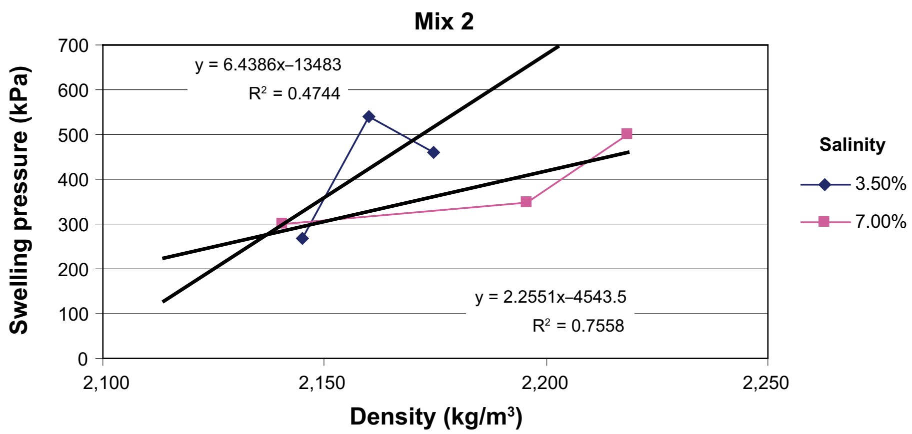


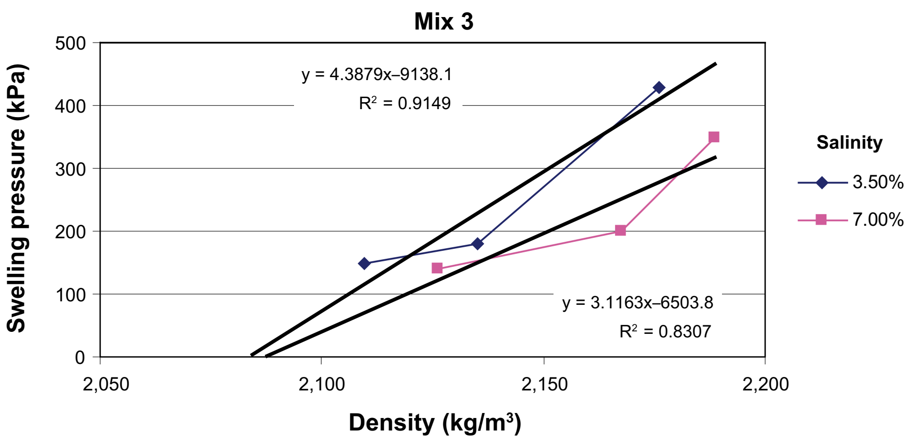


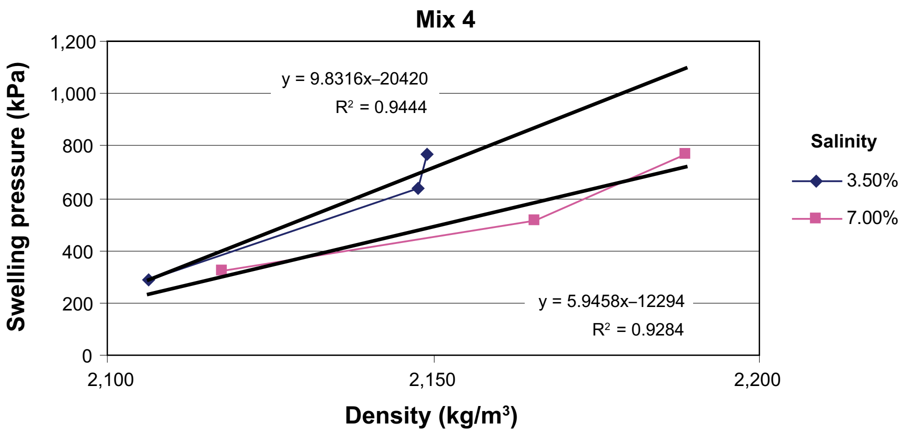


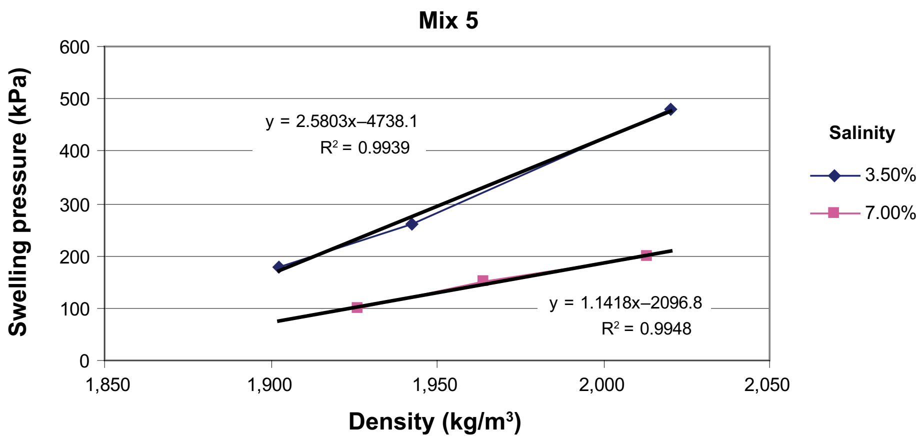

Ser 4, Friedland
Swelling pressure (kPa)
600
500
400
300
200
100
0
1,750
1,800
1,850
1,900
1,950
2,000
2,050
Density (kg/m³)
y = 1.8942x - 3329.7
R² = 0.9212
y = 2.8988x–5335,4
R² = 0.9876
Salinity
3.50%
7.00%

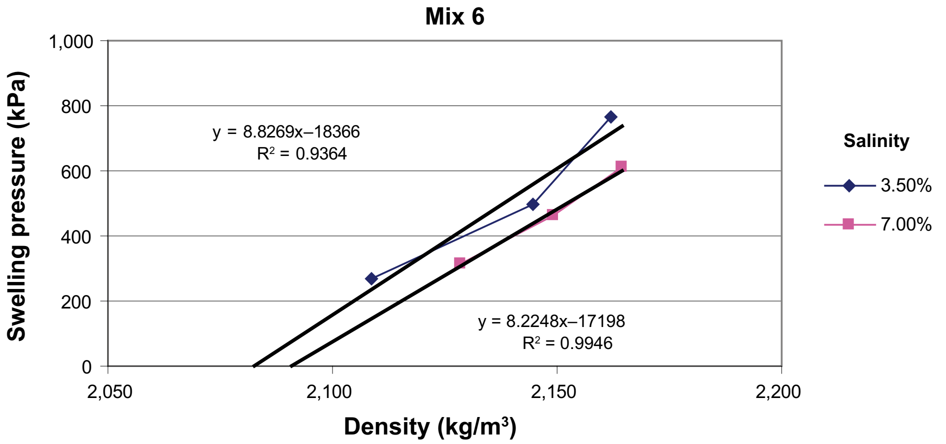

Mix 1
The yellow dotes are not included at the calculations of the straight lines
Swelling pressure (kPa)
2,500
2,000
1,500
1,000
500
0
2,000
2,050
2,100
2,150
2,200
2,250
2,300
Density (kg/m³)
y = 12.24x–25346
R² = 0.7972
y = 11.217x–23227
R² = 0.9831
Salinity
3.50%
7.00%


Mix 2
Swelling pressure (kPa)
700
600
500
400
300
200
100
0
2,100
2,150
2,200
2,250
Density (kg/m³)
y = 6.4386x–13483
R² = 0.4744
y = 2.2551x–4543.5
R² = 0.7558
Salinity
3.50%
7.00%

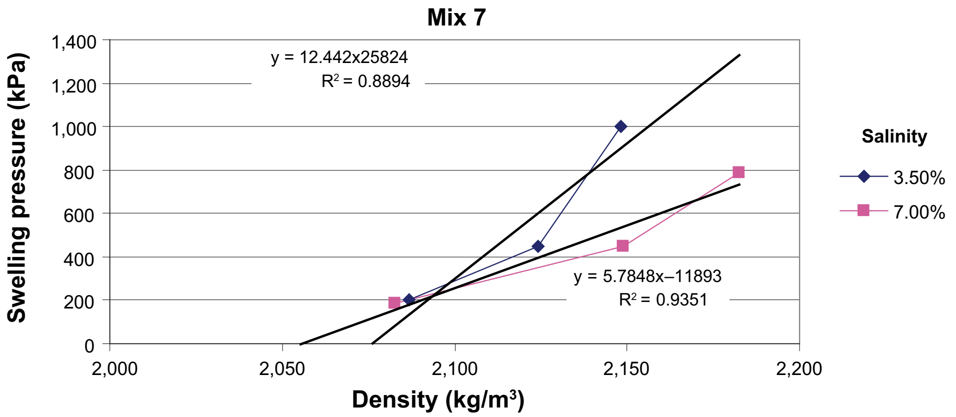

Mix 3
y = 4.3879x–9138.1
R² = 0.9149
y = 3.1163x–6503.8
R² = 0.8307
Swelling pressure (kPa)
Density (kg/m³)
Salinity
3.50%
7.00%
0
100
200
300
400
500
2,050
2,100
2,150
2,200


Mix 4
y = 9.8316x–20420
R² = 0.9444
y = 5.9458x–12294
R² = 0.9284
Swelling pressure (kPa)
Density (kg/m³)
Salinity
3.50%
7.00%
0
200
400
600
800
1,000
1,200
2,100
2,150
2,200


Mix 5
y = 2.5803x–4738.1
R² = 0.9939
y = 1.1418x–2096.8
R² = 0.9948
Swelling pressure (kPa)
Density (kg/m³)
Salinity
3.50%
7.00%
0
100
200
300
400
500
600
1,850
1,900
1,950
2,000
2,050



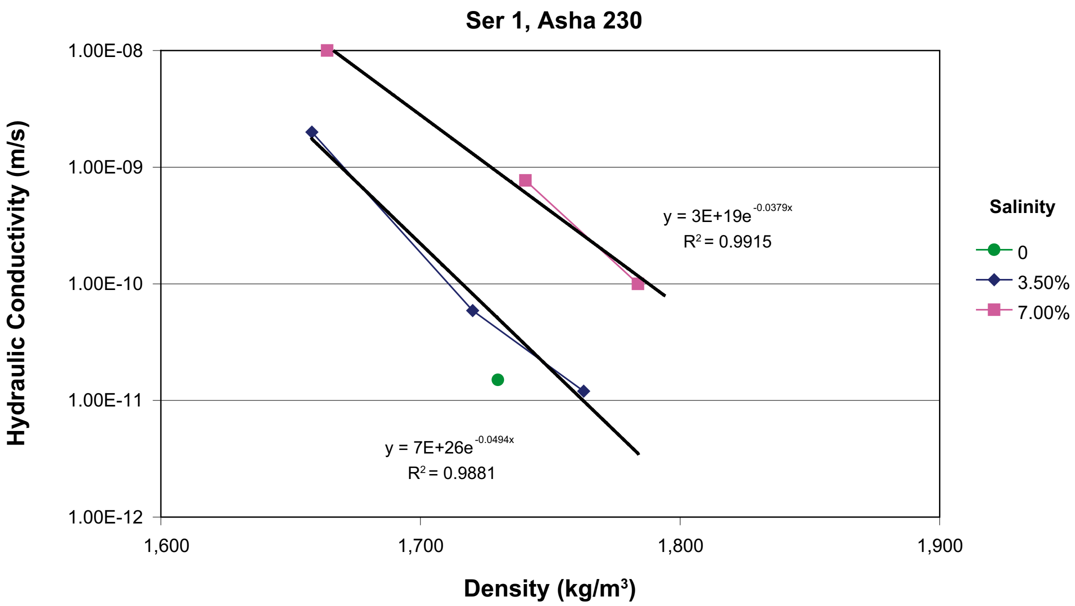
Mix 6
1,000
800
600
400
200
0
Swelling pressure (kPa)
y = 8.8269x–18366
R² = 0.9364
y = 8.2248x–17198
R² = 0.9946
2,050
2,100
2,150
2,200
Density (kg/m³)
Salinity
3.50%
7.00%

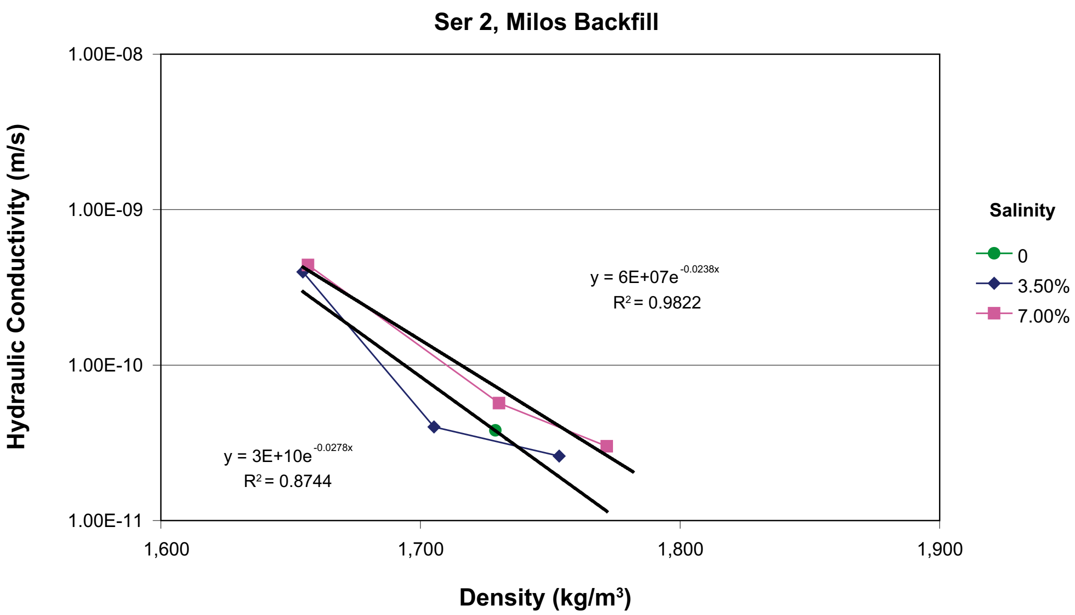


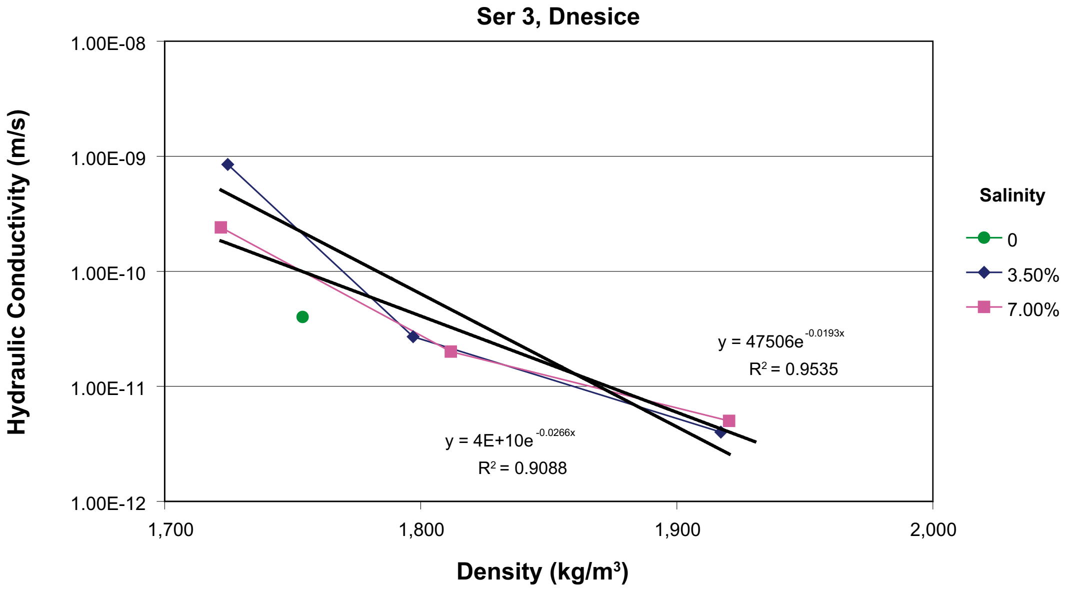
Mix 7
1,400
1,200
1,000
800
600
400
200
0
Swelling pressure (kPa)
y = 12.442x25824
R² = 0.8894
y = 5.7848x–11893
R² = 0.9351
2,000
2,050
2,100
2,150
2,200
Density (kg/m³)
Salinity
3.50%
7.00%

Appendix III

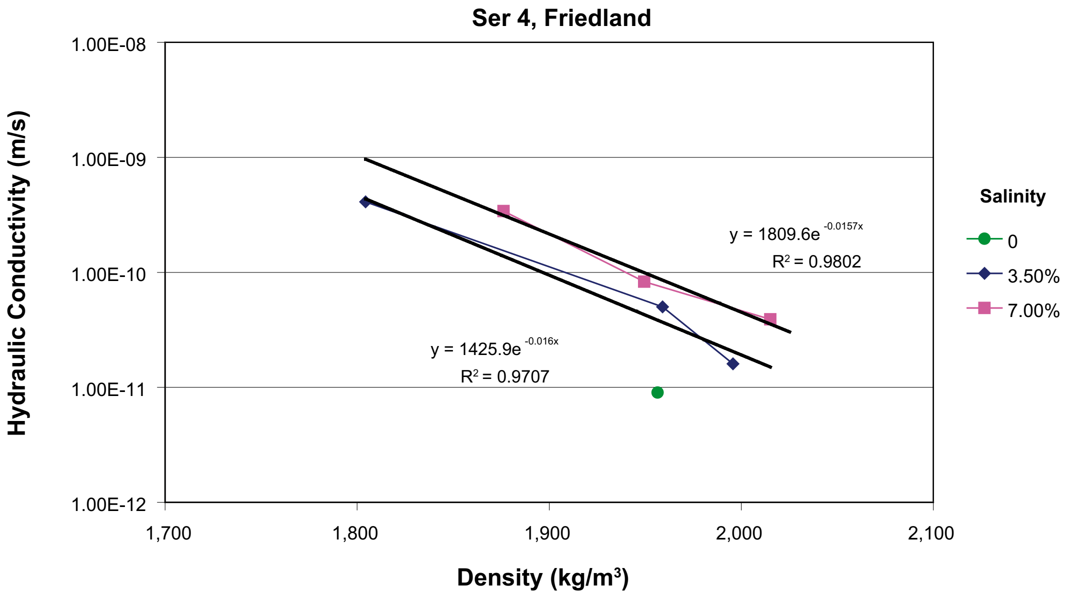
Measured hydraulic plotted as function of saturated density for the investigated materials



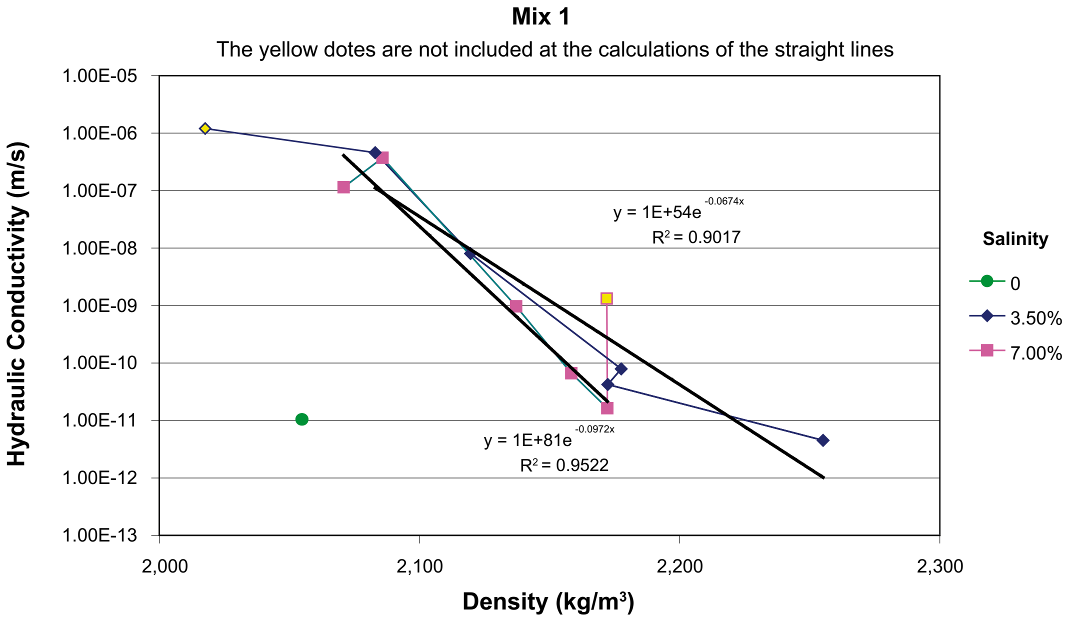


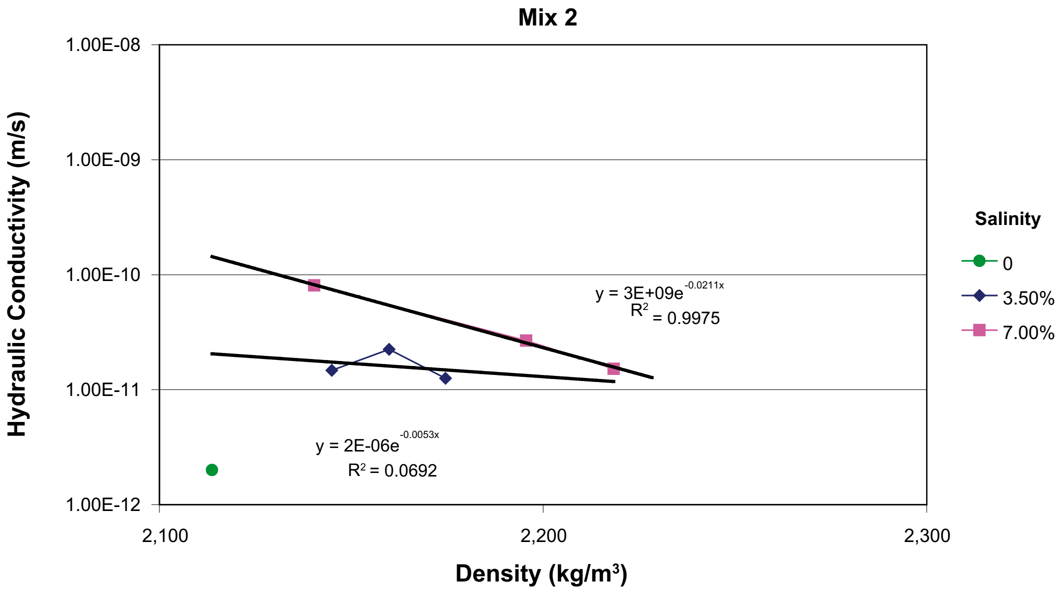


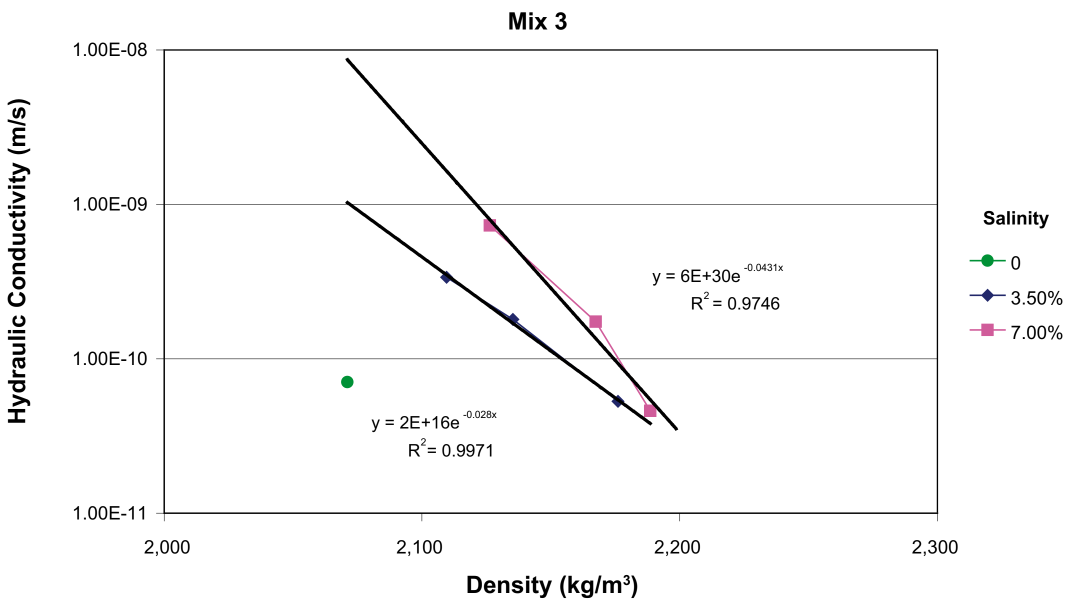
Ser 3, Dnesice
Hydraulic Conductivity (m/s)
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1,700
1,800
1,900
2,000
Density (kg/m³)
y = 47506e^-0.0193x
R² = 0.9535
y = 4E+10e^-0.0266x
R² = 0.9088
Salinity
0
3.50%
7.00%

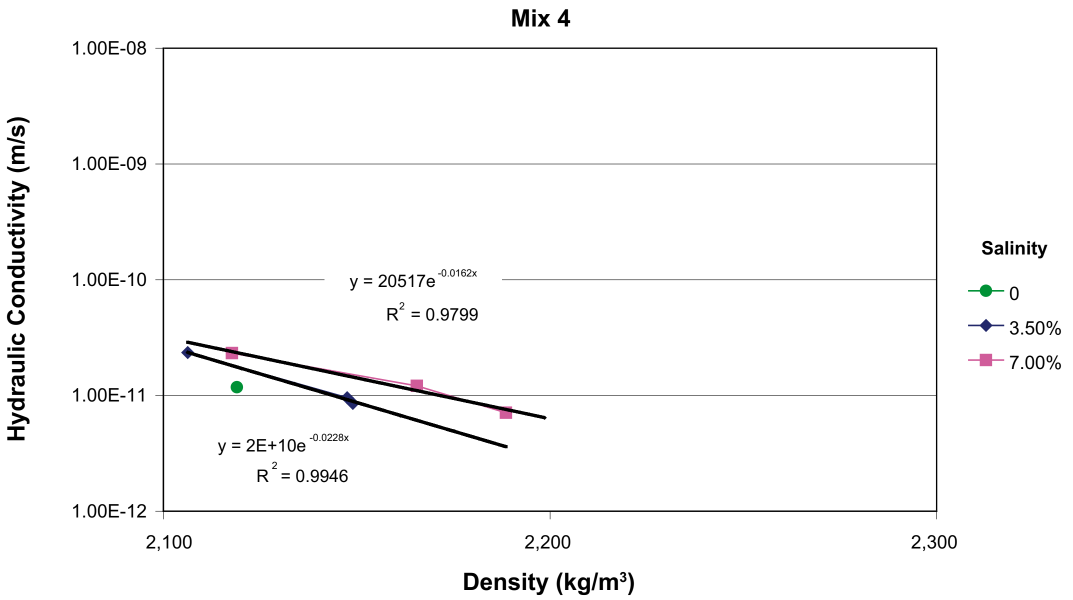


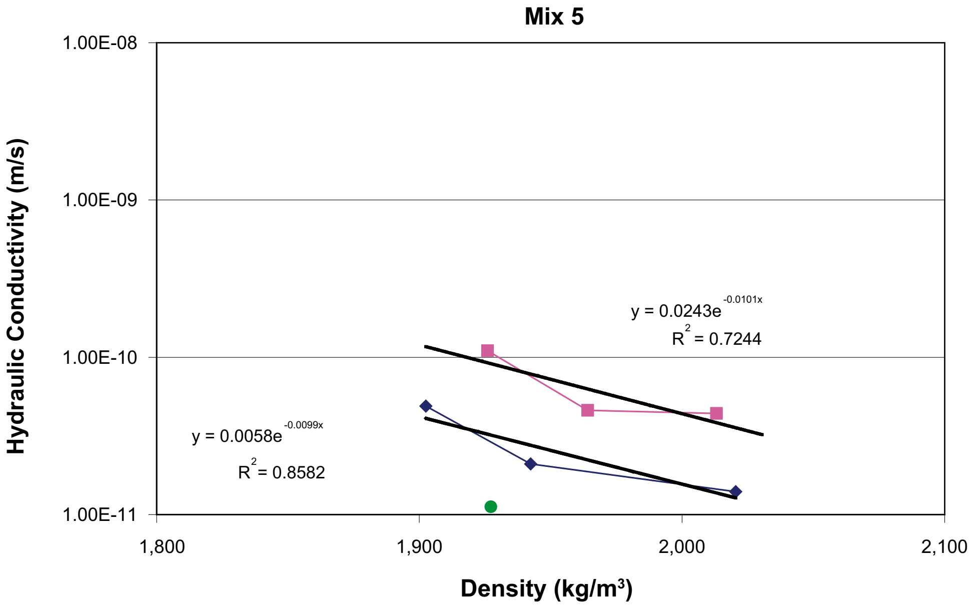
Ser 4, Friedland
Hydraulic Conductivity (m/s)
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1,700
1,800
1,900
2,000
2,100
Density (kg/m³)
y = 1809.6e^-0.0157x
R² = 0.9802
y = 1425.9e^-0.016x
R² = 0.9707
Salinity
0
3.50%
7.00%


Mix 1
The yellow dotes are not included at the calculations of the straight lines
Hydraulic Conductivity (m/s)
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
2,000
2,100
2,200
2,300
Density (kg/m³)
y = 1E+54e^-0.0674x
R² = 0.9017
y = 1E+81e^-0.0972x
R² = 0.9522
Salinity
0
3.50%
7.00%

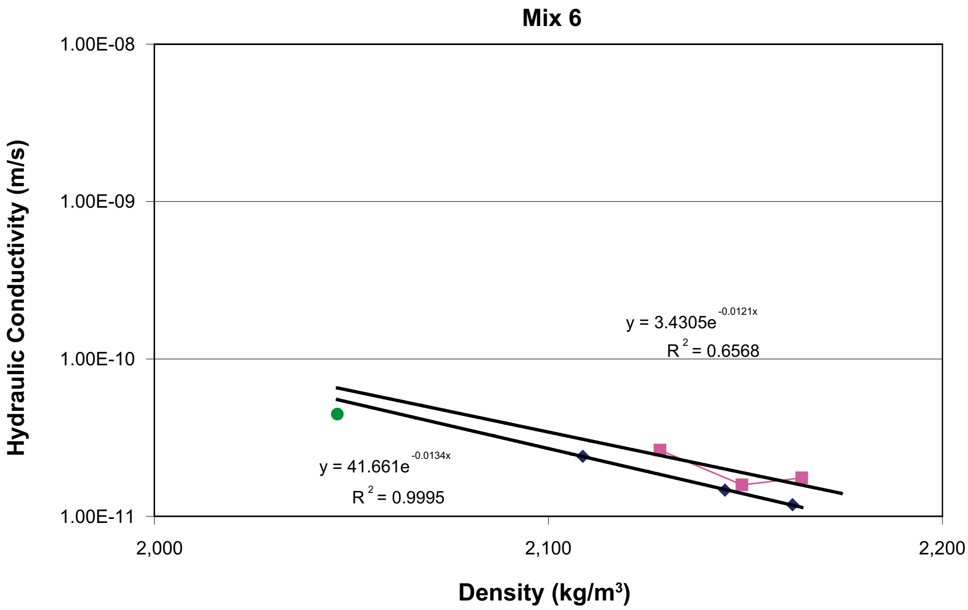

Mix 2
Hydraulic Conductivity (m/s)
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
2,100
2,200
2,300
Density (kg/m³)
y = 3E+09e^-0.0211x
R² = 0.9975
y = 2E-06e^-0.0053x
R² = 0.0692
Salinity
0
3.50%
7.00%


Mix 3
Hydraulic Conductivity (m/s)
1.00E-08
1.00E-09
1.00E-10
1.00E-11
2,000
2,100
2,200
2,300
Density (kg/m³)
y = 6E+30e -0.0431x
R2 = 0.9746
y = 2E+16e -0.028x
R2 = 0.9971
Salinity
0
3.50%
7.00%

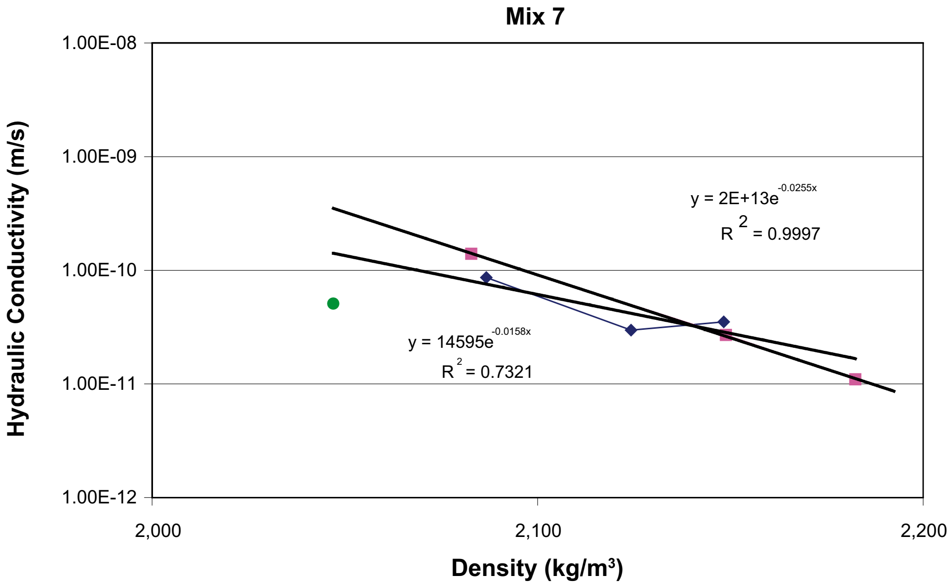

Mix 4
Hydraulic Conductivity (m/s)
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
2,100
2,200
2,300
Density (kg/m³)
y = 20517e -0.0162x
R2 = 0.9799
y = 2E+10e -0.0228x
R2 = 0.9946
Salinity
0
3.50%
7.00%



Mix 5
1.00E-08
1.00E-09
1.00E-10
1.00E-11
Hydraulic Conductivity (m/s)
y = 0.0243e^-0.0101x
R^2 = 0.7244
y = 0.0058e^-0.0099x
R^2 = 0.8582
1,800
1,900
2,000
2,100
Density (kg/m³)



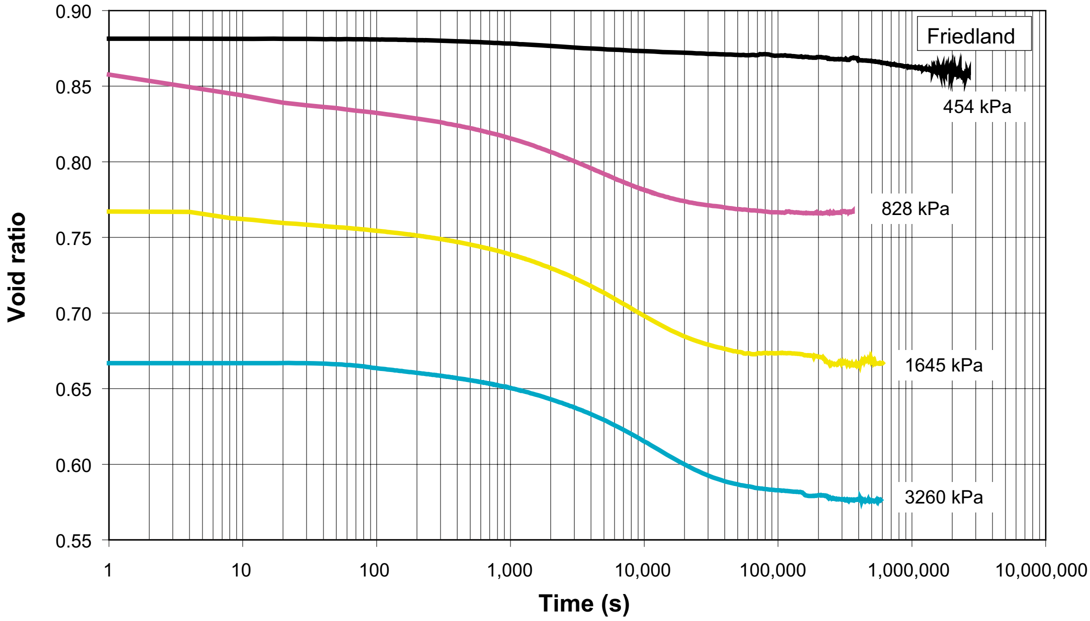
Mix 6
1.00E-08
1.00E-09
1.00E-10
1.00E-11
Hydraulic Conductivity (m/s)
y = 3.4305e^-0.0121x
R^2 = 0.6568
y = 41.661e^-0.0134x
R^2 = 0.9995
2,000
2,100
2,200
Density (kg/m³)

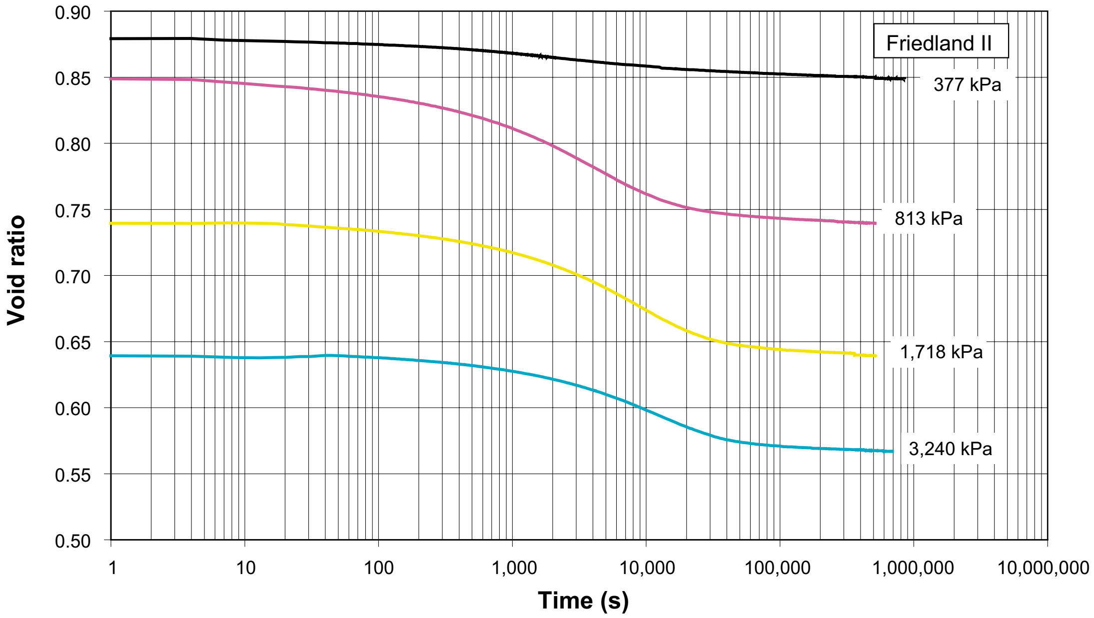


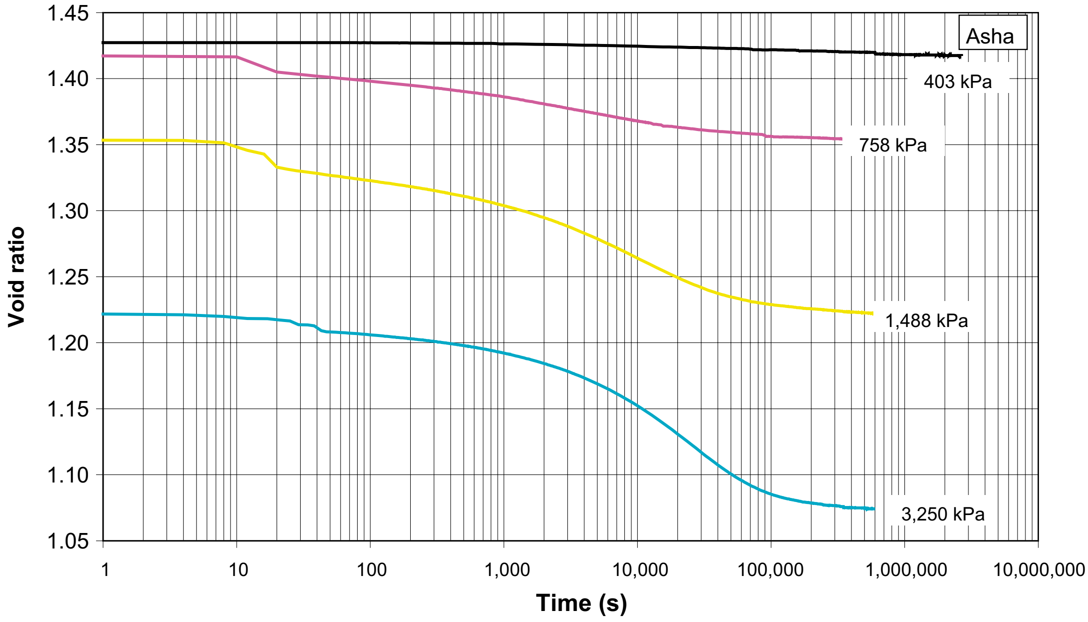
Mix 7
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
Hydraulic Conductivity (m/s)
y = 2E+13e^-0.0255x
R 2 = 0.9997
y = 14595e^-0.0158x
R 2 = 0.7321
2,000
2,100
2,200
Density (kg/m³)

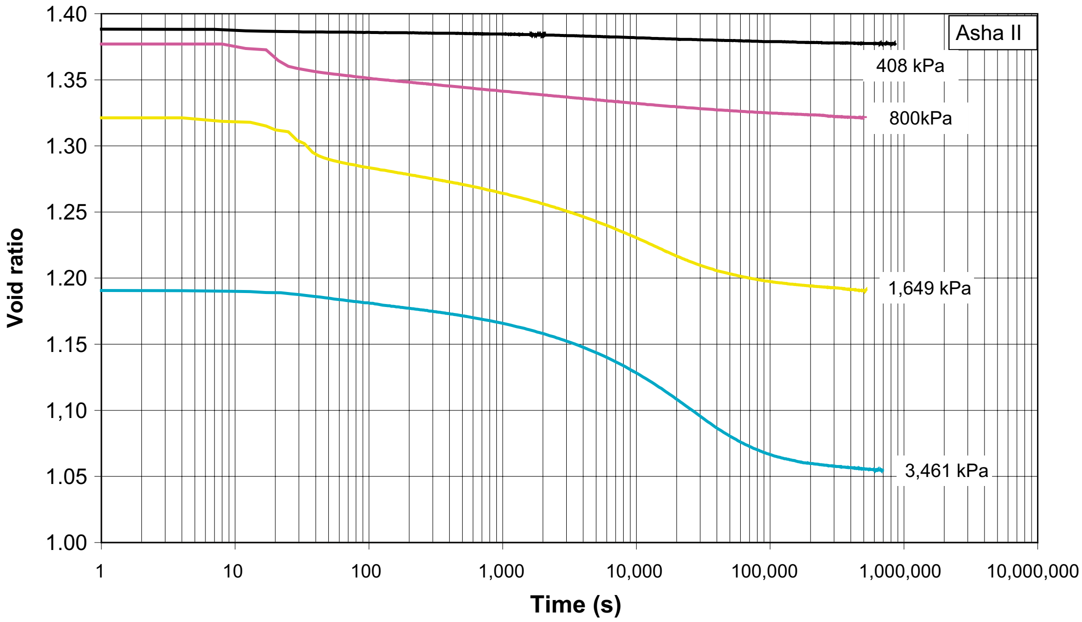
Appendix IV

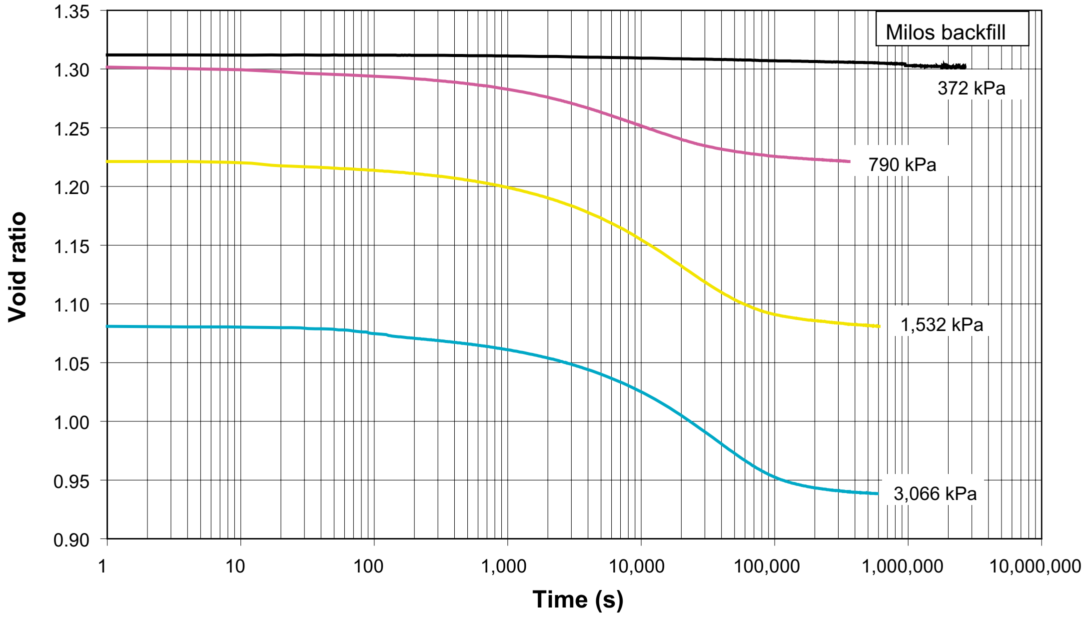
Oedometer tests

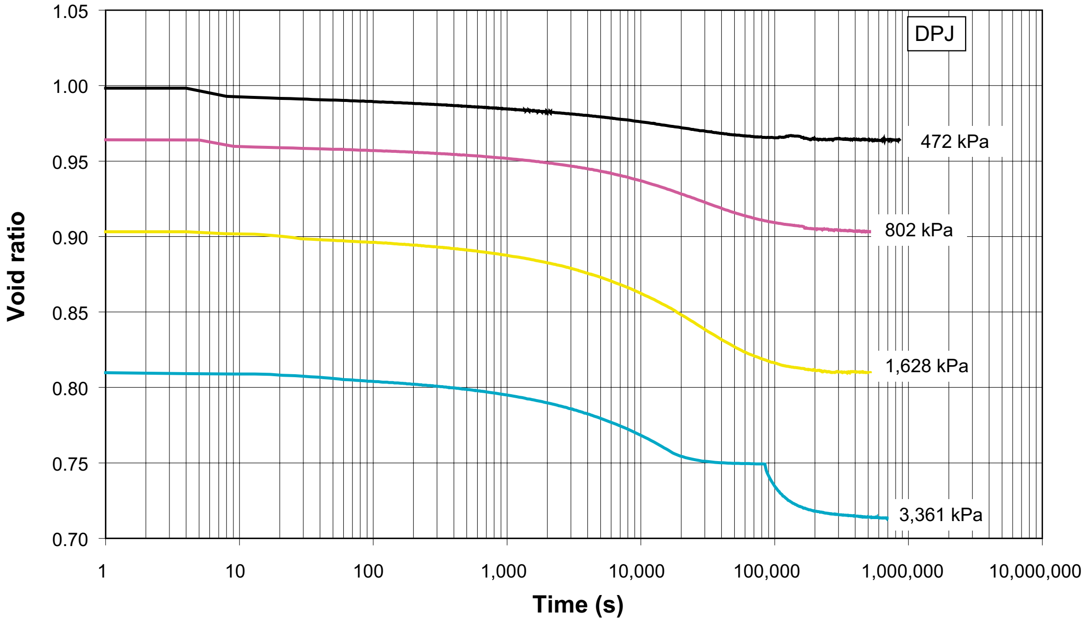


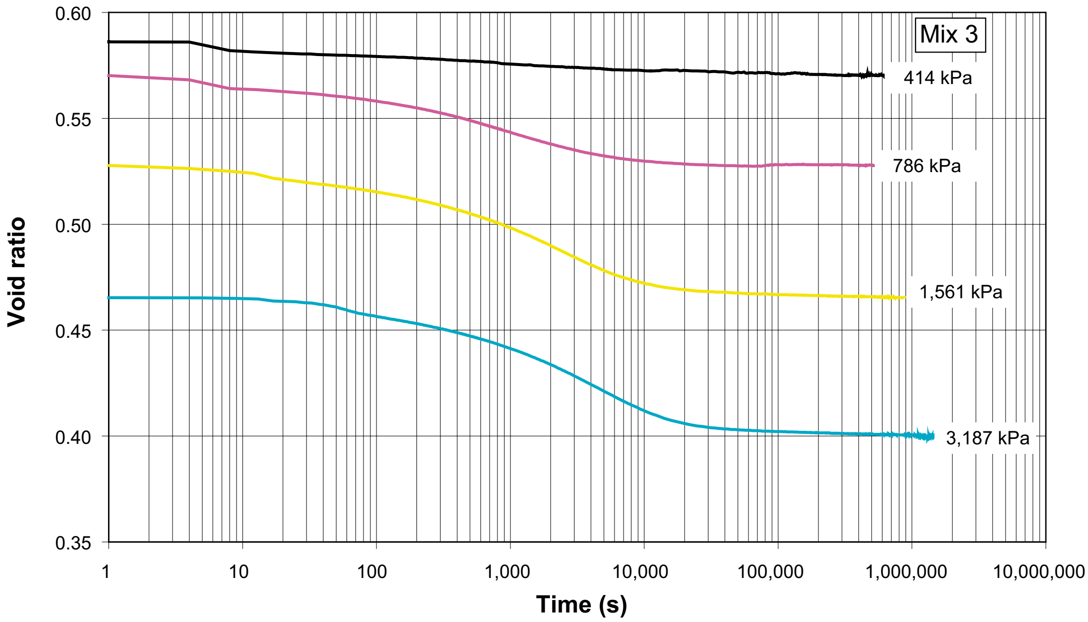


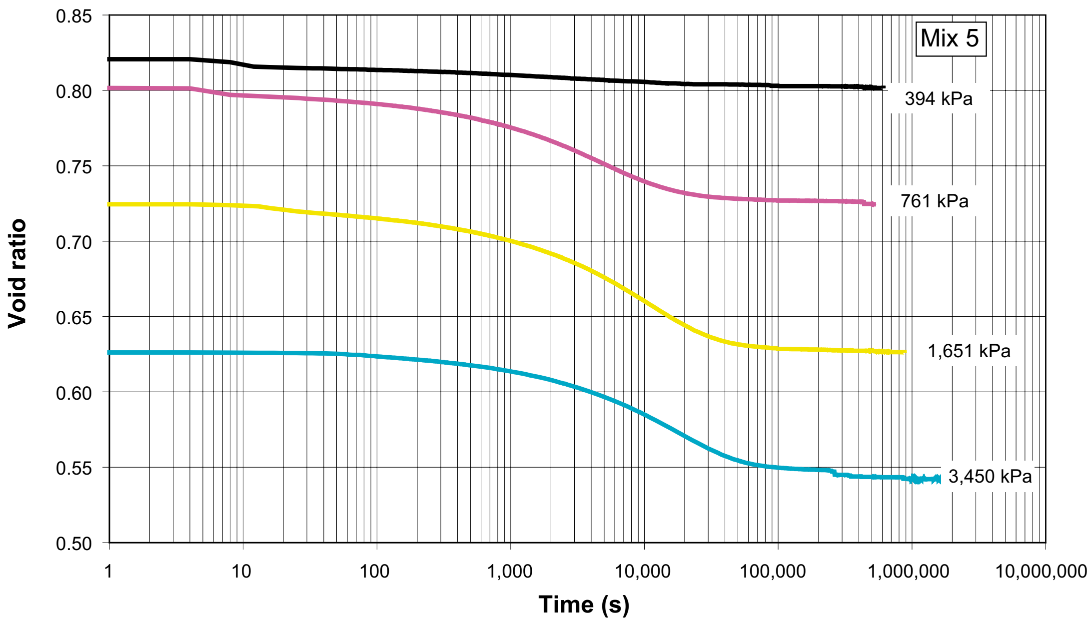

1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
Void ratio
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time (s)
Asha
403 kPa
758 kPa
1,488 kPa
3,250 kPa

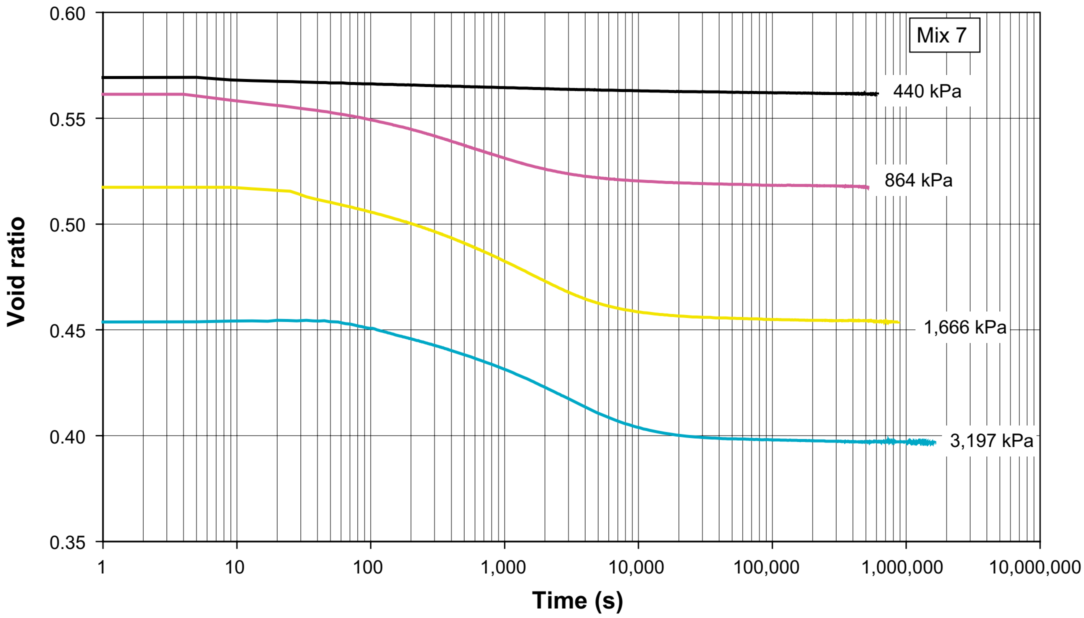

1.40
1.35
1.30
1.25
1.20
1.15
1,10
1.05
1.00
Void ratio
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time (s)
Asha II
408 kPa
800kPa
1,649 kPa
3,461 kPa


Milos backfill
Void ratio
Time (s)
372 kPa
790 kPa
1,532 kPa
3,066 kPa
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000

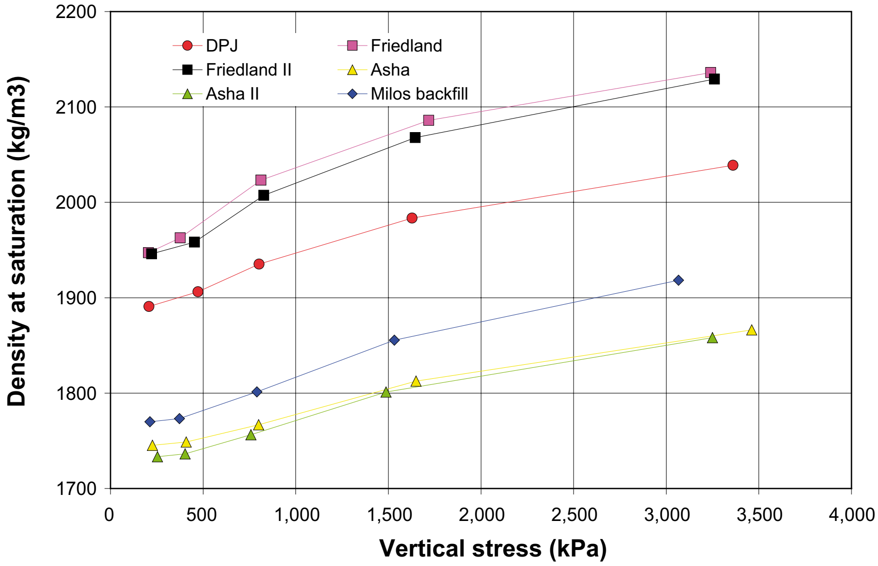

DPJ
Void ratio
Time (s)
472 kPa
802 kPa
1,628 kPa
3,361 kPa
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000


Mix 3
414 kPa
786 kPa
1,561 kPa
3,187 kPa
Void ratio
0.60
0.55
0.50
0.45
0.40
0.35
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time (s)

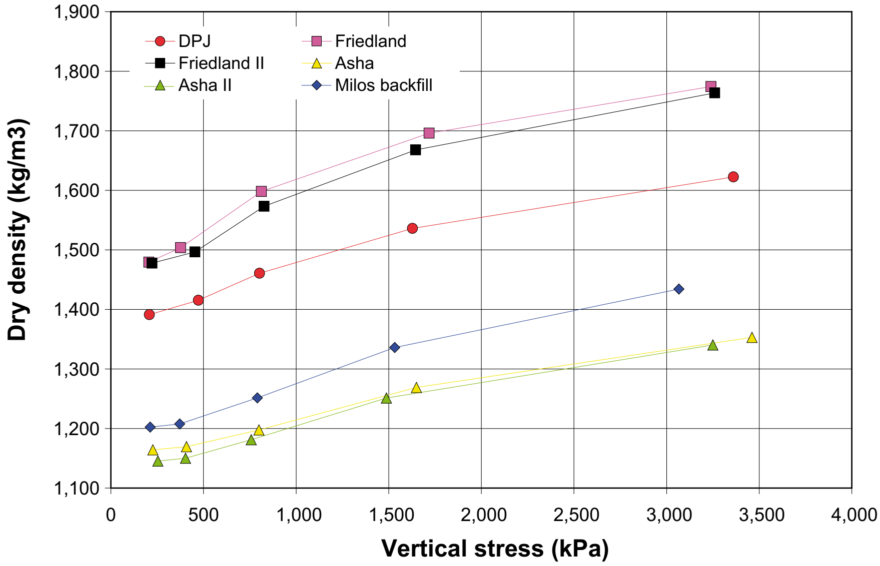

Mix 5
394 kPa
761 kPa
1,651 kPa
3,450 kPa
Void ratio
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time (s)



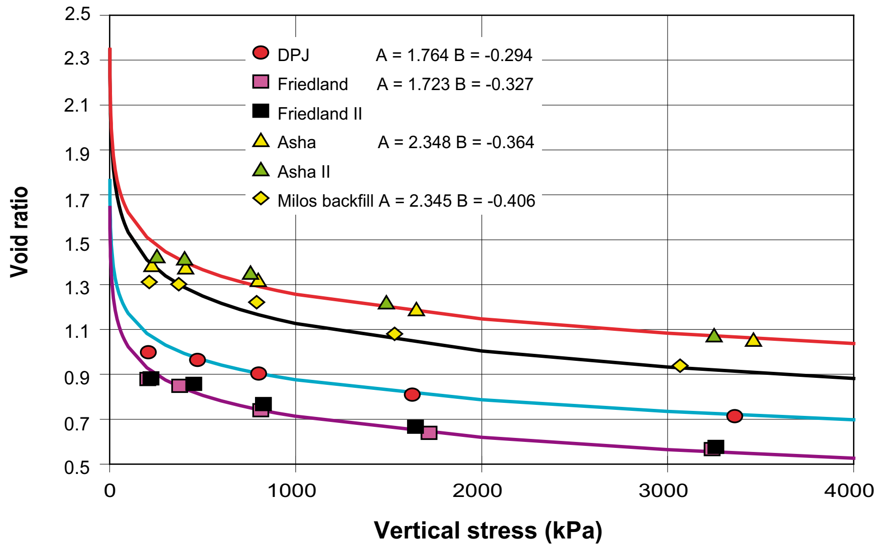
Mix 7
440 kPa
864 kPa
1,666 kPa
3,197 kPa
Void ratio
0.60
0.55
0.50
0.45
0.40
0.35
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time (s)

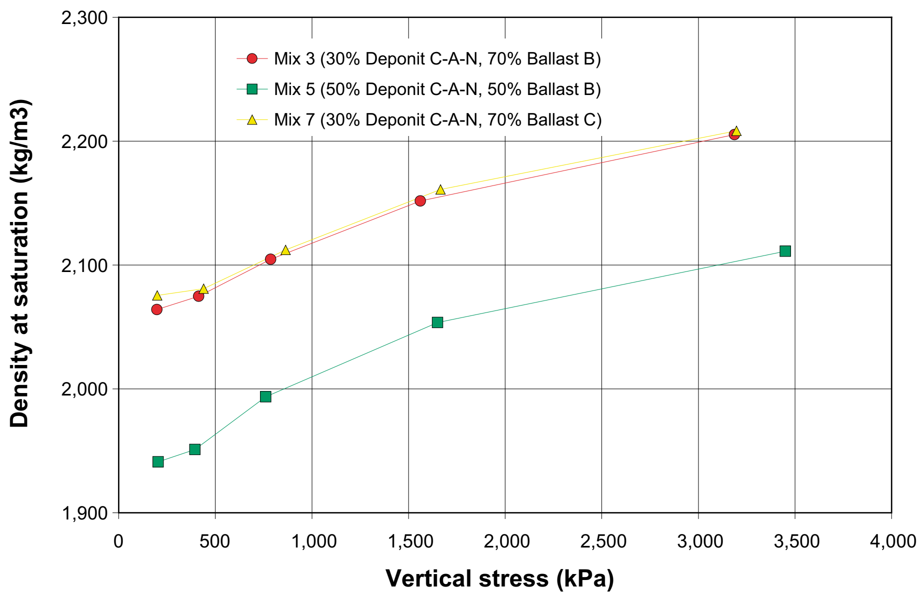


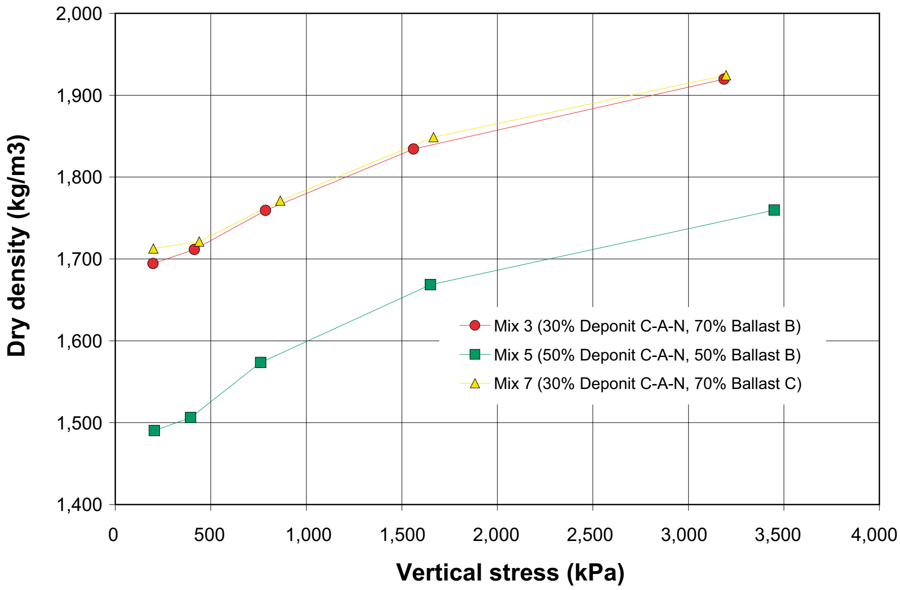
Density at saturation (kg/m3)
Vertical stress (kPa)
DPJ
Friedland
Friedland II
Asha
Asha II
Milos backfill
2200
2100
2000
1900
1800
1700
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000

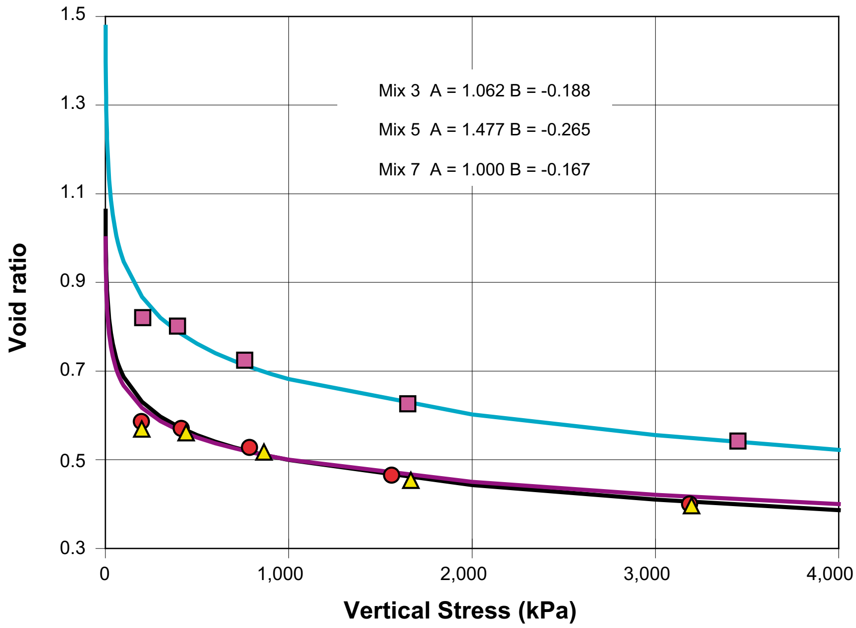


Dry density (kg/m3)
Vertical stress (kPa)
DPJ
Friedland
Friedland II
Asha
Asha II
Milos backfill
1,900
1,800
1,700
1,600
1,500
1,400
1,300
1,200
1,100
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000


DPJ A = 1.764 B = -0.294
Friedland A = 1.723 B = -0.327
Friedland II
Asha A = 2.348 B = -0.364
Asha II
Milos backfill A = 2.345 B = -0.406
Void ratio
Vertical stress (kPa)
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0
1000
2000
3000
4000

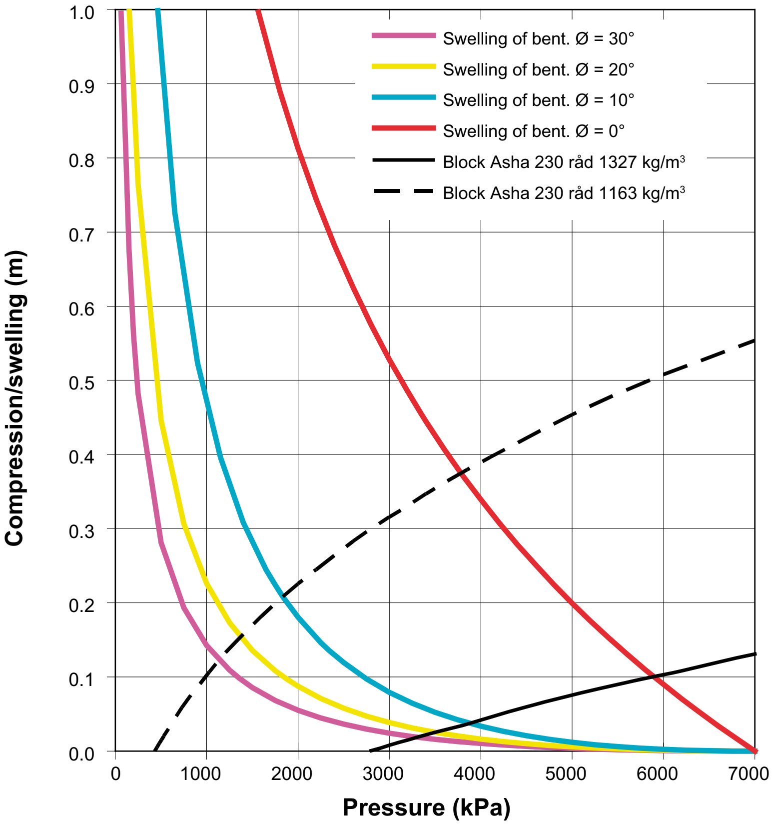

Mix 3 (30% Deponit C-A-N, 70% Ballast B)
Mix 5 (50% Deponit C-A-N, 50% Ballast B)
Mix 7 (30% Deponit C-A-N, 70% Ballast C)
Density at saturation (kg/m3)
Vertical stress (kPa)
2,300
2,200
2,100
2,000
1,900
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000

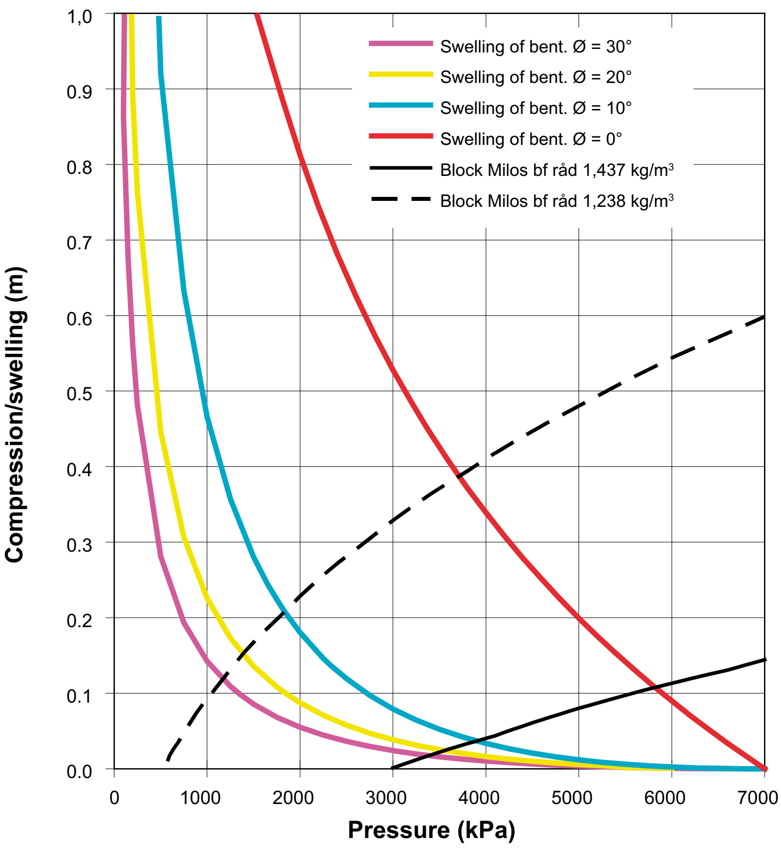

Dry density (kg/m3)
2,000
1,900
1,800
1,700
1,600
1,500
1,400
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Vertical stress (kPa)
Mix 3 (30% Deponit C-A-N, 70% Ballast B)
Mix 5 (50% Deponit C-A-N, 50% Ballast B)
Mix 7 (30% Deponit C-A-N, 70% Ballast C)

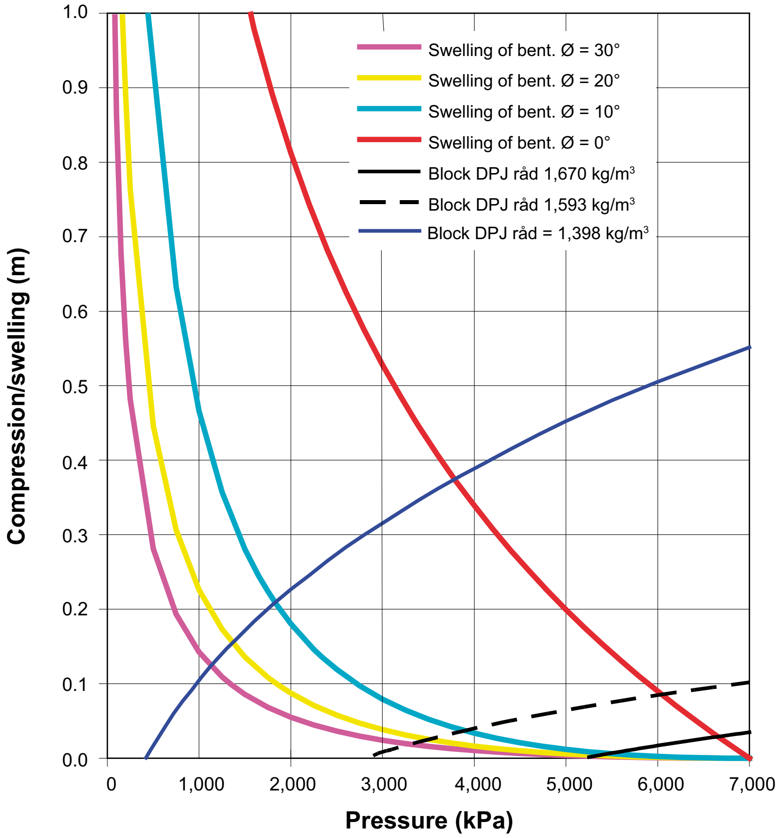

Void ratio
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0
1,000
2,000
3,000
4,000
Vertical Stress (kPa)
Mix 3 A = 1.062 B = -0.188
Mix 5 A = 1.477 B = -0.265
Mix 7 A = 1.000 B = -0.167

Appendix V

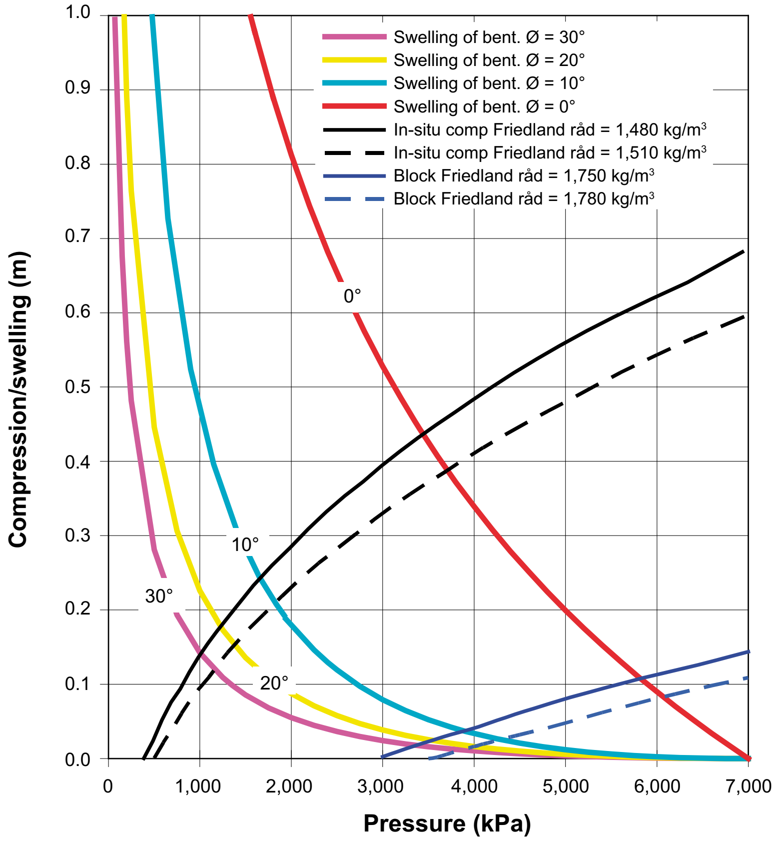
Plots from calculation of the compression of the backfill



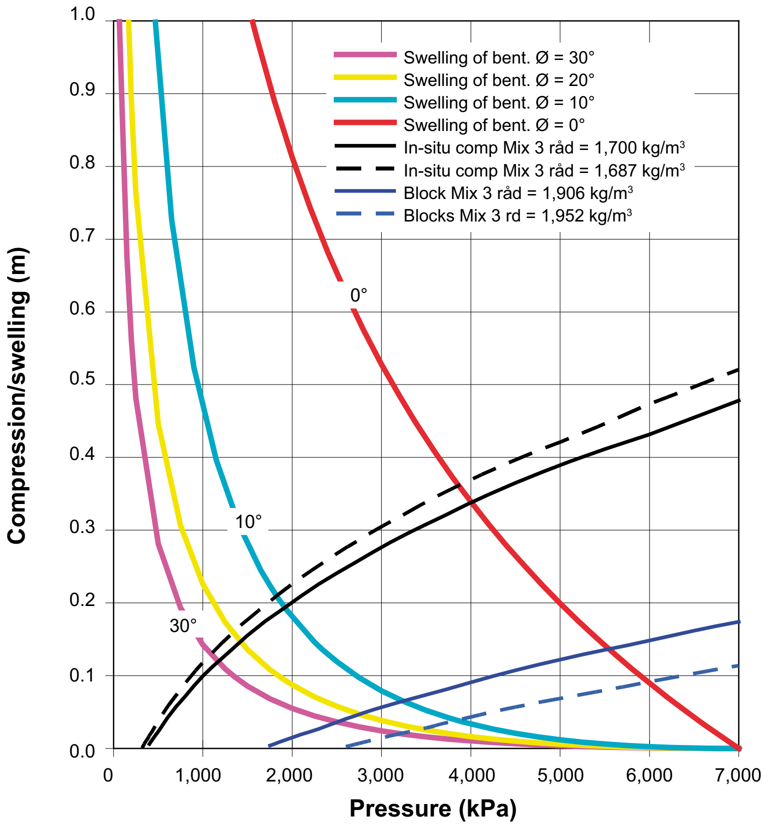


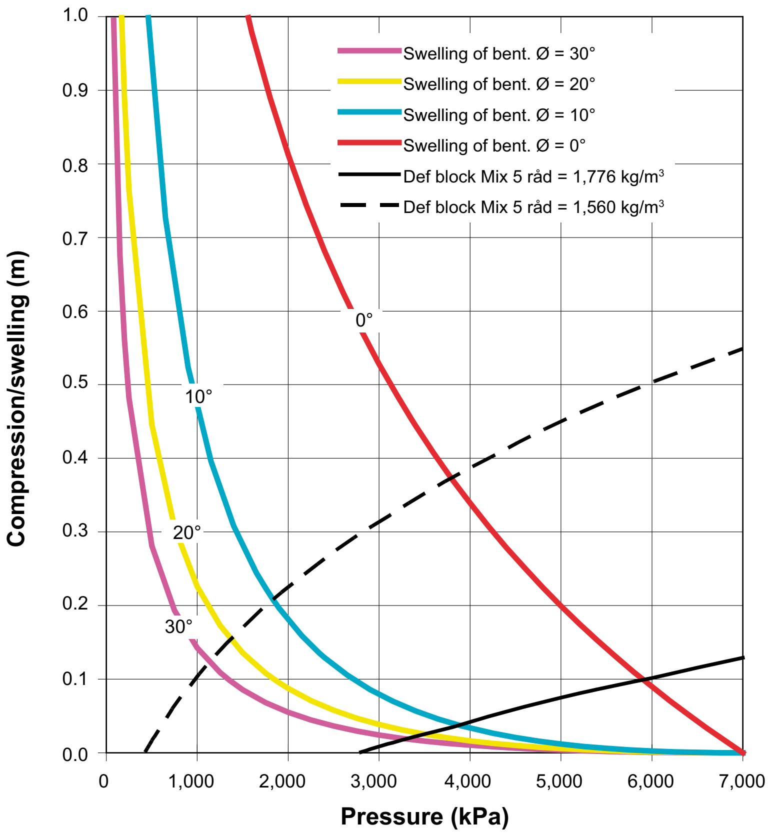


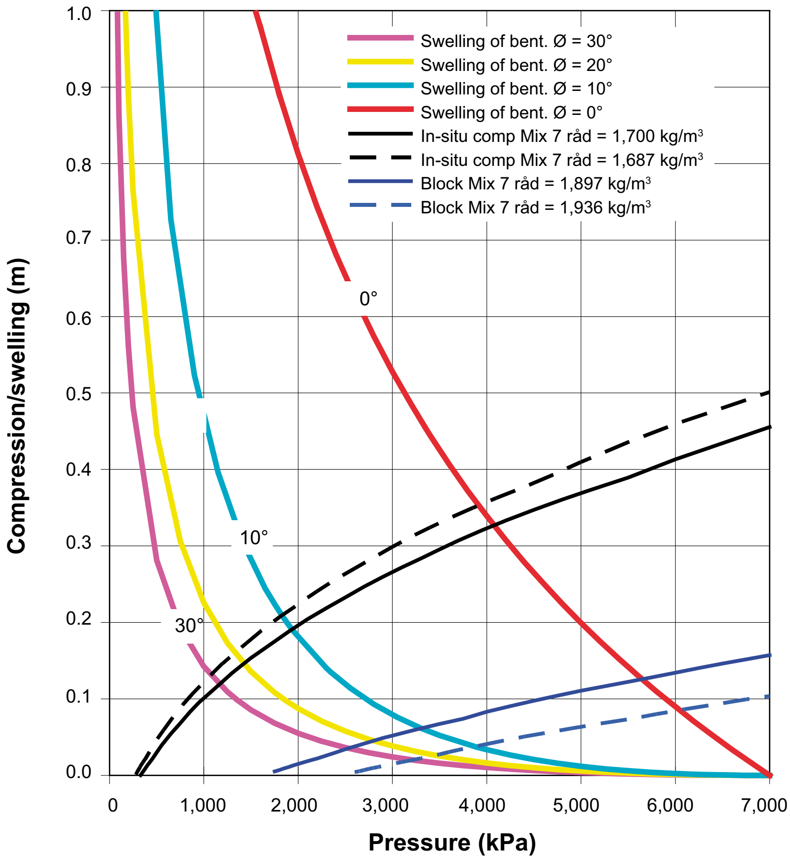
Swelling of bent. Ø = 30°
Swelling of bent. Ø = 20°
Swelling of bent. Ø = 10°
Swelling of bent. Ø = 0°
Block DPJ råd 1,670 kg/m³
Block DPJ råd 1,593 kg/m³
Block DPJ råd = 1,398 kg/m³
Compression/swelling (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Pressure (kPa)



Swelling of bent. Ø = 30°
Swelling of bent. Ø = 20°
Swelling of bent. Ø = 10°
Swelling of bent. Ø = 0°
In-situ comp Friedland råd = 1,480 kg/m³
In-situ comp Friedland råd = 1,510 kg/m³
Block Friedland råd = 1,750 kg/m³
Block Friedland råd = 1,780 kg/m³
0°
10°
30°
20°
Compression/swelling (m)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Pressure (kPa)


Swelling of bent. Ø = 30°
Swelling of bent. Ø = 20°
Swelling of bent. Ø = 10°
Swelling of bent. Ø = 0°
In-situ comp Mix 3 råd = 1,700 kg/m³
In-situ comp Mix 3 råd = 1,687 kg/m³
Block Mix 3 råd = 1,906 kg/m³
Blocks Mix 3 rd = 1,952 kg/m³
0°
10°
30°
Compression/swelling (m)
Pressure (kPa)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Swelling of bent. Ø = 30°
Swelling of bent. Ø = 20°
Swelling of bent. Ø = 10°
Swelling of bent. Ø = 0°
Def block Mix 5 råd = 1,776 kg/m³
Def block Mix 5 råd = 1,560 kg/m³
0°
10°
20°
30°
Compression/swelling (m)
Pressure (kPa)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



Swelling of bent. Ø = 30°
Swelling of bent. Ø = 20°
Swelling of bent. Ø = 10°
Swelling of bent. Ø = 0°
In-situ comp Mix 7 råd = 1,700 kg/m³
In-situ comp Mix 7 råd = 1,687 kg/m³
Block Mix 7 råd = 1,897 kg/m³
Block Mix 7 råd = 1,936 kg/m³
0°
10°
30°
Compression/swelling (m)
Pressure (kPa)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000