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Äspö Hard Rock Laboratory

Backfill materials based on crushed rock (part 2)

Geotechnical properties determined in laboratory

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December 1999

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FOREWORD

This report describes results from ongoing laboratory tests on backfill materials that will be used in the Backfill and Plug Test in Äspö HRL. It is the second progress report in an intended series of 3.

The results from measurements of hydraulic conductivity described in chapter 3 is replacing the results from earlier tests described in the first progress report, since some of those results were incorrect due to problems with the test apparatus. *Thus, chapter 3 in this report is replacing chapter 5 in the progress report HRL-96-15.*

ABSTRACT

Laboratory tests on backfill material of crushed rock and mixtures of crushed rock and bentonite are described in this report. The tests have mainly been made during 1997. The bentonite content of the backfill varies between 0 and 30% and the ballast material consists of crushed TBM-muck in all tests. The tests have been made in order to supplement, and concerning hydraulic conductivity, also replace results from earlier tests, described in PR-HRL-96-15.

The tests have yielded the following results:

- Measurement of hydraulic conductivity at different bentonite content, density, salt content of added water, and initial water ratio at compaction.

- Measurement of swelling pressure at different bentonite content, density, and initial water ratio at compaction.

- Measurement of swelling potential of different backfill mixtures, which were compacted to 90% degree of compaction and saturated with Äspö water.

- Measurement of negative pore water pressure (suction) of unsaturated backfill materials. Both the total suction and the matric suction have been measured. Three different measuring techniques have been used and backfill material with different bentonite content, density, salt content of added water, and water ratio have been tested.

- Measurements of water transport and water saturation process in unsaturated backfill materials. Free water has been supplied from a filter in one end of samples confined in oedometers. The tests have been interrupted at different times and the water ratio distribution in the samples measured.

The results from the tests are indicting the following:

- The measured hydraulic conductivity of the tested backfill materials decreased with increasing clay content and density. The hydraulic conductivity of the bentonite free material varied between 2,0 E-9 and 1,0 E-7 m/s; the higher value for a sample with a dry density of 2,10 g/cm^3 and the lower value for a dry density of 2,35 g/cm^3. The hydraulic conductivity of the bentonite mixed materials were also very much depending on the salt content of the pore water. It increased with increasing salt content. The hydraulic conductivity of samples with 30% bentonite tested with Äspö water (1,2% salt content) varied between 1,0 E-9 m/s (dry density 1.7 g/cm^3) and 4,0 E-11 m/s (dry density 1.85 g/cm^3).

- The measured swelling pressure of the backfill material depended very much on the clay content, the salt content of the water and the density.

- The measured swelling potential was also a function of the clay content. The measured swelling varied from 12% for a 10/90 mixture to almost 40% for a 30/70 mixture.

- The measured total suction described as a function of the clay water ratio was independent of the dry density and the clay content but influenced by the salt content of the pore water.

- The measured water transport rate decreased with increasing bentonite content and increase with increasing salt content of the pore water. The water transport rate also seemed to depend on the initial water content.

SAMMANFATTNING

Denna rapport redovisar resultat från laboratorieförsök på återfyllningsmaterial av krossat berg och blandningar krossat berg/bentonit som utförts under i huvudsak 1997. Bentonitinnehållet varierar mellan 0% och 30% i de undersökta återfyllningsmaterialen. Ballastmaterialet har bestått av krossade TBM-massor. Försöken har utförts för att komplettera och för hydrauliska konduktiviteten även ersätta resultat erhållna vid tidigare tester, som redovisats i PR-HRL-96-15.

Följande tester har utförts:

- Mätning av hydraulisk konduktivitet vid olika bentonithalt, densitet, saltinnehåll i tillsatt vatten och initiell vattenkvot vid inpackning.

- Mätning av svälltryck vid några olika bentonithalter, densiteter och initiell vattenkvot vid inpackning.

- Mätning av svällningspotentialen hos olika blandningar som kompakterats till 90% packningsgrad och mättats med Äspövatten.

- Mätning av porvattenundertrycket hos omättade återfyllningsmaterial varvid både det ”totala undertrycket” (total suction) och ”kapillärundertrycket” (matric suction) mätts. Mätningarna är gjorda med tre olika metoder på blandningar med olika bentonitinnehåll, olika densitet, salt halt i tillsatt vatten och olika vattenkvot.

- Mätning av vattentransport och vattenmättnadsprocesser i omättade återfyllningsmaterial har gjorts genom att fritt vatten varit tillgängligt i ett filter i ena änden av prover instängda i ödometrar, låta porvattenundertrycket suga in vattnet, bryta försöken vid olika tidpunkter och bestämma vattenkvotsfördelningen i proverna.

De utförda försöken gav följande:

- De testade återfyllningsmaterialens hydrauliska konduktivitet minskade med ökande lerinnehåll och densitet. Hydrauliska konduktiviteten hos det bentonitfria materialet varierade mellan 2,0 E-9 och 1,0 E-7 m/s för torr-densiteter mellan 2,10 g/cm^3 och 2,35 g/cm^3. Den hydrauliska konduktiviteten hos bentonitblandad återfyllning var beroende av porvattnets saltinnehåll. Den hydrauliska konduktiviteten ökade med ökande saltinnehåll. För ett material med 30% bentonit och med 1,2 % salt i porvattnet (Äspö-vatten) varierade den hydrauliska konduktiviteten mellan 1,0E-9 m/s (torrdensitet 1,7 g/cm^3) och 4,0 E-11 m/s (torrdensitet 1,85 g/cm^3).

- Det mätta svälltrycket hos återfyllningsmateralen var beroende av mängden bentonit, salt koncentrationen i porvattnet samt densiteten.

- Den mätta svällningspotentialen var också beroende av lerinnehållet. Uppmätt svällning varierade mellan 12% för 10/90 blandning upp till nästan 40% för 30/70 blandning.

- De totala porvattenundertrycket (total suction) beskriven som funktion av ler-vattenkvoten var oberoende av återfyllningarnas torrdensitet och lerinnehåll. Både totala undertrycket och ”kapilärundertrycket” var en funktion av saltkoncentrationen i porvattnet.

- Vattentransportshastigheten minskade med ökande bentonithalt. Den ökade också med ökande saltkoncentration i porvattnet. Utförda försök indikerade också att vattentransportshastigheten beror på materialets vattenkvot vid inpackningen.

EXECUTIVE SUMMARY

Laboratory tests on backfill material of crushed rock and mixtures of crushed rock and bentonite are described in this report. The tests have mainly been made during 1997. The bentonite content of the backfill varies between 0 and 30% and the ballast material consists of crushed TBM-muck in all tests. The tests have been made in order to supplement, and concerning hydraulic conductivity also replace results from earlier tests, described in PR-HRL-96-15.

The following tests have been made and preliminary results reached:

The hydraulic conductivity has been measured at different bentonite content, density, salt content of added water, and initial water ratio at compaction. The results show that the hydraulic conductivity of bentonite mixed backfill

- decreases about 10 times at an increase in bentonite content with 10 percentage points

- increases about 50 times when 1.2% salt is added to the water (Äspö water)

- decreases about 20 times when the dry density (or degree of compaction) increases 10%.

The swelling pressure has been measured at different bentonite contents, densities, and initial water ratio at compaction. The results show i.a. that 30% bentonite and a degree of compaction higher than 85% (of the maximum proctor density) are required for reaching a swelling pressure above 100 kPa if Äspö water is added.

The swelling potential of different backfill mixtures, that were compacted to 90% degree of compaction and saturated with Äspö water, has been measured. The results show that the swelling potential at free swelling of such backfill materials is about equal to the bentonite content (10-30%).

The negative pore water pressure (suction) of water unsaturated backfill materials has been measured. Both the total suction and the matric suction have been measured. Three different measuring techniques have been used and backfill materials with different bentonite content, density, salt content of added water, and water ratio have been tested. The results show i.a. that matric suction is considerably lower than total suction at high clay water ratios and that the total suction is a function of only the clay water ratio independently of the density and the clay content.

Measurements of water transport and water saturation processes in unsaturated backfill materials have been made. Free water has been supplied a filter in one end of samples confined in oedometers. The tests have been interrupted at different times and the water ratio distribution in the samples measured. The results show

i.a. that the rate of saturation is considerably faster if the bentonite mixed backfill materials were saturated with salt Äspö water than with distilled water. They also showed that the rate of saturation is faster for backfill mixtures with low initial water ratio than with high initial water ratio. The results are used for calibrating the material model that describes the dependence of the hydraulic conductivity on the degree of saturation.

TABLE OF CONTENT

1 INTRODUCTION

Tunnels and shafts in a repository are planned to be backfilled. There are several purposes with the backfill. According to FUD 96 the required functions are:

- to obstruct upwards swelling of bentonite from deposition holes
- to prevent or restrict the water flow in the tunnel and around the canister
- to resist chemical conversion during a long period of time
- not to cause any significant chemical conversion of the buffer surrounding the canister

In Äspö HRL a full scale in situ project (Backfill and Plug Test) is running with the purpose to i.e. study the function of the backfill and its interaction with the near field rock in a tunnel excavated by blasting. A laboratory program for investigating the hydro-mechanical properties of possible backfill materials is in progress. The results will be reported in a series of 3 intended progress reports. The laboratory program contains investigations of mainly the following properties:

- Compaction properties
- Compression properties
- Swelling properties
- Shear properties
- Hydraulic properties of water saturated and unsaturated backfill materials
- Piping resistance

This report is the second one and describes investigations on mainly swelling and hydraulic properties of both saturated and unsaturated materials. The tests have been made on mixtures of bentonite and crushed rock, at which crushed TBM-muck has been used. The report ends the investigations on backfill materials with crushed TBM-muck as ballast material. The final report will deal with ballast material from crushed and ground rock (the waste product from the excavation by blasting).

2 MATERIAL DESCRIPTION

The tests were made on backfill material composed of 0-30% MX-80 bentonite and 70-100% ballast material. TBM-muck crushed to a suitable grain size distribution was used as ballast material.

The grain size distribution of the ballast material is shown in Fig 2-1. The maximum grain size is 20 mm and the desired content of fine soil is 10-15%. In some tests where the diameter of the samples were maximised to 50 mm, the grains larger than 2 mm were separated from the crushed TBM muck and sand was added to the material in order to get the same amount of fine soil as in the original material.

MX-80 is a natural sodium bentonite. The granule size distribution of the bulk material with its natural water content is shown in Fig 2-2. The granules of the bentonite are smaller than 1 mm. The grain size in dispersed form is also shown in Fig 2-2. The figure indicates that MX-80 consists of about 85% clay particles (< 0.002 mm).

The different backfill materials were produced by mixing crushed TBM muck, bentonite and water in a mixer. In most tests water corresponding to optimum water ratio at Proctor compaction was added, but other water ratios were also tested. Both distilled water and water with 0.53% NaCl and 0.68% $CaCl_2$ were added. The salt water with a total salt content of 1.2% corresponds to the average salt content of the ground water at 420 m depth at Äspö (Äspö water).

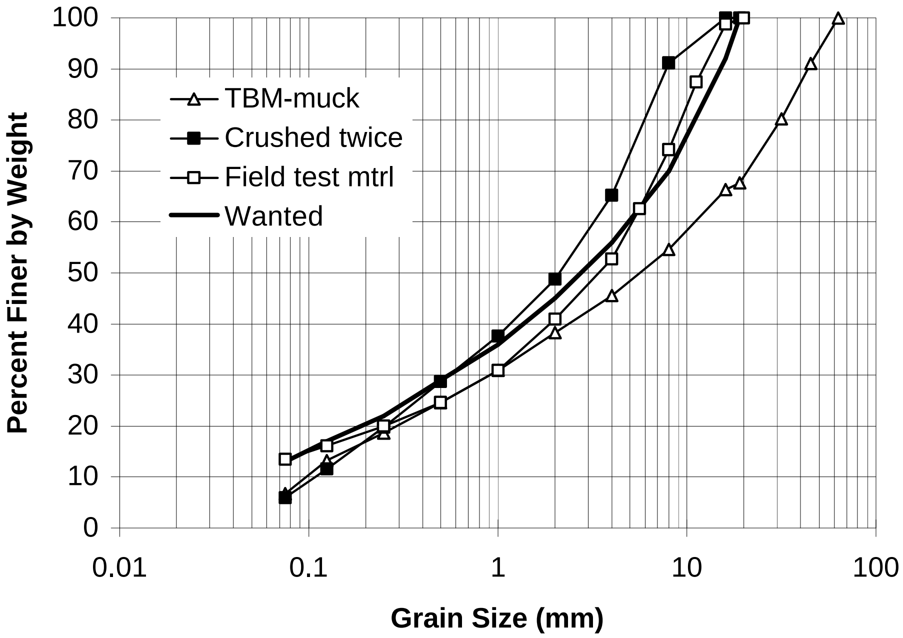


Figure 2-1. *Grain size distribution of the natural uncrushed TBM muck, the ballast material used in the lab tests (Crushed twice) and the ballast material used in preparatory field tests.*

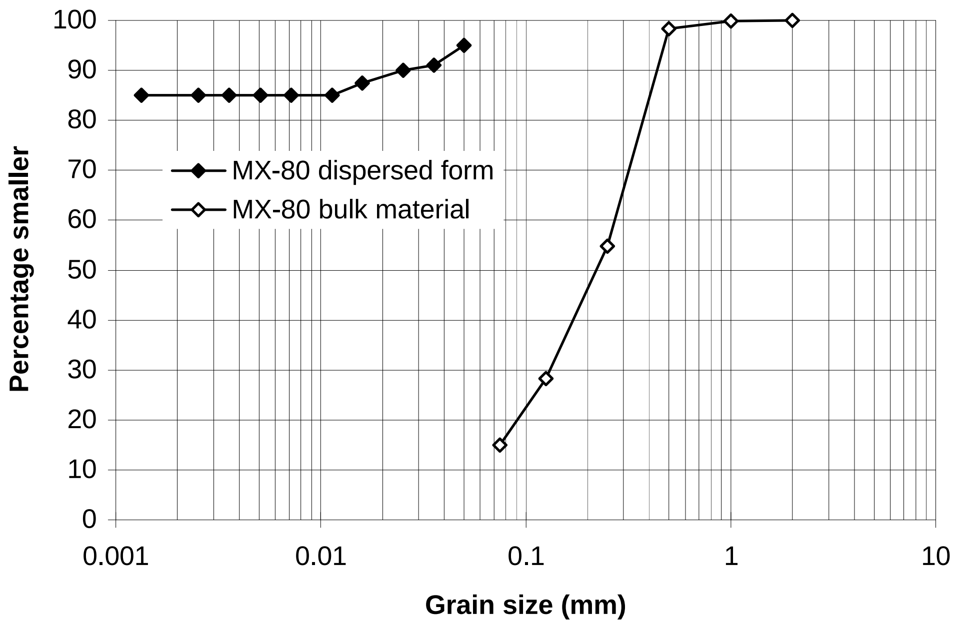


Figure 2-2. *Granule size distribution of MX-80 as bulk material and grain size distribution of dispersed MX-80.*

3 HYDRAULIC TESTS

3.1 GENERAL

The hydraulic conductivity of soils is generally measured in oedometers. The maximum grain size of the soil determines the choice of oedometer dimensions. A generally applied rule when determining the hydraulic conductivity is that the diameter of the oedometer should not be smaller than 5- 10 times the maximum grain size. The maximum grain size for the tested backfill materials is 20 mm which means that the oedometer should have a diameter larger than 100 mm. The tests were made using two different kinds of equipment; a so-called Rowe oedometer with 250 mm diameter and a ”Proctor cylinder” with a diameter of 101 mm.

The hydraulic conductivity of a specified backfill material is mainly a function of the density, the clay content and the salt content in the pore water and these quantities have been varied in the tests. The hydraulic conductivity is also to some extent a function of the water ratio at compaction, the compaction technique and the mixing technique. However the last dependencies have not been investigated in detail.

3.2 TEST TECHNIQUE

Previous results of the measured hydraulic conductivity of different backfill materials were derived from tests made in Rowe oedometers. However, it turned out that some of the results were incorrect due to test technique problems. After reporting the first test series (PR-HRL-96-15) it was discovered that the small filter stone in the pipe (through connection) that leads water into the bottom filter was clogged and almost impervious. Accordingly, most of these tests were repeated and supplemented. The results reported in chapter 5 of that report shall thus be replaced by the results shown in this report.

A schematic drawing of a Rowe oedometer is shown in Fig 3-1. The backfill is manually compacted into the sample holder in 5 layers to the desired density. The 80 mm high sample with a 250 mm diameter is confined by a filter at both ends. The filters in the through connections were removed After completed preparation a diaphragm is pressurised with water to a pressure equal to the estimated swelling pressure of the backfill sample at water saturation.

After installation the samples are deaired with a vacuum pump and water supplied from both ends. During water saturation, the displacement of the upper filter is measured and recorded. After completed saturation a hydraulic gradient is applied to the sample and the water percolation measured. The hydraulic conductivity is evaluated with Darcy´s law when steady flow has been reached.

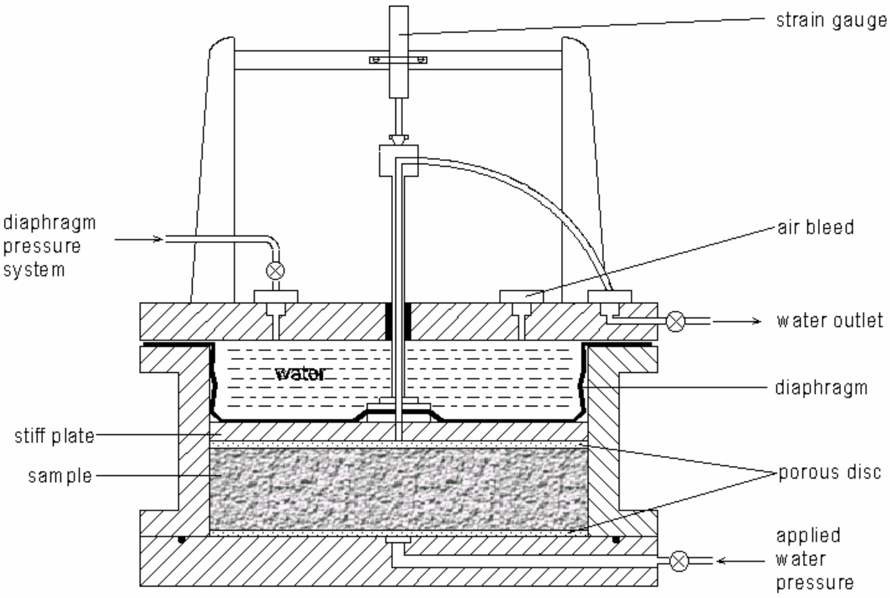


Figure 3-1. *Rowe oedometer*

Some tests were performed in a ”Proctor cylinder” (see Fig 3-2). The same installation procedure is used for this apparatus i.e. the backfill is manually compacted into the cylinder in 5 layers to the desired density to a height of about 100 mm. The sample is confined by filters, a fixed bottom plate and a movable piston at the top. An effective stress is applied on the top of the sample by loading the piston. The load is applied by bracing the bolts.

In these tests, the samples were saturated by applying a water pressure at the bottom and letting air seep out from the top of the sample. After saturation a hydraulic gradient was applied to the sample and the hydraulic conductivity determined.

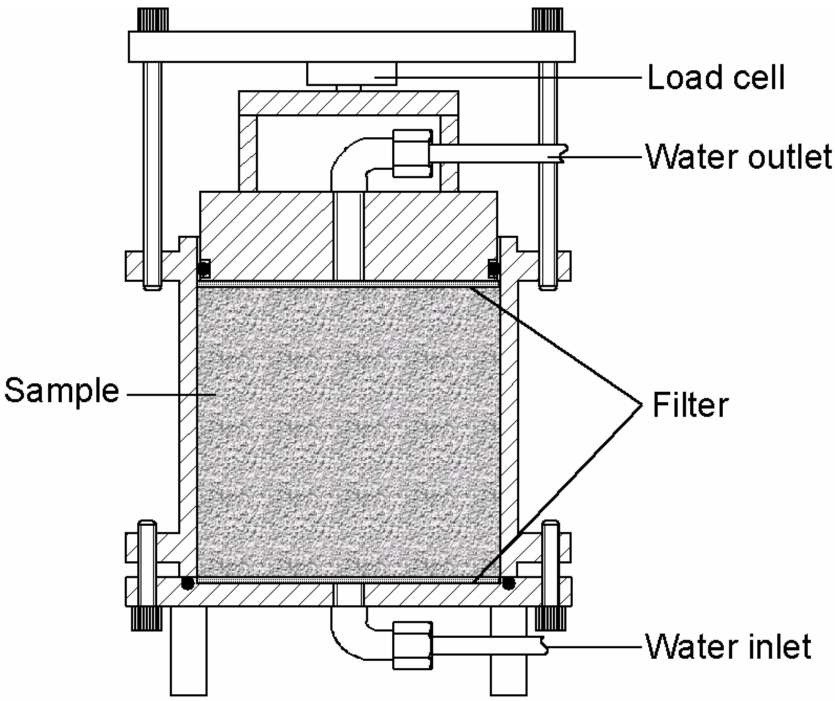


Figure 3-2. *Proctor cylinder adapted for measuring hydraulic conductivity.*

After completed testing the bulk density (r) and the water ratio (w) were determined. The measured values were used to calculate the degree of saturation (S_r), the void ratio (e) and the dry density (r_d) with the following equations:

$$S_r = \frac{w \times \rho \times \rho_s}{[\rho_s \times (w+1) - \rho] \times \rho_w} \tag{3-1}$$

$$e = \frac{\rho_s - \rho}{\rho - \rho_w \times S_r} \tag{3-2}$$

$$\rho_d = \frac{\rho_s}{1+e} \tag{3-3}$$

where

w = water ratio of the material
ρ = bulk density of the sample
ρ_s = density of particles (ρ_s = 2.7 g/cm^3)
ρ_w = density of the water (ρ_w = 1.00 g/cm^3)

In some of the Rowe oedometer tests the samples were tested at different effective stress by increasing the stress stepwise. The deformation and hydraulic conductivity were measured at each step. The densities were calculated from the measured deformation and the determined density at the final load step.

In most tests measurements were also made with a back pressure of 80 - 280 kPa applied on the pore water.

Two types of water were used for saturating the backfill, distilled water and Äspö water.

3.3 TEST RESULTS

The tested materials, their basic properties and the results of the measurements are summarised in Table 3-1.

The hydraulic conductivity was primarily measured on the outflow side by measuring the displacement of the meniscus in a very thin tube. Some measurements were also made on the inflow side by use of a GDS-apparatus, capable of keeping a high constant pressure and recording the volume change with an accuracy of 1 mm^3. The hydraulic conductivity was evaluated when steady flow had been established.

Table 3-1 Summary of the hydraulic conductivity tests. The tests marked * are performed in a Rowe oedometer while the rest are performed in a Proctor cylinder.

				Final properties						
Test No.	Clay cont. (%)	Water	w_{ini} (%)	Proct (%)	w (%)	ρ_d (t/m^3)	e	Sr (%)	K (m/s)	K with Back Pr. (m/s)
1	0	Dist.	5.6	96	8.6	2.21	0.24	97	1.40E-08	1.96E-08
2	0	Dist.	5.6	91	10.4	2.11	0.31	95	6.19E-08	1.33E-07
3	0	Dist.	5.6	101	5.7	2.33	0.19	90	1.66E-09	4.55E-09
4*	0	Dist.	5.6	94	8.3	2.18	0.26	88	8.50E-08	-
5*	0	Dist.	5.6	92	7.8	2.12	0.30	73	1.00E-07	-
6	10	Dist.	7.0	94	12.4	2.02	0.37	96	2.87E-10	3.40E-10
7	10	Äspö	7.0	94	12.1	2.04	0.36	96	5.12E-09	1.13E-08
8	10	Dist.	7.0	94	13.4	2.02	0.36	102	2.79E-10	5.62E-10
9	10	Äspö	7.0	94	12.4	2.04	0.35	99	2.67E-09	5.59E-09
10	10	Dist.	7.0	88	16.0	1.90	0.45	98	2.02E-10	1.34E-10
11	10	Äspö	7.0	90	14.1	1.95	0.42	95	4.26E-09	2.70E-08
12*	10	Äspö	7.0	98	10.7	2.11	0.30	97	1.77E-09	-
13	20	Dist.	8.0	93	15.5	1.91	0.45	97	4.62E-11	5.22E-11
14*	20	Äspö	8.0	94	15.2	1.93	0.43	98	4.14E-10	9.46E-10
15	20	Dist.	8.0	87	18.1	1.79	0.57	93	5.53E-11	6.25E-11
16*	20	Äspö	8.0	90	17.1	1.85	0.50	96	3.27E-09	5.51E-09
17*	20	Äspö	8.0	87	18.8	1.78	0.54	95	1.46E-09	2.17E-09
18	20	Äspö	8.0	79	23.1	1.62	0.69	91	5.36E-08	-
19	30	Äspö	13.0	91	19.7	1.77	0.56	98	4.71E-11	7.84E-11
20	30	Äspö	13.0	89	21.5	1.72	0.61	99	4.25E-10	4.49E-10
21*	30	Äspö	13.0	89	19.6	1.72	0.60	91	9.73E-11	2.01E-10
22	30	Äspö	13.0	88	21.5	1.71	0.61	96	6.32E-10	9.09E-10
23	30	Äspö	13.0	78	27.3	1.52	0.81	93	7.22E-09	-
24*	30	Äspö	4.6	96	15.9	1.86	0.47	95	6.00E-11	-
25*	30	Dist.	13.7	96	17.3	1.87	0.48	101	4.09E-12	-
26*	30	Dist.	13.7	95	17.1	1.85	0.48	99	1.10E-12	-
27	30	Äspö	6.5	89	20.8	1.73	0.59	97	2.86E-09	2.98E-09

The results from the tests are plotted in Figs. 3-3 to 3-6. Tests 24, 25 and 26 are made in connection with compression tests. The figures shown in the table correspond to the final load step. The hydraulic conductivity was measured after each load step, which accounts for the results from the tests on 30/70 shown in Fig 3-6 but not presented in the table.

The results from measurements on crushed TBM muck without bentonite are plotted in Fig 3-3. The dry density varies between 2.11 - 2.33 g/cm^3, corresponding to 91 - 100% Proctor. The plot indicates that the hydraulic conductivity is rather sensitive for the attained density.

The results from the tests performed on the 10/90 mixture are plotted in Fig. 3-4. Tests were performed using both Äspö water and distilled water. The dry density varies between 1.90 - 2.11 g/cm^3 (88-98 % Proctor). These results show a strong influence of the salt content, increasing the hydraulic conductivity by one to two orders of magnitude.

The results from the tests on the 20/80 mixture are plotted in Fig. 3-5. The tests were performed using both Äspö water and distilled water. The dry density of the samples varies between 1.62 - 1.93 g/cm^3 (79-94 % Proctor). The influence of salt content is strong.

Fig. 3-6 shows the results from measurements on the 30/70 mixture. The dry density varies between 1.52 - 1.87 g/cm^3, corresponding to 78 - 96% Proctor.

Fig. 3-6 shows a large scatter in the hydraulic conductivity at dry density close to 1.75 g/cm^3 where salt water is used. A possible explanation could be that different techniques and equipment were used. The high value 3. 10^{-9} m/s comes from a test where the initial water ratio at compaction is considerably lower than for the rest of the tests (see Table 3-1).

It is interesting to study the influence of the bentonite content and the pore water composition on the hydraulic conductivity when the same compaction energy is used. In Fig 3-7 the hydraulic conductivity is plotted as a function of the bentonite content for backfill mixed and saturated with Äspö water and distilled water at the dry densities corresponding to 90% modified Proctor. The strong influence of both bentonite content and pore water composition is clearly seen.

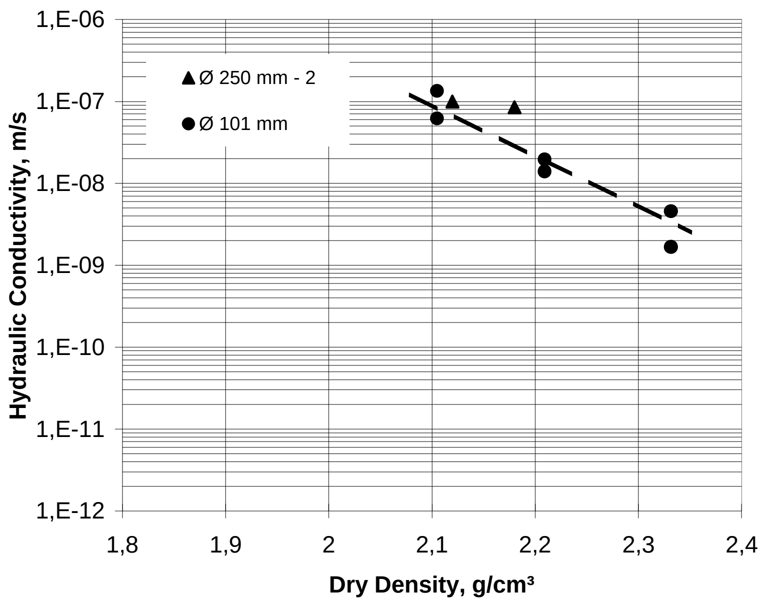


Figure 3-3. *Measured hydraulic conductivity as a function of the dry density for crushed TBM muck (0/100).*

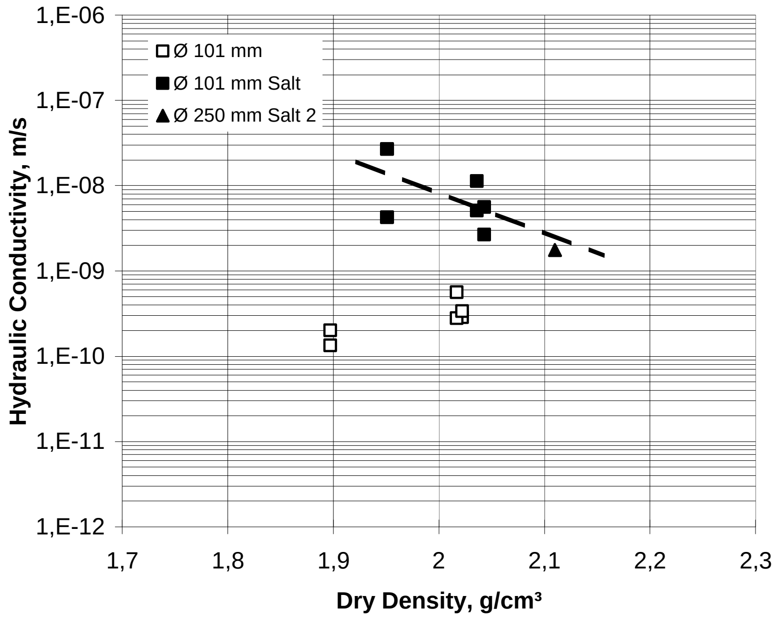


Figure 3-4. *Measured hydraulic conductivity as a function of the dry density for 10/90 bentonite/crushed TBM muck. The tests are performed both with distilled water /unfilled symbols) and Äspö water.*

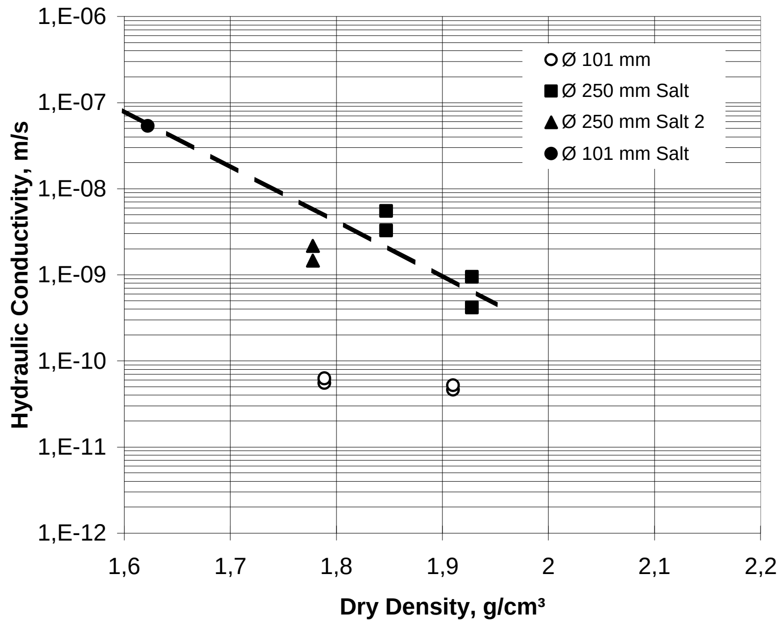


Figure 3-5. *Measured hydraulic conductivity as a function of the dry density for 20/80 bentonite/crushed TBM muck. The tests are performed both with distilled water (unfilled symbols) and Äspö water.*

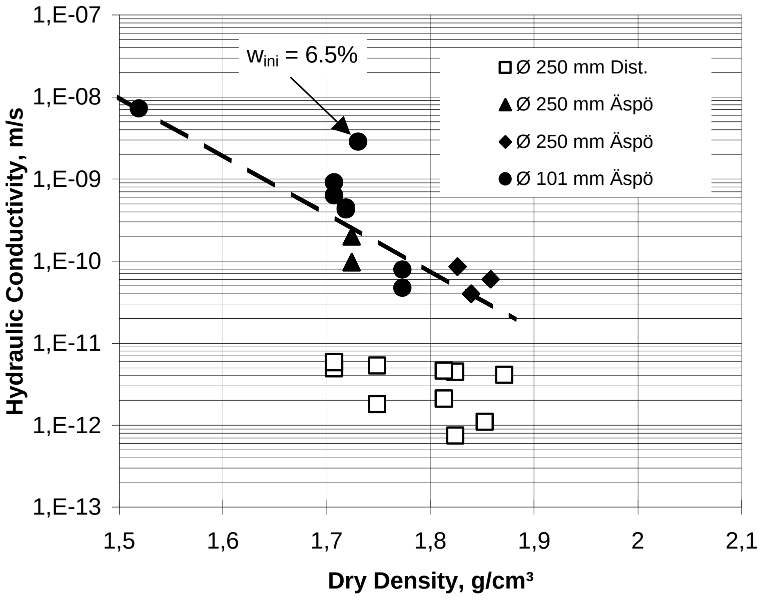


Figure 3-6. *Measured hydraulic conductivity as a function of the dry density for 30/70 bentonite/crushed TBM muck. The tests are performed both with distilled water and Äspö water.*

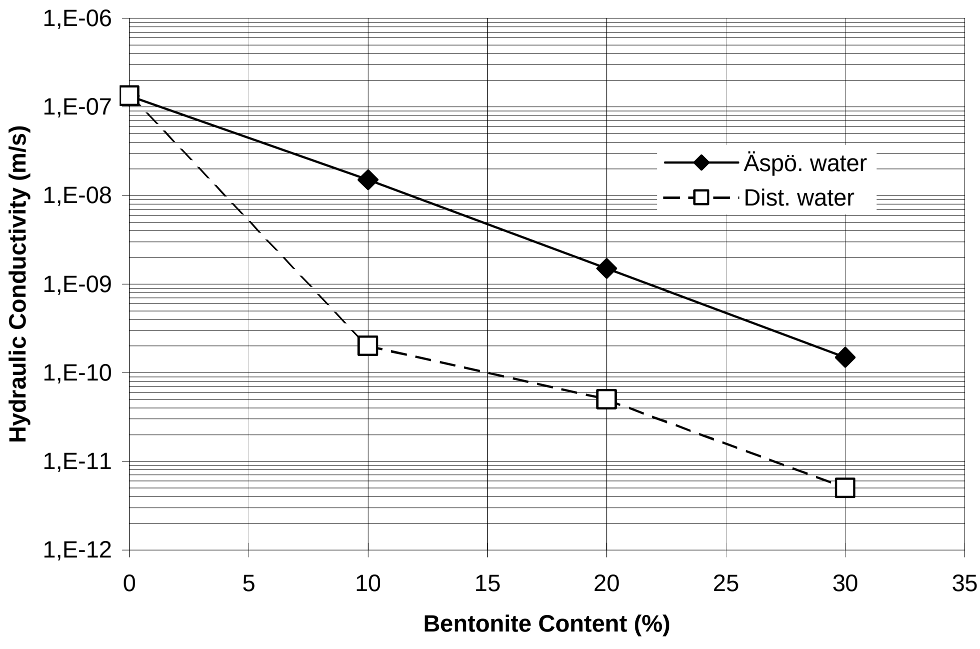


Figure 3-7. *Evaluated relation between bentonite content and hydraulic conductivity at 90% Proctor.*

3.4 CONCLUSIONS

The following general conclusions can be made:

- The scatter in measured hydraulic conductivity is quite large for most of the investigated materials.

- The hydraulic conductivity of the mixtures is strongly affected by the salt content of the pore water. The hydraulic conductivity increases 1 to 2 orders of magnitude when Äspö water is used instead of distilled water.

- The hydraulic conductivity is strongly affected by the dry density. It decreases about 20 times when the dry density (or degree of compaction) increases 10%.

- The hydraulic conductivity is strongly influenced by an increase in bentonite content. It decreases about 10 times at an increase in bentonite content with 10 percentage points

- The results from the tests performed on 30/70 mixture indicate that the initial water content at the compaction of the material affect the hydraulic conductivity at saturation (see Fig. 3-6). Also other factors like the mixing and compaction technique may have an influence. Additional tests to study these phenomena are required.

4 SWELLING TESTS

4.1 GENERAL

The tunnel backfill serves several purposes. Except for preventing the buffer material from swelling the backfill also needs to support the roof and minimise the axial water flow in the tunnel. When placing and compacting the backfill in the tunnel it is difficult to obtain a good contact between the backfill and the rock surface and a high density of the backfill close to the roof. A swelling backfill material facilitates a good contact between the rock and the backfill. The swelling potentials as well as the swelling pressure of backfill with low density need to be investigated. Previous tests on mixtures of bentonite and ballast material indicate that the swelling pressure is higher than the swelling pressure of pure bentonite at the same clay density.

4.2 TEST TECHNIQUES

4.2.1 Measurement of swelling pressure

The following test technique has been used for measuring the swelling pressure:

The backfill material is compacted in the Proctor cylinder described in Section 3.2. A load cell is applied on the top of the piston. The sample is saturated with Äspö water by applying a low water pressure at the bottom of the sample and allowing the air to seep out from the top during the water inflow. The swelling pressure is recorded by continuous readings of the load cell. After completion of the test, the density (r) and the water ratio (w) are determined. The measured values are then used to calculate the degree of saturation (S_r), the void ratio (e) and the dry density (r_d) using Eqn. 3-1 - 3-4.

4.2.2 Measurement of swelling potential

The swelling potential for the different backfill materials was investigated in the following way: After compaction of the material in a Rowe oedometer, described in section 3.2, a filter is placed on top of the sample, filled with Äspö water and a water table established above the filter. The water uptake causes a swelling of the material. The swelling is measured continuously with three deformation gauges placed on the filter. After completed test the water ratio (w) is determined at different distances from the top of the sample. Assuming the sample to be fully saturated, the void ratio (e) can be calculated.

4.3 TEST RESULTS

4.3.1 Swelling pressure

Three tests with a mixture of 30% bentonite and 70% crushed TBM muck and one test with 20/80 mixture have been made. The data and results from the tests are summarised in Table 4-1 and Fig 4-1. The interruptions in the swelling pressure curves were caused by measurements of the hydraulic conductivity, since it was not possible to measure the swelling pressure and the water flow simultaneously. The plots show that the swelling pressure increased after this period, which may be caused by an increase in the degree of saturation and some homogenisation. The results show that:

- the swelling pressure is low and increases as expected with increasing density and bentonite content
- a density corresponding to 80% Proctor is not enough to reach 100 kPa in swelling pressure for any of the tested materials
- the initial water ratio at compaction, which had a significant influence on the hydraulic conductivity, does not seem to affect the swelling pressure very much
- 30/70 mixture with a dry density of about 1.6 t/m^3 is required in order to reach a swelling pressure of 100 kPa

Table 4-1 Summary of the swelling pressure tests performed with Äspö water.

			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	1.73	0.59	97	220
2	30	13	88	21	1.71	0.61	96	244
3	30	13	78	27	1.52	0.81	93	68
4	20	8	79	23	1.62	0.69	91	21

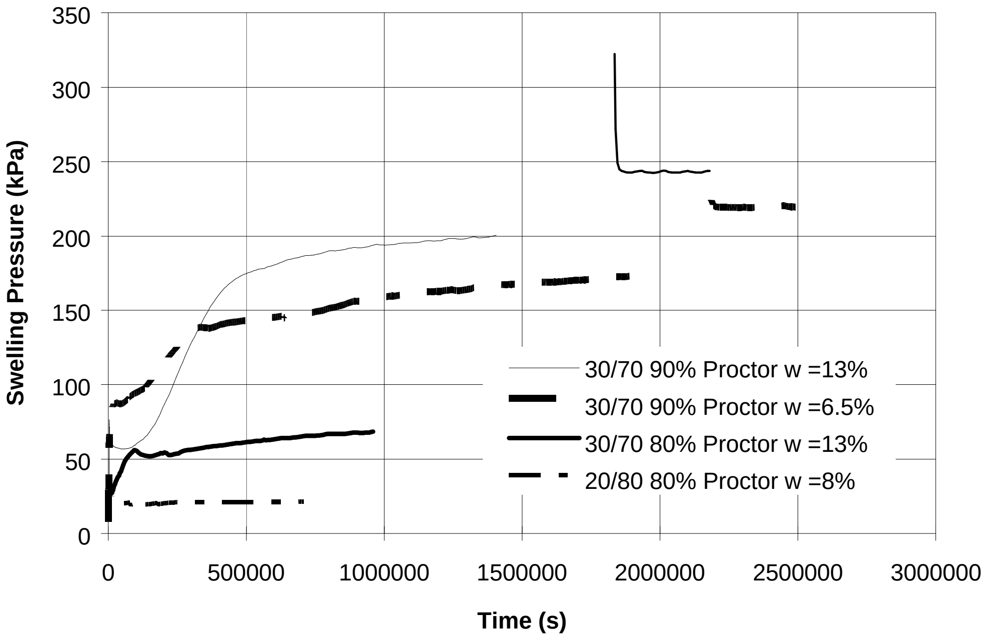


Figure 4-1. *Measured swelling pressure as a function of time. The tests were performed with Äspö water.*

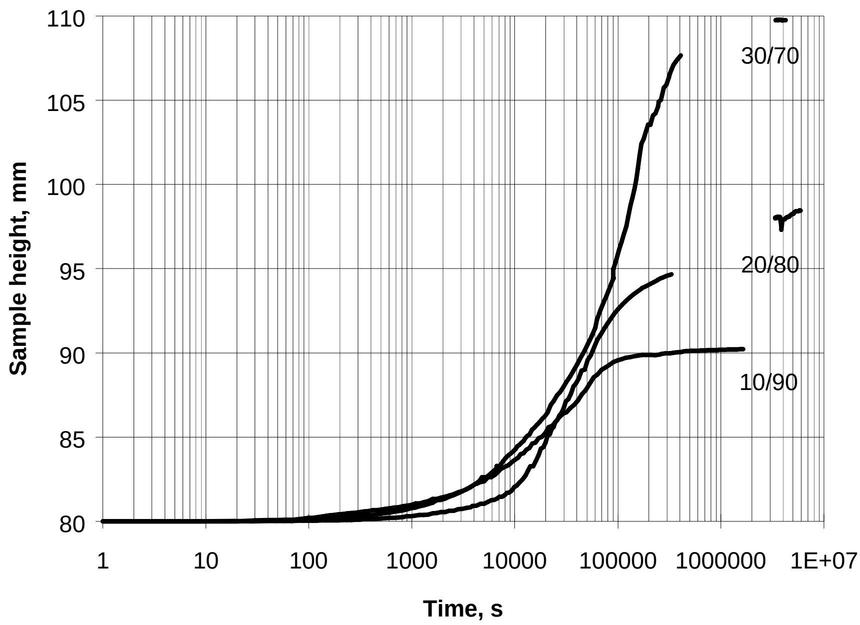
4.3.2 Swelling potential

Swelling potential tests have been made on five samples with mixtures of bentonite, crushed TBM muck, and Äspö water. One test was performed at a pressure of 50 kPa applied on top of the sample (10/90 mixture). The other tests were made at zero pressure. The initial height of the samples was 80 mm. The initial conditions of the samples are listed in Table 4-2.

The result from measurement of the swelling of the samples during the water uptake is shown in Fig. 4-2. The figure shows, as expected, that the sample with the highest clay content had the largest swelling. The figure also shows that the swelling is quite large varying from 12% for 10/90 to almost 40% for 30/70 but also that a rather small vertical effective stress on the 10/90 sample prevents the swelling.

Table 4-2 Summary of the swelling potential tests performed with Äspö water. S_{ro} is the initial degree of saturation and S_r is the final degree of saturation

Test No.	Clay cont. (%)	Vert. stress (kPa)	Proctor (%)	w (%)	ρ_d (t/m^3)	e	S_{ro} (%)	S_r (%)
1	30	~ 0	90	13.7	1.74	0.58	65	95
2	20	~ 0	90	7.8	1.85	0.49	44	98
3	10	~ 0	90	7.1	1.94	0.41	47	98
4	10	50	90	7.1	1.94	0.41	47	
5	0	~ 0	90	5.6	2.08	0.32	48	



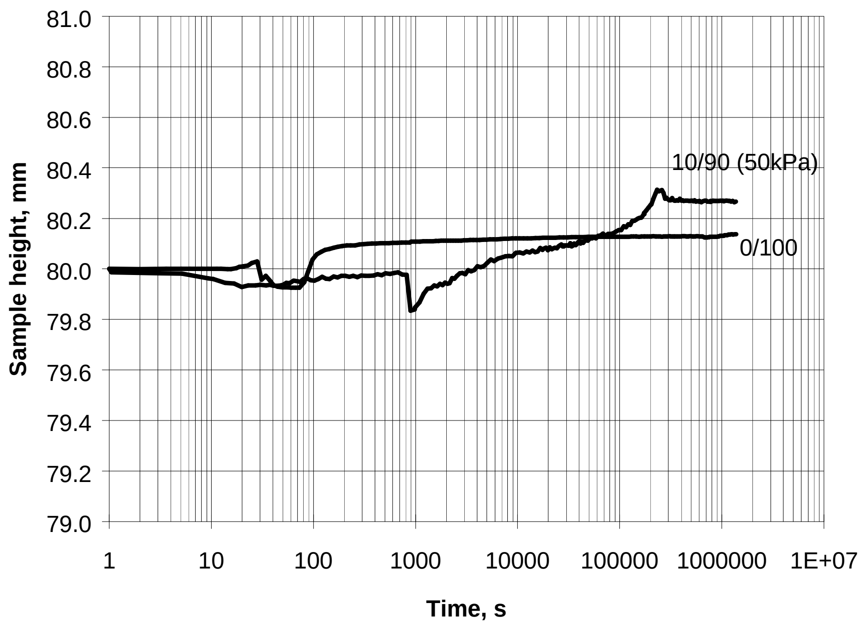
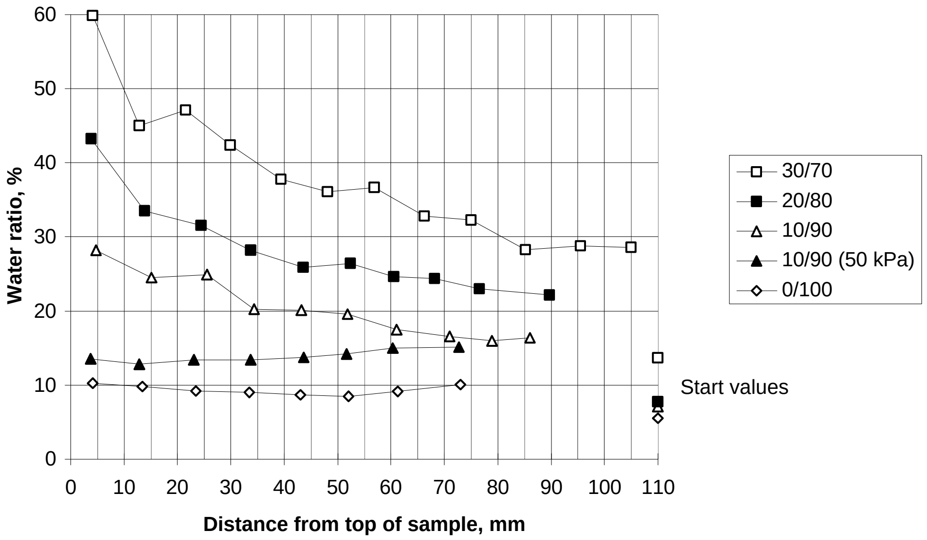


Figure 4-2. *Measured sample height during water uptake as function of time. The tests were performed with Äspö water.*

After completing the tests the axial water ratio distribution of the sample was determined. The results are shown in Fig. 4-3, where the initial water ratios and void ratios also are plotted. The void ratio was calculated with the assumption that the samples were completely water saturated. The figure shows that the swelling of the samples was not uniform. The maximum swelling occurred close to the top of the samples. The difference is very large and not completely understood. The reason could be that this material is very sensitive to external stresses. The overburden pressure of the overlying material is about 1 kPa at the bottom of the sample. Friction against the cylinder wall adds to the resistance. The lack of swelling for the 10/90 material is natural since the swelling pressure is according to the results shown in Fig. 4-1 expected to be lower than 50 kPa.



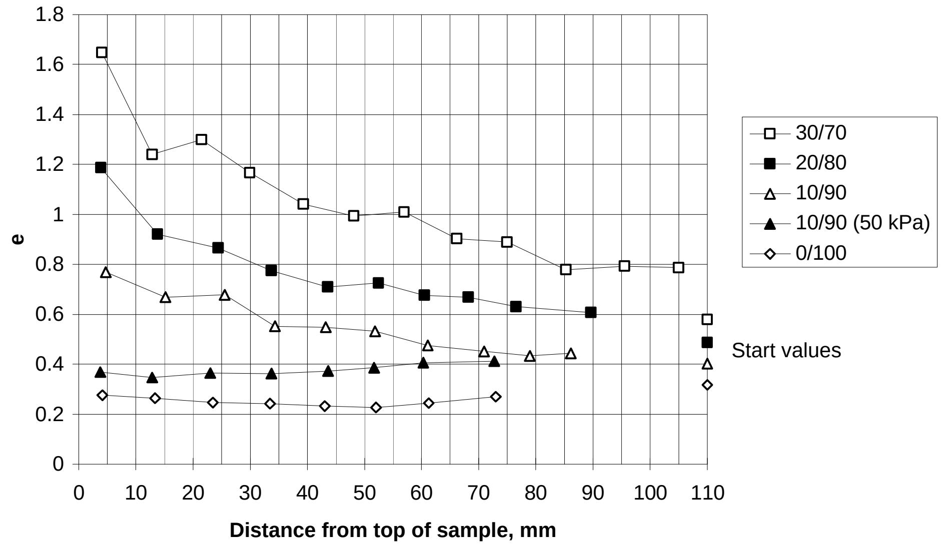


Figure 4-3. *Measured water ratio and calculated void ratio as function of distance from top of sample. The tests were performed with Äspö water.*

5 SUCTION TESTS

5.1 INTRODUCTION

In an unsaturated soil a negative water pressure called suction is present. Suction, or the water pressure potential, can according to soil mechanical standards be divided into matric suction and osmotic suction (Fredlund and Rahardjo, 1993).

$$S_t = S_m + S_o \tag{5-1}$$

where

S_t = total suction
S_m = matric suction
S_o = osmotic suction

The physical representation of suction in a salt-free granulated soil is the capillary pressure (capillary rise). This type of suction in a granulated soil is related to capillary phenomena in the soil structure and corresponds to matric suction. The matric suction can be calculated as;

$$S_m = u_{air} - u_w \tag{5-2}$$

where

u_{air}= air pressure in the porous system
u_w= water pressure in the porous system

Suction is positive in an unsaturated soil and at atmospheric pressure the water pressure is consequently below the atmospheric pressure. In order to determine the matric suction it is convenient to increase the air pressure so that the measured water pressure will be higher than the atmospheric pressure.

Osmotic suction is associated with the ion concentration in the pores. The total suction is the sum of the matric suction and the osmotic suction. From a thermodynamic standpoint the total suction theoretically can be expressed with Eqn. 5-3 (Kelvin equation);

$$S_t = \frac{RT}{V_w} \ln(p / p_0) \tag{5-3}$$

where

R= molar gas constant

$T=$ the Kelvin temperature
$V_w=$ the molar volume of water
p/p_0 the relative humidity of the pore air

This way of describing the phenomena is well known for non-swelling soils and assumed to be valid also for bentonite.

5.2 TECHNIQUE FOR MEASURING TOTAL SUCTION

5.2.1 General

The Kelvin equation (5-3) shows that it is possible to determine total suction by measuring the relative humidity in the pore system. The following two techniques have been used for determination of the total suction of different mixtures of bentonite and crushed TBM muck:

- to use a calibrated soil psychrometer
- measurement of equilibrium water content of soil samples for given relative humidity

5.2.2 Suction determined at given relative humidity

In this type of tests both compacted and uncompacted samples were placed in a chamber where a constant relative humidity was established. The constant relative humidity (RH) was reached by use of saturated salt solutions. Saturated aqueous solutions of salt produce a stable equilibrium with the relative humidity (RH) in the air above the surface of the solution. RH in the air can thus be controlled by selecting an appropriate salt. The samples reach equilibrium with the constant relative humidity by loosing or taking up water from the surrounding air. The range of RH is 81.3 – 94%, which correspond to the suction 8.000 – 28.000 kPa according to the Kelvin equation.

5.2.3 Suction measured by soil psychrometer

The second technique to determine the suction of the materials is to measure the relative humidity in a small volume of air, which is in equilibrium with the pore system of the mixtures. This type of test has been made with WESCOR soil psychromters (Fig. 5-1).

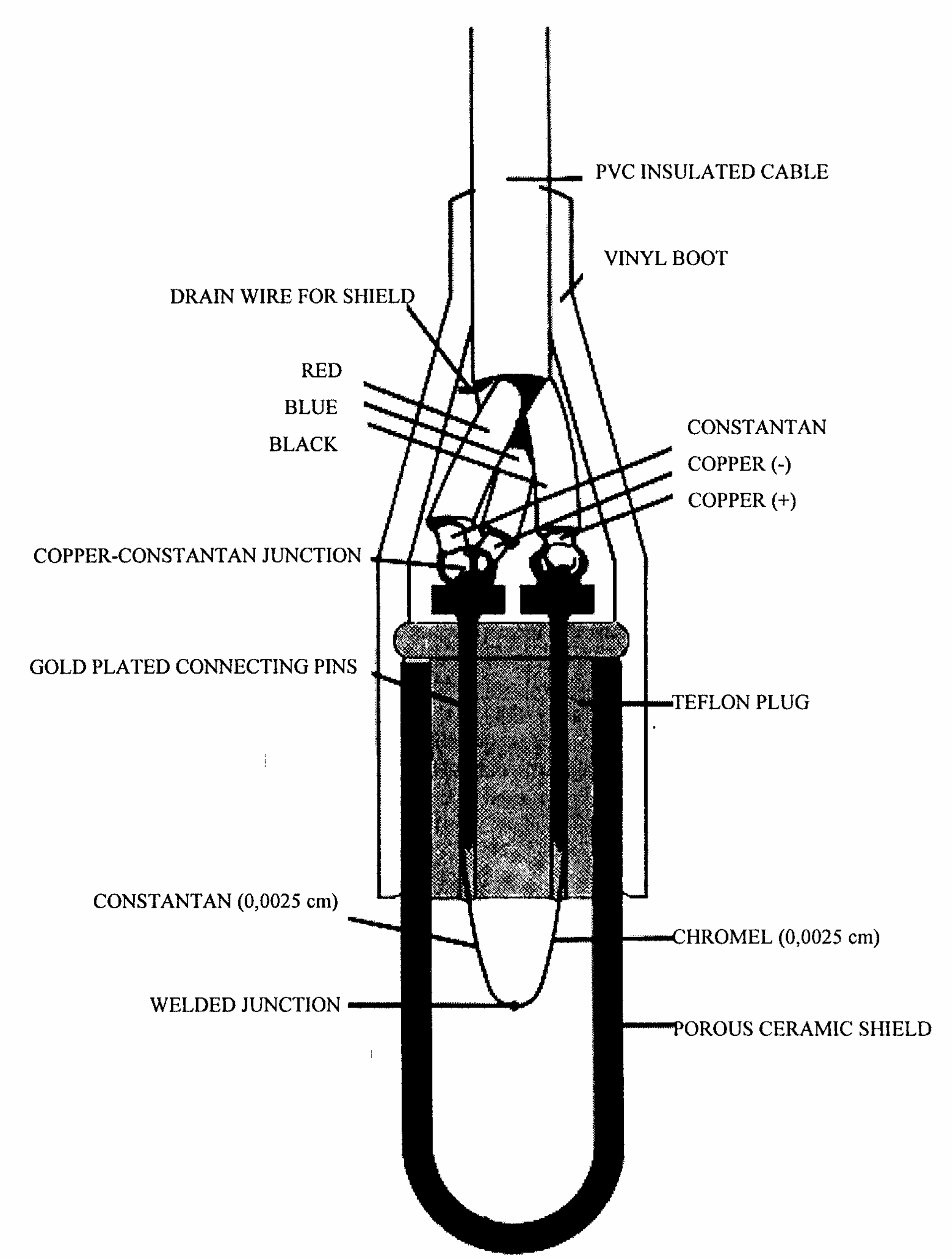


Figure 5-1. *Soil psychrometer of type Wescor.*

The measurement with the psychrometer can be made in two ways; the dew point method and the wet bulb method. In the first method the temperature at the dew point is measured. This yields an accurate measurement of the relative humidity but it cannot at the present be used when a large number of Wescor soil psychrometers are continuously logged by a data measurement system. In the second method the relative humidity is measured by determining the wet bulb depression temperature. This method is used in the laboratory tests. A thermocouple is cooled below the dew point by means of the Peltier Effect causing droplets of condensed water on the junction surface of the psychrometer. The output from the thermocouple during the cooling is shown in Fig. 5-2, as part a to b. The cooling is then interrupted and water is allowed to evaporate, causing the temperature of the junction to be depressed below the ambient temperature due to the evaporative cooling (part b-c). The wet bulb temperature depression persists until all the water has evaporated (part c-d). Then the thermocouple returns to the ambient temperature (part d-e). The relative humidity is evaluated from the measurement by determine the voltage output at the wet bulb temperature. There is proportionality between this output and the relative humidity in the air at the thermocouple.

The measuring range for the psychrometer is 300 – 6.000 kPa.

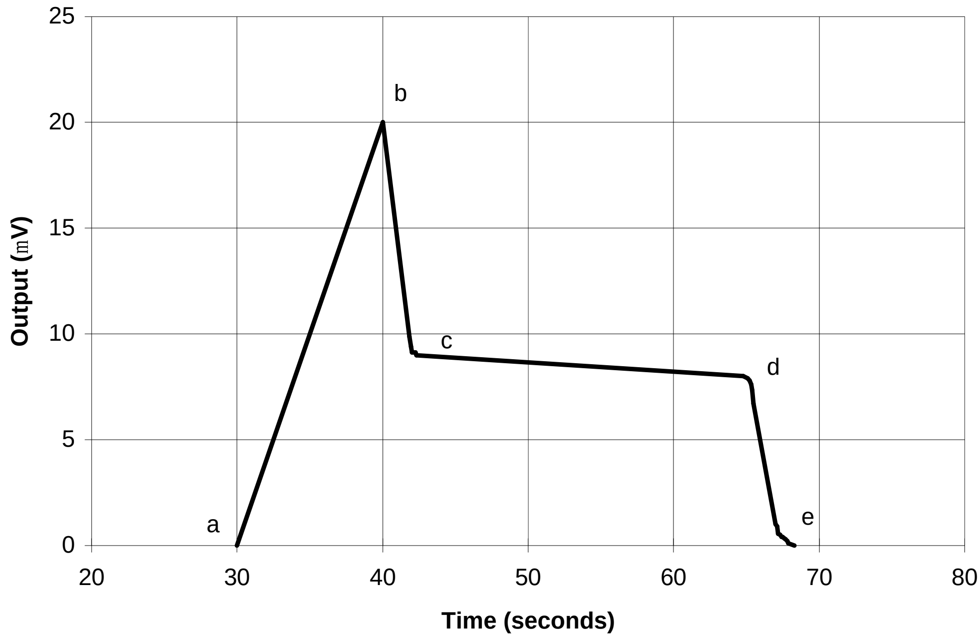


Figure 5-2. *Output of psychrometer (wet bulb method).*

5.3 TECHNIQUE FOR MEASURING MATRIC SUCTION

Tests in order to determine the matric suction were made by use of the equipment shown in Fig. 5-3. The sample is put on a high air entry disk and placed in a triaxial cell with a water-filled compartment below the disk. During the tests the compartment can be flushed with water. It is of great importance that the compartment is completely filled with water for the entire duration of the test. A pore pressure transducer measures the water pressure (u_w) in the compartment below the high air entry disk. The measured pressure is assumed to correspond to the pore water pressure in the sample. By increasing the air pressure (u_{air}) in the triaxial cell it is possible to produce a pore water pressure above atmospheric pressure and the matric suction can be calculated with Eqn. 5-2

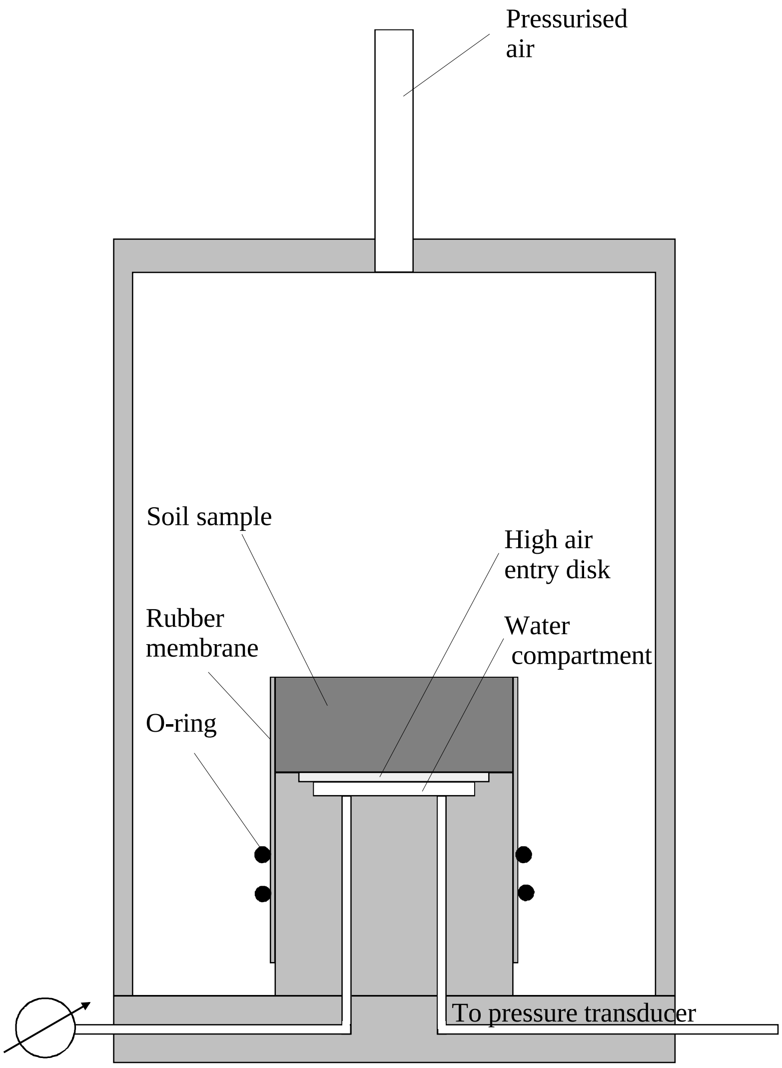


Figure 5-3. *Equipment used for measuring matric suction.*

5.4 RESULTS

5.4.1 General

Parameters assumed to be significant for the measured suction of the different mixtures are;

- the salt content in the pore water
- whether the material is absorbing or emitting water (wetting or drying)
- the clay content of the mixtures
- the initial void ratio
- the water ratio

The water ratio of different mixtures of bentonite and ballast material can be expressed as the water ratio of the clay phase with Eqn. 5-4.

$$w_{cl} = \frac{[w - (1-k) \times w_b]}{k} \qquad (5\text{-}4)$$

where

w_{cl} =	clay water ratio
k =	ratio between the dry weight of the solid mass of bentonite and the dry weight of the total solid mass of the mixture. For a 30/70 mixture k is = 0.3
w_b=	water ratio of the ballast material
w=	water ratio of the mixture

In this section the determined suctions of different mixtures are compared with each other by plotting them as functions of the clay water ratio.

The water ratio of the ballast material was determined for suctions between 6.000 - 28.000 kPa (see Fig. 5-2). At lower suctions than 6.000 kPa the water ratio in the ballast material is assumed to be 0.6% when the clay water ratio is calculated with Eqn 5-4.

5.4.2 Total suction

Measurements at a given relative humidity

Table 5-1 shows the salt types used for the measurements described in chapter 5.2.1, their relative humidity (at 20 °C) and the corresponding suction calculated by Eqn. 5-3.

Table 5-1 Saturated salt solutions used for the tests, their relative humidity and the corresponding suction at 20 °C.

Salt	Relative humidity (%)	Suction (kPa)
$(NH_4)_2SO_4$	81.3	28032
KCl	85.4	21371
$BaCl_2$	89.8	14568
KH_2PO_4	96.5	4808

Samples containing both loosely filled and compacted material were used with 0, 10, 20, 30 and 100% bentonite content. Several test series with both Äspö and distilled water added to the sample have been made. Both drying and wetting conditions have been investigated.

For most test series the natural water ratio of the bentonite and the ballast material were used as initial water content, which means that wetting conditions prevailed.

For some series water was added to such an extent that for all RH conditions the backfill material dried during the test.

In the test series with Äspö water added to the backfill, the samples at first were dried in an oven at 105 °C. Äspö water was then added to yield either a low water ratio causing a wetting path to equilibrium, or a high water ratio causing a drying path to equilibrium. This procedure yields a somewhat inconsistent situation at equilibrium, since the change from initial water content to equilibrium water content is made with salt free water, which means that the salt content in the pore water will be too high in the drying tests and too low in the wetting tests.

The test results are shown in Figs 5-4 to 5-8, were suction is plotted as a function of water ratio for each backfill type (and 100% bentonite).

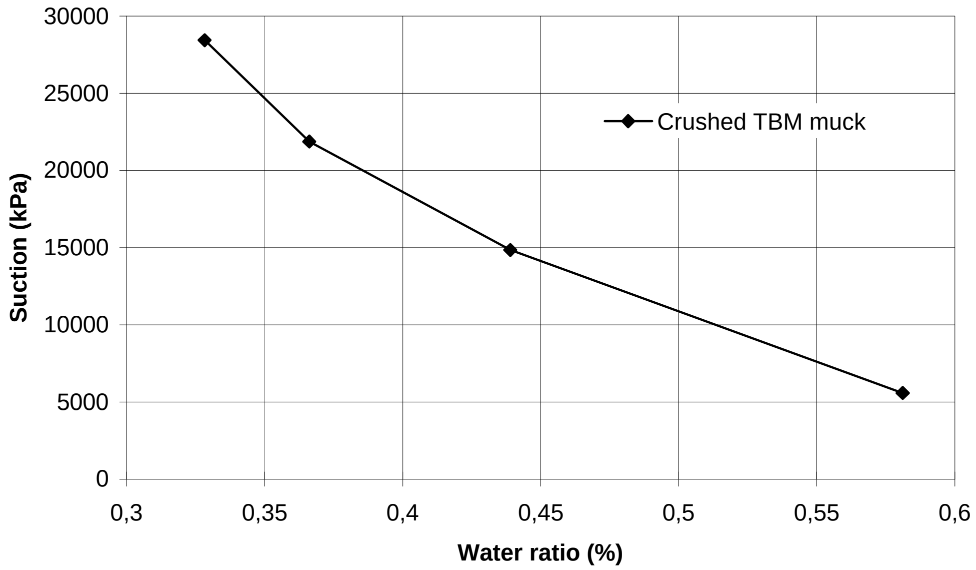


Figure 5-4. *Measured total suction of crushed TBM muck as function of water ratio. Distilled water has been added. (RH-method)*

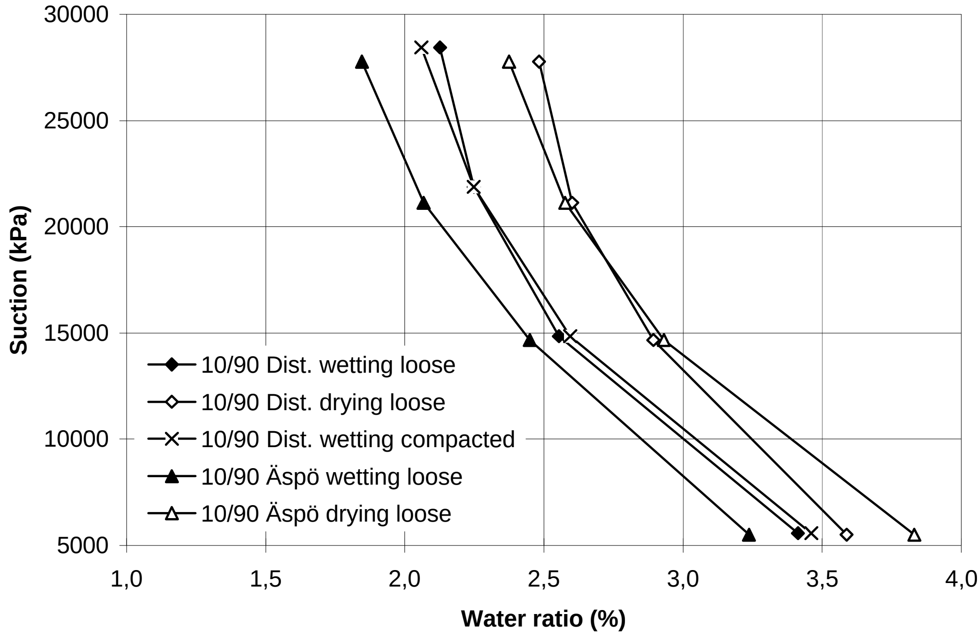


Figure 5-5. *Measured total suction of a mixture of 10% bentonite and 90% ballast material of crushed TBM muck as function of water ratio. Water composition, density, and wetting path are varied. (RH-method)*

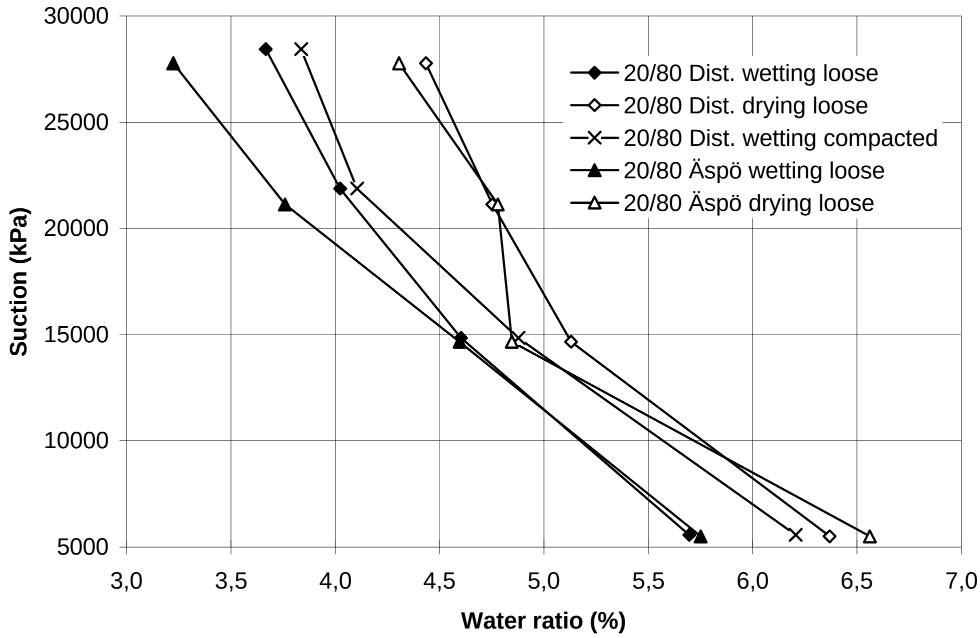


Figure 5-6. *Measured total suction of a mixture of 20% bentonite and 80% ballast material of crushed TBM muck as function of water ratio. Water composition, density, and wetting path are varied. (RH-method).*

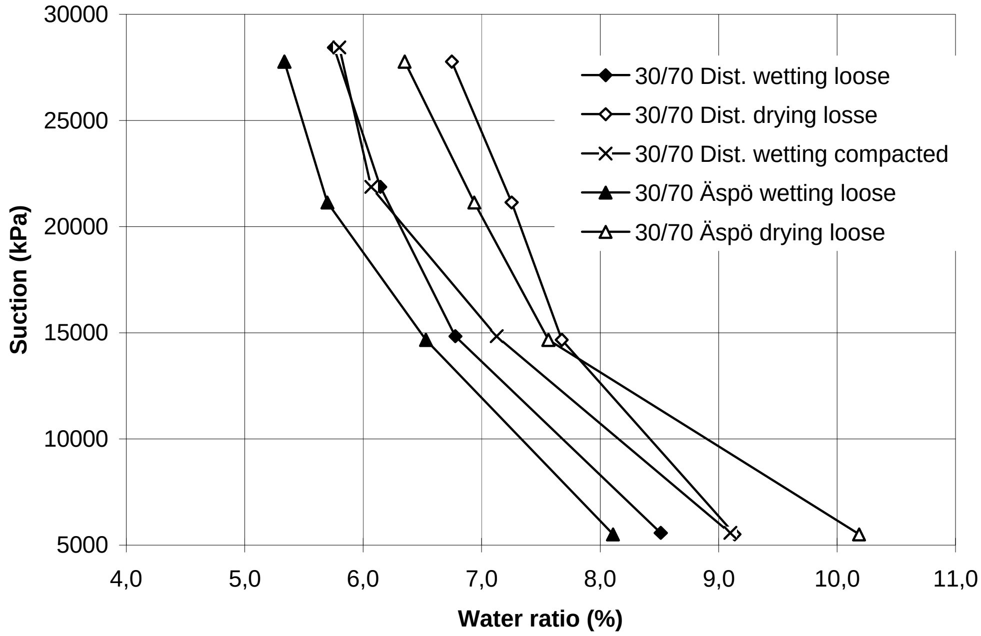


Figure 5-7. *Measured total suction of a mixture of 30% bentonite and 70% ballast material of crushed TBM muck as function of water ratio. Water composition, density, and wetting path are varied. (RH-method).*

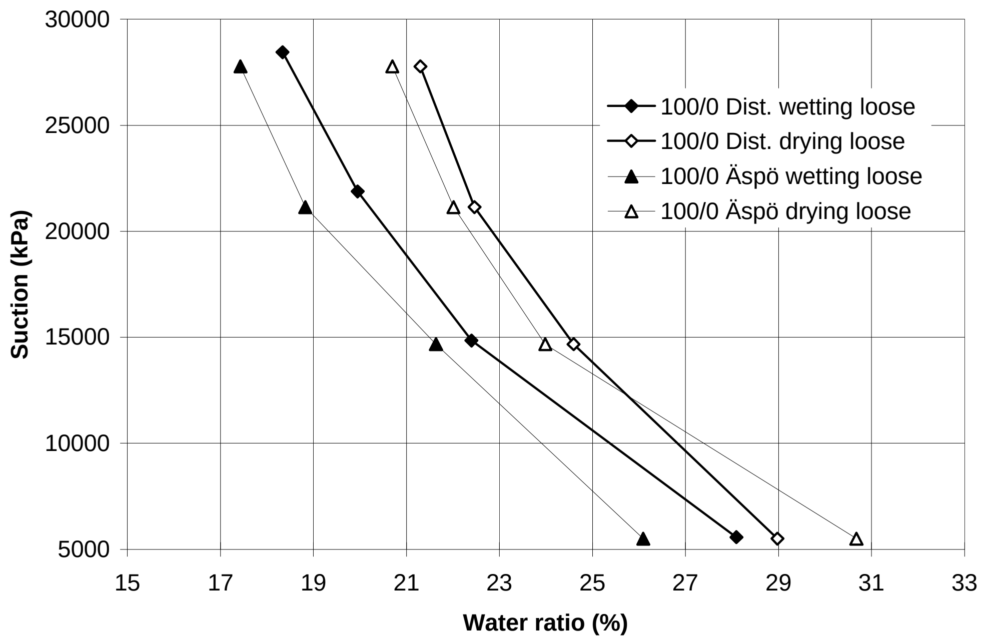


Figure 5-8. *Measured total suction of 100% bentonite as function of water ratio. Distilled water and Äspö water has been added. (RH-method).*

In spite of some scatter the figures show some obvious trends:

- The bentonite content has a major influence on the suction

- There is a substantial difference between the wetting and drying relations
- There is a some influence of the water composition although it is not large
- There is no significant influence of the density

The influence of the bentonite content is illustrated in Fig 5-9, were the suction is plotted as a function of the water ratio for 4 different bentonite contents.

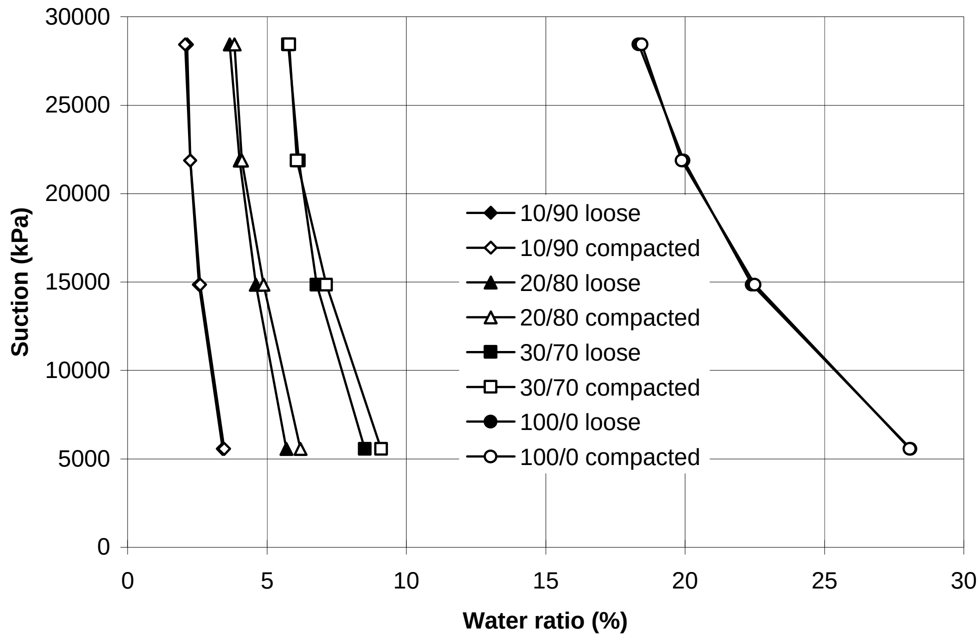


Figure 5-9. *Measured total suction of different mixtures of bentonite and crushed TBM muck as function of water ratio. Distilled water has been added. (RH-method)*

Psychrometer measurements

The psychrometer method has been used for measurements on backfill with 0 and 30% bentonite and on bentonite with no ballast (100/0). 30/70 backfill has been tested both with distilled water and with Äspö water. Water has been added before testing in all measurements.

The results are shown in Figs 5-10 to 5-13 where the suction is plotted as a function of the water ratio.

Fig 5-10 shows the results of the measurements on 100% bentonite. The total suction is in average about 1000 kPa higher for the bentonite mixed with Äspö water and it does not seem to change with water ratio. Since_Äspö water is a salt solution with an equilibrium relative humidity of about 99.3%, corresponding to the suction 950 kPa, it is suggested that the difference in suction in Fig 5-10 is only caused by the suction induced salt content in the water.

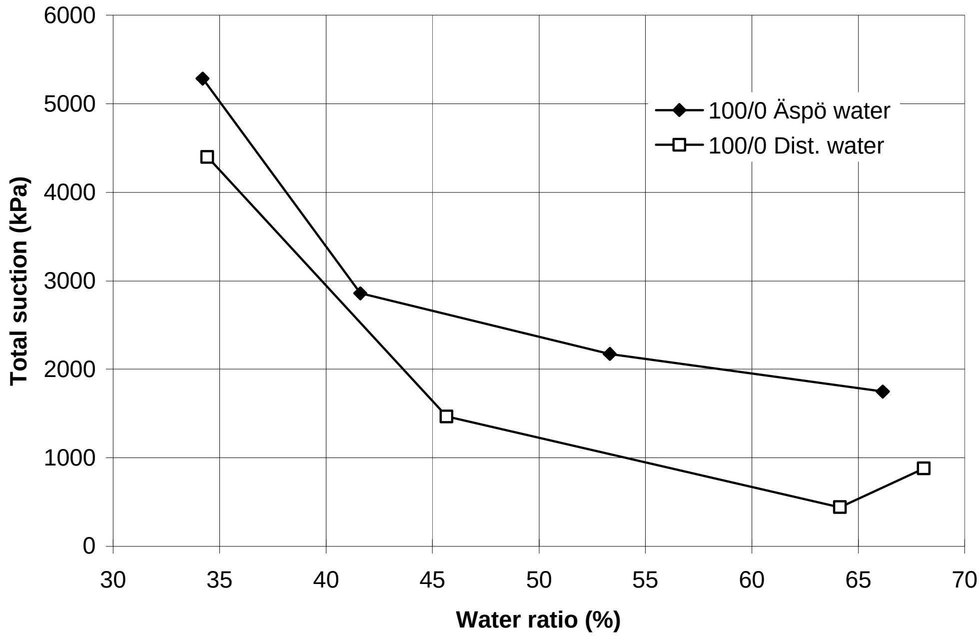


Figure 5-10. *Measured total suction of 00% bentonite as function of water ratio. (Psychrometer-method)*

Figs 5-11 and 5-12 show the results of the measurements on backfill containing 30% bentonite. The difference in suction between the backfill mixed with Äspö water and the backfill mixed with distilled water is only evident at water ratios higher than about 13%.

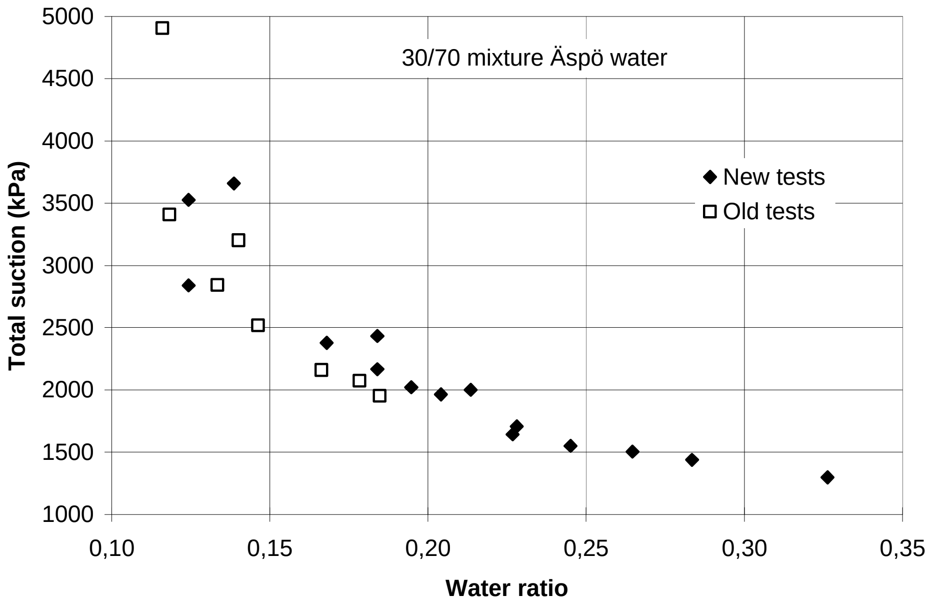


Figure 5-11. *Measured total suction of a mixture of 30% bentonite and 70% ballast material of crushed TBM muck as function of water ratio. Äspö water has been added. (Psychrometer-method)*

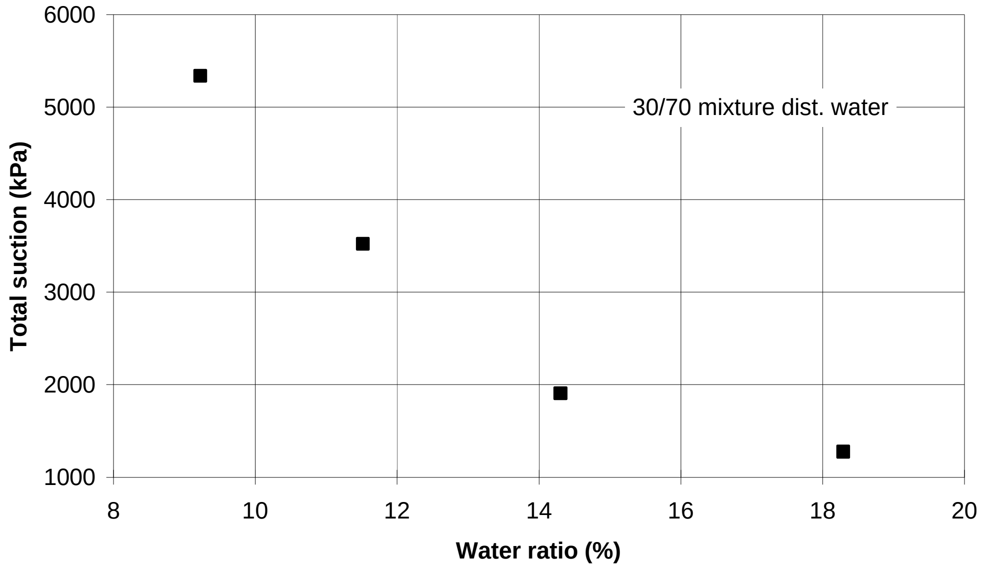


Figure 5-12. *Measured total suction of a mixture of 30% bentonite and 70% ballast material of crushed TBM muck as function of water ratio. Distilled water has been added. (Psychrometer-method)*

Figure 5-13 shows the results from the measurements on bentonite free backfill. The relation for backfill with distilled water is a logical continuation of the curve in Fig 5-4 while the increasing total suction with increasing water ratio for the backfill with Äspö water is caused by the salt concentration

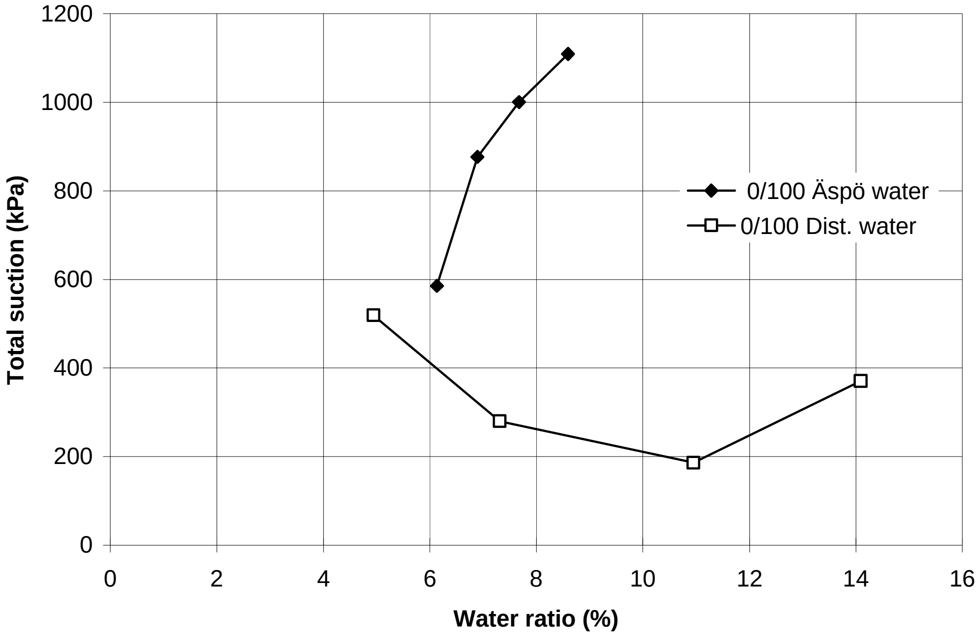


Figure 5-13. *Measured total suction of 100% ballast material of crushed TBM muck as function of water ratio. Distilled water has been added. (Psychrometer-method)*

5.4.3 Matric suction

Some tests of the matric suction determined by use of the equipment described in section 5.3 have been performed. The results are summarised in Table 5-2 below. The tests were performed by applying different air pressure (u_{air}) in the triaxial cell and measure the pore water pressure (u_w). Both Äspö water and distilled water has been added. After completed testing, the density (r) and the water ratio (w) were determined. The measured values were used to calculate the degree of saturation (S_r), the void ratio (e) and the dry density (r_d) with (Eqn. 3-1 to 3-3).

Table 5-2 Summary of the matric suction tests on 30/70 mixture.

No.	Water	u_{air} (kPa)	u_w (kPa)	S_m (kPa)	ρ (g/cm3)	w (%)	e	S_r (%)
1	dist.	300	90	210	2.12	17.8	0.53	92
2	dist.	100	31	69	1.85	37.3	1.05	98
3	dist.	750	74	676	2.10	14.7	0.50	80
4	Äspö.	750	30	720	2.14	14.1	0.47	82
5	Äspö	304	19	285	2.10	14.9	0.51	80
6	Äspö	202	83	118	1.97	25.7	0.75	94
7	Äspö	108	90	18	1.89	31.5	0.92	94
8	Äspö	204	41	163	2.07	19.5	0.59	91
9	Äspö	400	247	153	2.05	15.2	0.55	77
10	Äspö	200	186	14	1.85	33.5	0.98	94
11	dist.	201	20	181	1.90	29.9	0.88	94
12	dist.	306	1060	200	1.95	24.2	0.75	88

The measured matric suction is plotted as a function of the water ratio in Fig 5-14 for backfill with both Äspö water and distilled water added. There seems to be some scatter, but it is not quite clear if the plateau between 15% and 30 % which occurs for both waters, is cause by chance due to the uncertainties in the measuring technique or if it has some physical background. In spite of these uncertainties the figure shows that

- the matric suction decreases with increasing water ratio

- the influence of the water composition is insignificant at low water ratios but very obvious at high water ratios

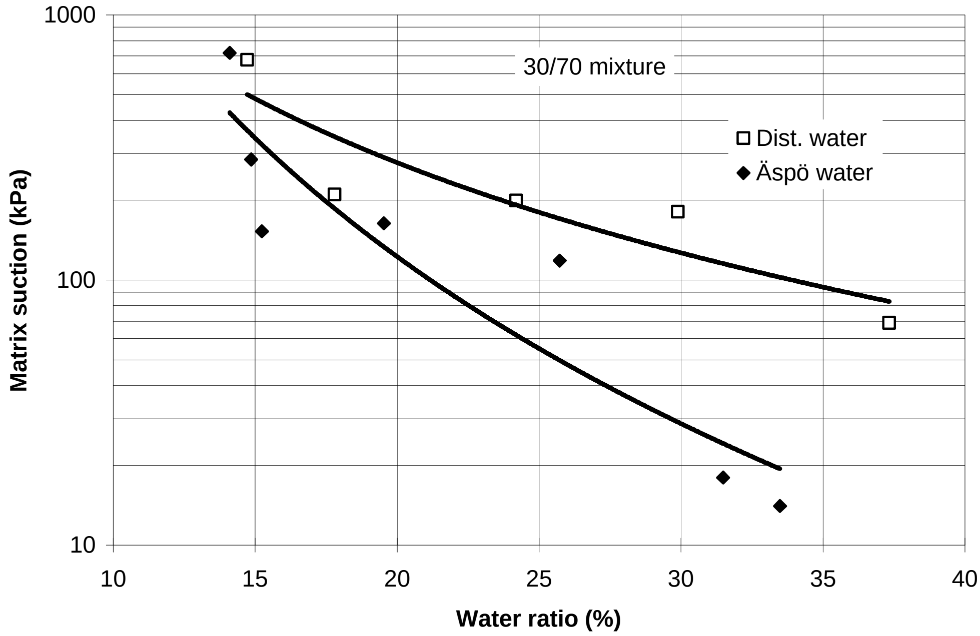


Figure 5-14. Measured matric suction of a mixture of 30% bentonite and 70% ballast material of crushed TBM muck as function of water ratio.

5.5 COMPILATION AND EVALUATION OF SOME RESULTS

30/70 and Äspö water

All measurements on backfill with 30% bentonite and Äspö water added have been compiled and plotted in one diagram in Fig 5-15. The figure shows that the RH and psychrometer methods, which measure the total suction, go well together and that the matric suction is about 1.5 MPa lower than the total suction. If the osmotic suction is evaluated according to Eqn 5-1 the osmotic suction is approximately 1.5 MPa and does not change very much with water ratio.

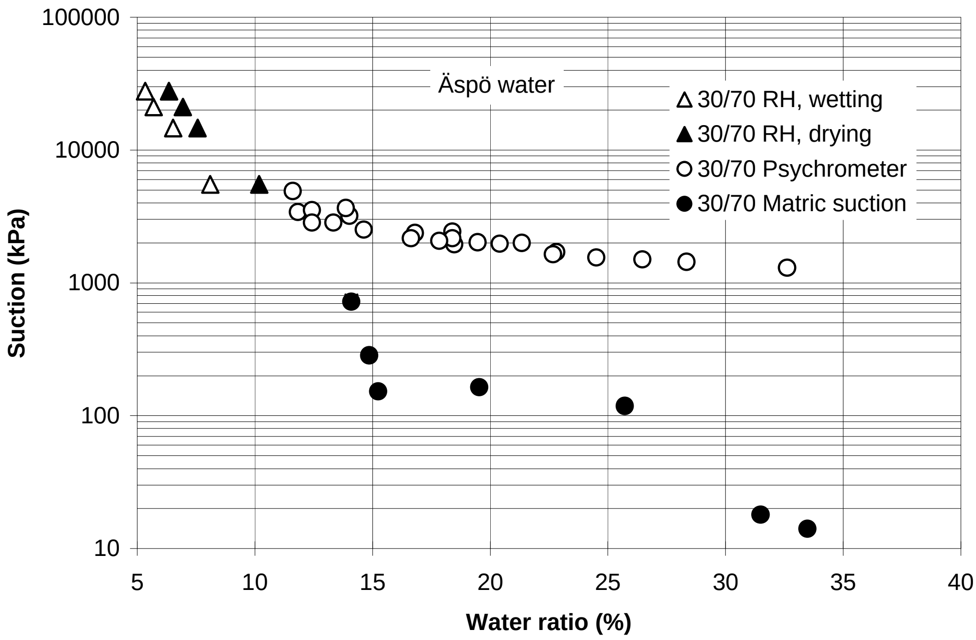


Figure 5-15. *Compilation of all measurements on backfill with 30% bentonite and Äspö water.*

30/70 and distilled water

An identical compilation for backfill with 30% bentonite and distilled water added has been made in Fig 5-16. Although the number of measurements are less, the figure shows that the trends are the same but the difference between the total and matric suction, corresponding to the osmotic suction, seems to be less than 1 MPa at high water ratios.

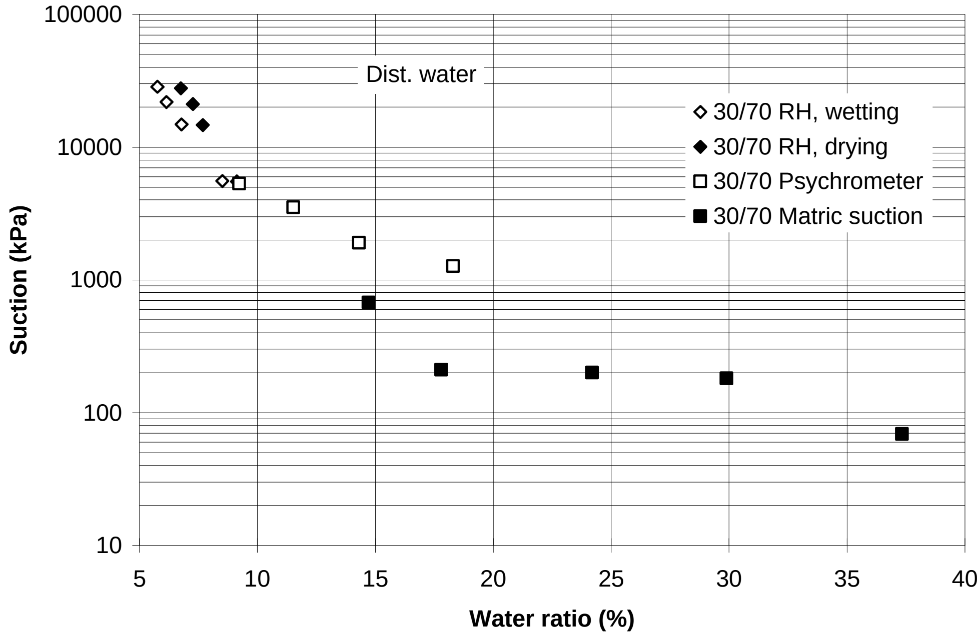


Figure 5-16. *Compilation of all measurements on backfill with 30% bentonite and distilled water.*

100% bentonite

All measurements on 100% bentonite are compiled in Fig 5-17. The relative influence of Äspö water is significant only at high water ratios.

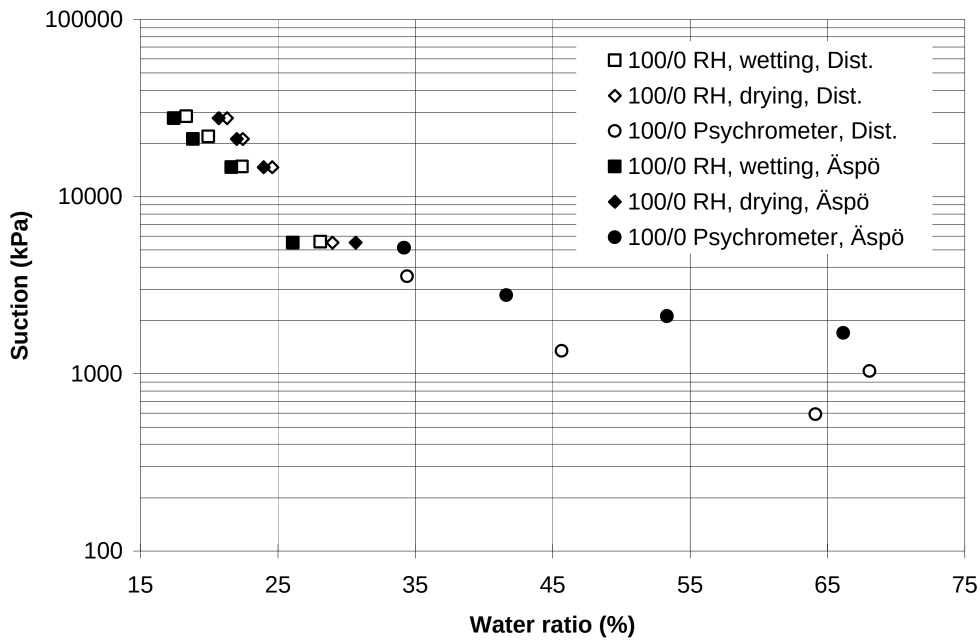


Figure 5-17. *Compilation of all measurements of total suction on 100% bentonite.*

Clay water ratio

Since the suction of the ballast material of crushed rock is very small compared to the suction of the bentonite it is reasonable to believe that the clay alone is responsible for the magnitude of the suction. Figs 5-18 and 5-19 confirm this. The figures show suction plotted as a function of the clay water ratio, calculated according to Eqn 5-4.

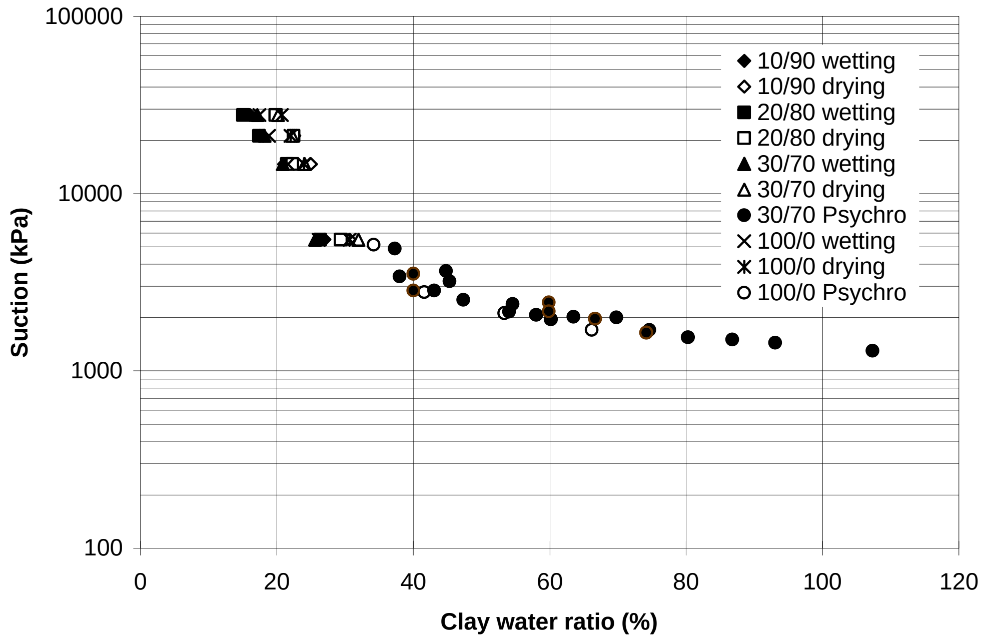


Figure 5-18. *Total suction as a function of clay water ratio for all measurements on all backfill materials with Äspö water added.*

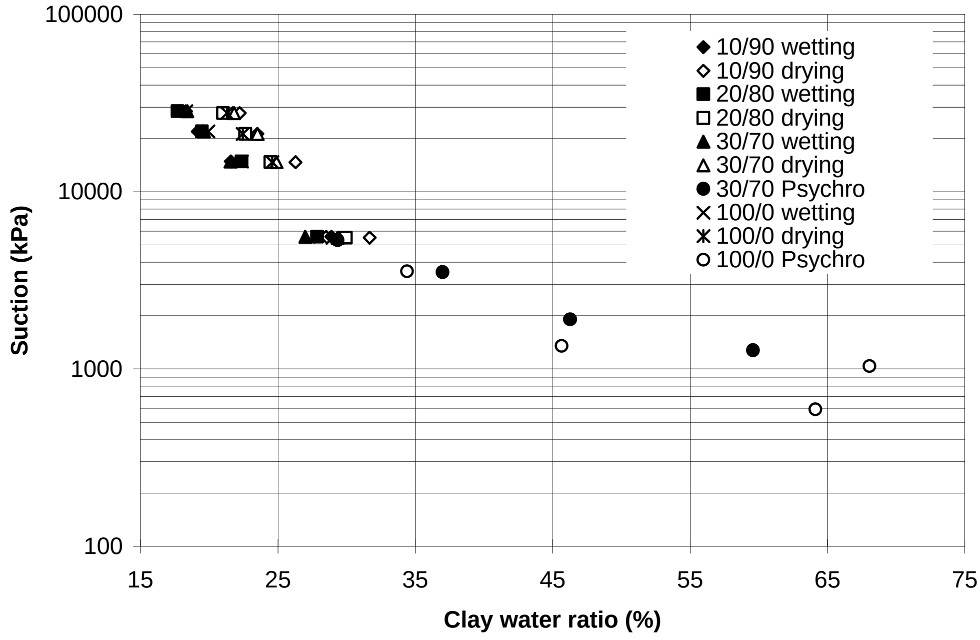


Figure 5-19. *Total suction as a function of clay water ratio for all measurements on all backfill materials with distilled water added.*

Comparison with swelling pressure

The swelling pressure of 100% bentonite at water saturation has been measured for many densities (Börgesson et al, 1995). In Figs 5-20 and 5-21 these measurements have been plotted in the same diagrams as the suction vs. clay water ratio results. The swelling pressure and the matric suction seem to agree very well for bentonite mixed with distilled water. No measurements of the swelling pressure of bentonite mixed with Äspö water have been made and the swelling pressure results shown in Fig 5-21 are derived from measurements on bentonite mixed with water containing 3.5% NaCl.

The figures clearly indicate that the matric suction and swelling pressure agree quite well.

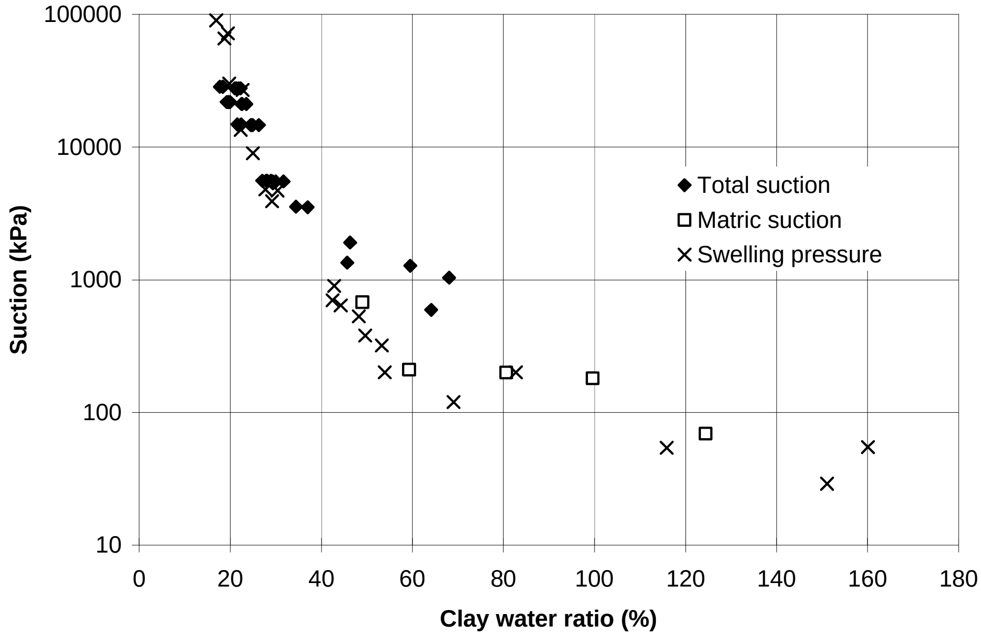


Figure 5-20. *Compilation of measurements of total suction, matric suction, and swelling pressure as functions of clay water ratio for buffer and backfill materials with distilled water added.*

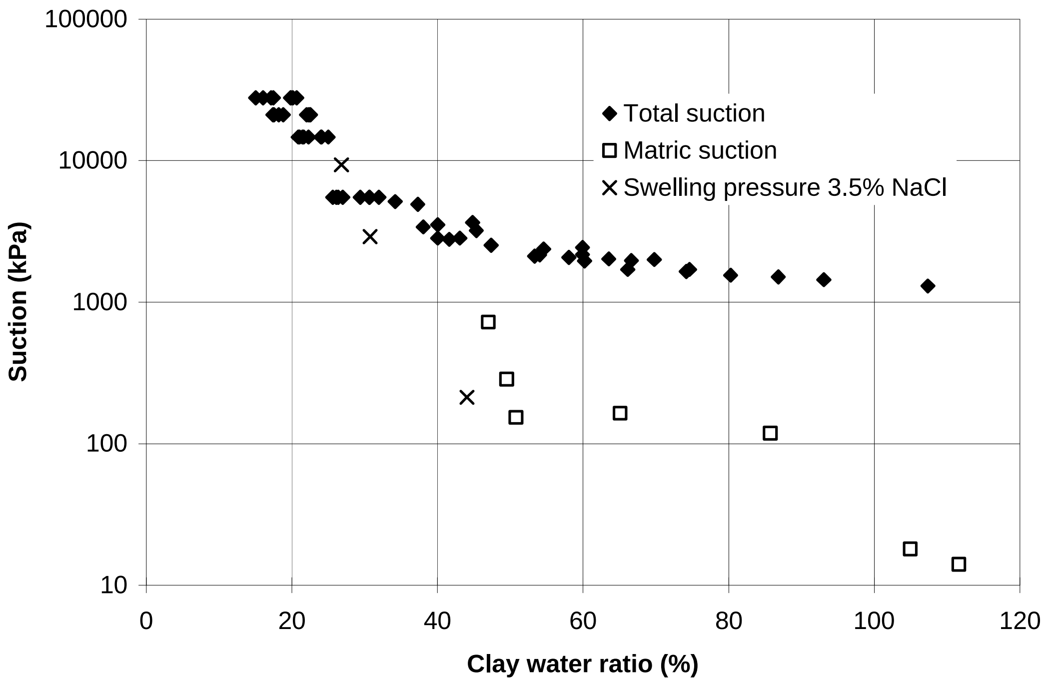


Figure 5-21. *Compilation of measurements of total suction, matric suction, and swelling pressure as functions of clay water ratio for buffer and backfill materials with Äspö water added.*

5.6 CONCLUSIONS

The measurements of suction have yielded data and information valuable for the modelling and understanding of the behaviour of unsaturated backfill materials. The laboratory testing will continue, especially with measurement of matric suction.

The results yield some preliminary conclusions and observations:

- total suction seems to be independent of the void ratio of the mixtures
- total suction of the different soil mixtures are similar when it is expressed as function of the clay water ratio
- total and matric suction are influenced by the salt content of the pore water
- matric suction for high clay water ratios is significantly lower than total suction
- matric suction and swelling pressure seem to agree

6 WATER UPTAKE TESTS

6.1 GENERAL

The water saturation in bentonite mixed backfill materials is a rather slow process, which may be critical for the time schedule of the Backfill and Plug Test. The process is modelled to be governed by Darcy's law and driven by the matric suction. The main parameters for modelling this process are thus the matric suction and the hydraulic conductivity of the water unsaturated backfill. These parameters are in their turn functions of the degree of saturation, the void ratio, and the composition of the water.

The hydraulic conductivity of unsaturated soils cannot be directly measured. An indirect way is to make well defined laboratory tests of the saturation phase and use them to calibrate the dependency of the hydraulic conductivity on the degree of saturation and the void ratio. A number of such tests have been made and are described in this chapter.

It is important to understand the mechanisms of the water saturation process of the backfill material in order to be able to predict the saturation phase of the backfill. The parameters assumed to govern the water uptake are the hydraulic conductivity, the suction of the material and the salt content of the water etc. Tests have been performed where the water uptake of different backfill materials were studied in the laboratory. The purpose with the tests is to find out what parameters are affecting the water uptake.

6.2 TEST SET-UP

Different mixtures of backfill material are compacted in five 20 mm thick layers in a proctor cylinder. The cylinder, which has a diameter of 115 mm, is placed on a bottom plate with a filter. A piston is then placed on the top of the sample and a total pressure applied to the sample by loading the piston. Water is lead to the sample from the filter at the bottom with a pressure of about 5-7 kPa. The water supply is interrupted at a specified time and the water content determined at different distances from the water inlet by cutting the sample in slices. The parameters that has been varied in the tests are:

- the initial density and water content
- the bentonite content (0, 10, 20 and 30% bentonite)
- the water type (Distilled and Äspö water)
- the time the samples have access to water

A total number of 28 tests have been performed with the described technique. All tests are made with crushed TBM-muck as ballast material.

6.3 TEST RESULTS

6.3.1 Crushed rock

The results from the tests performed with crushed TBM muck (0/100) are shown in Fig. 6-1. The tests were made with the same initial dry density and water ratio. The access time to water varied between 20 and 120 minutes. The figure shows that the samples took up water very rapidly although the water ratio at full saturation (11.6%) was not reached anywhere in the samples. These results are implying that it is difficult to reach full saturation without pressurising the water. The maximum degree of saturation in any sample was S_r = 83%.

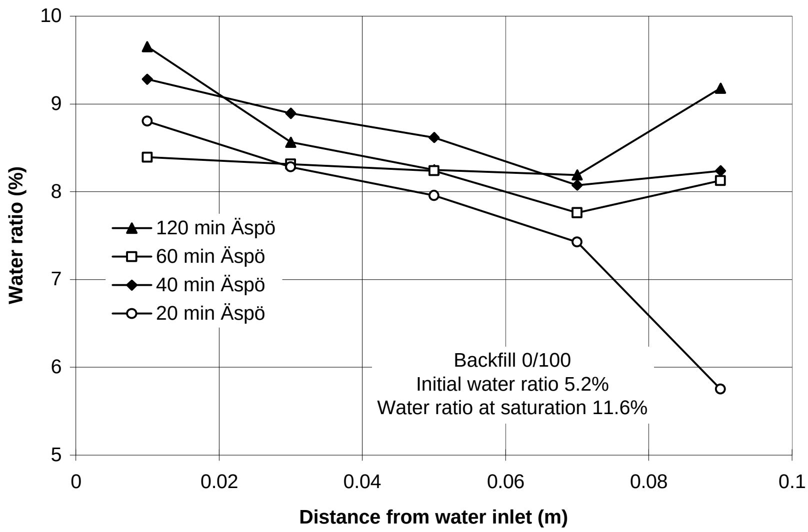


Figure 6-1. *Results from water uptake tests performed on crushed TBM muck. The initial density of the material was r_d = 2.08 g/cm^3, corresponding to 90% Proctor. The tests were performed with Äspö water.*

6.3.2 10/90 mixtures

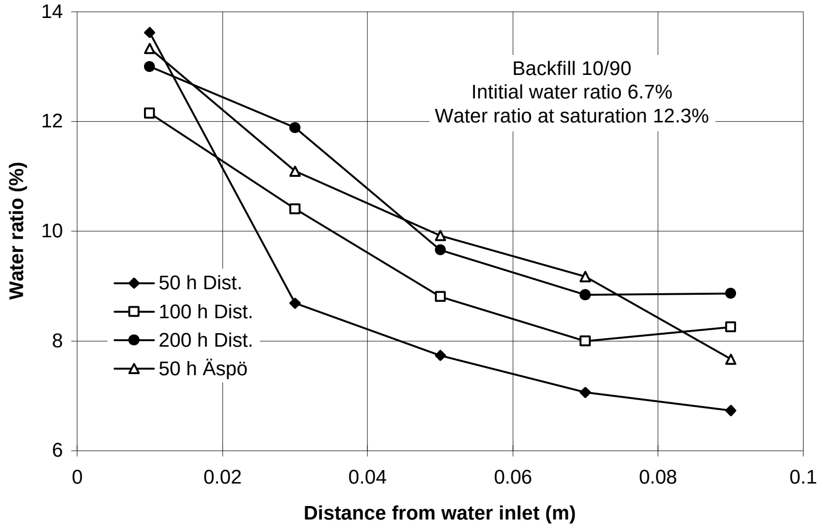
Test results from measurements on backfill with 10% bentonite content are shown in Fig. 6-2. All the tests were performed with the same initial dry density. The parameters that were varied in the tests were the water type, the initial water ratio and the time which the samples had access to water. The following observations can be made:

- All the samples were close to fully saturated (w = 12.3%) at the water inlet side. Some of the samples reached a somewhat higher water ratio than 12.3%. A small swelling of the material, causing a higher void ratio at the water inlet can explain this.

- Fig. 6-2a shows that by using Äspö water instead of distilled water the same distribution of water ratio was reached in much shorter time (50 hours instead of 200 hours)

- Similar average water ratio was reached in much shorter time if the initial water ratio was low (compare curve 50 h Äspö in Fig. 6-2 a with curve 16 h Äspö in Fig. 6-2 b)

- Fig. 6-2 shows that the water uptake process yields different water ratio distribution. When distilled water is used the process seems to be of a diffusion type while the water seems to move like a front when Äspö water is used.



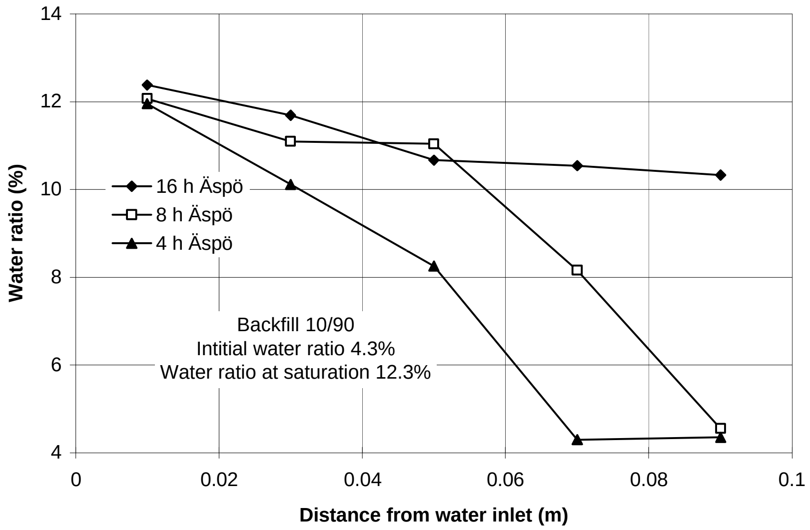


Figure 6-2. *Results from water uptake tests performed on 10/90 mixture. The initial density of the material was* r_d *= 2.05 g/cm*^{3}*, corresponding to 95% Proctor. The tests were performed with both distilled water and Äspö water.*

6.3.3 20/80 mixtures

Test results from measurements on backfill with 20% bentonite content are shown in Fig. 6-3. The same conditions prevailed as for the 10/90 mixtures.

The results agree very well with the results observed from the tests on 10/90 mixture, the only difference being that the rate of water uptake is about 4 times slower for the 20/80 mixture.

6.3.4 30/70 mixtures

The results from the tests with 30/70 mixture are shown in Fig. 6-4. One test was performed with the dry density ρ_d = 1.84 g/cm^3 and the rest of the tests were performed with ρ_d = 1.75 g/cm^3. Furthermore the water type, the initial water ratio and the time the samples had access to water were varied in the tests.

The trends observed in the other tests can also be seen in the tests of 30/70 mixtures. The water uptake is faster when Äspö water is used and when a low initial water ratio is used, but it is slower for 30/70 than for 20/80 mixtures.

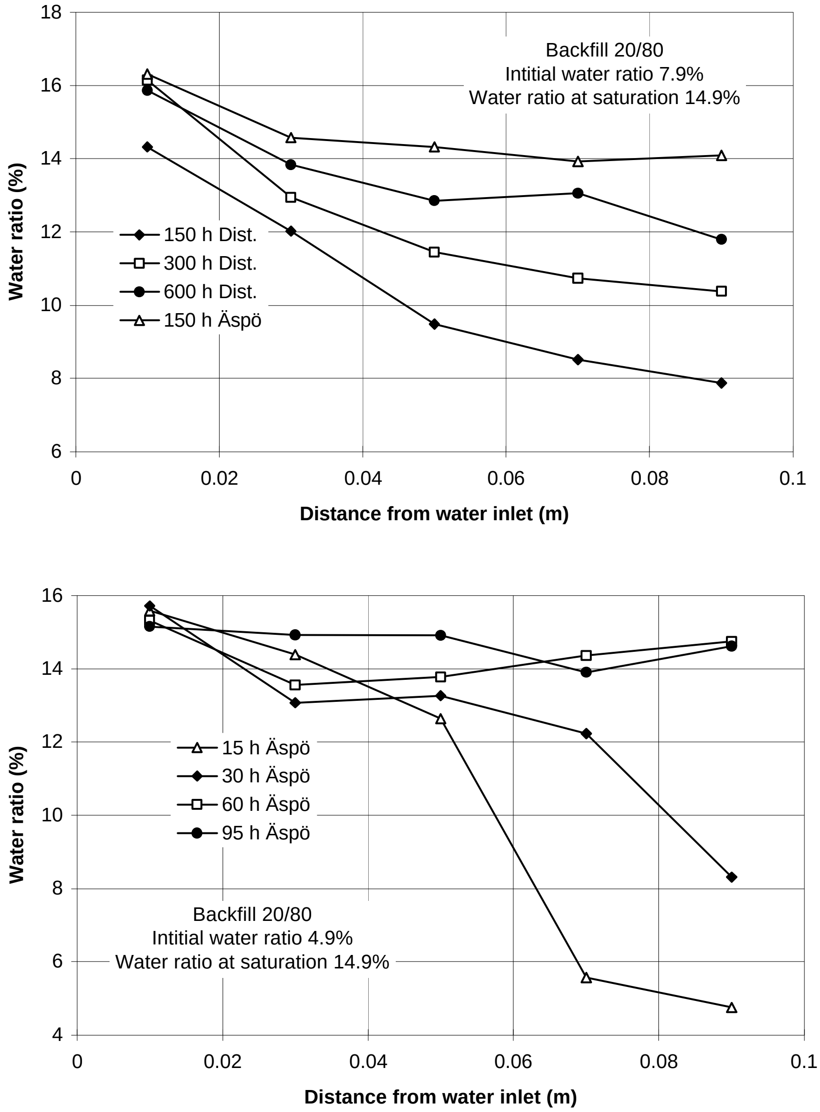


Figure 6-3. *Results from water uptake tests performed on 20/80 mixture. The initial density of the material was r_d = 1.95 g/cm^3, corresponding to 95% Proctor. The tests were performed with both distilled water and Äspö water.*

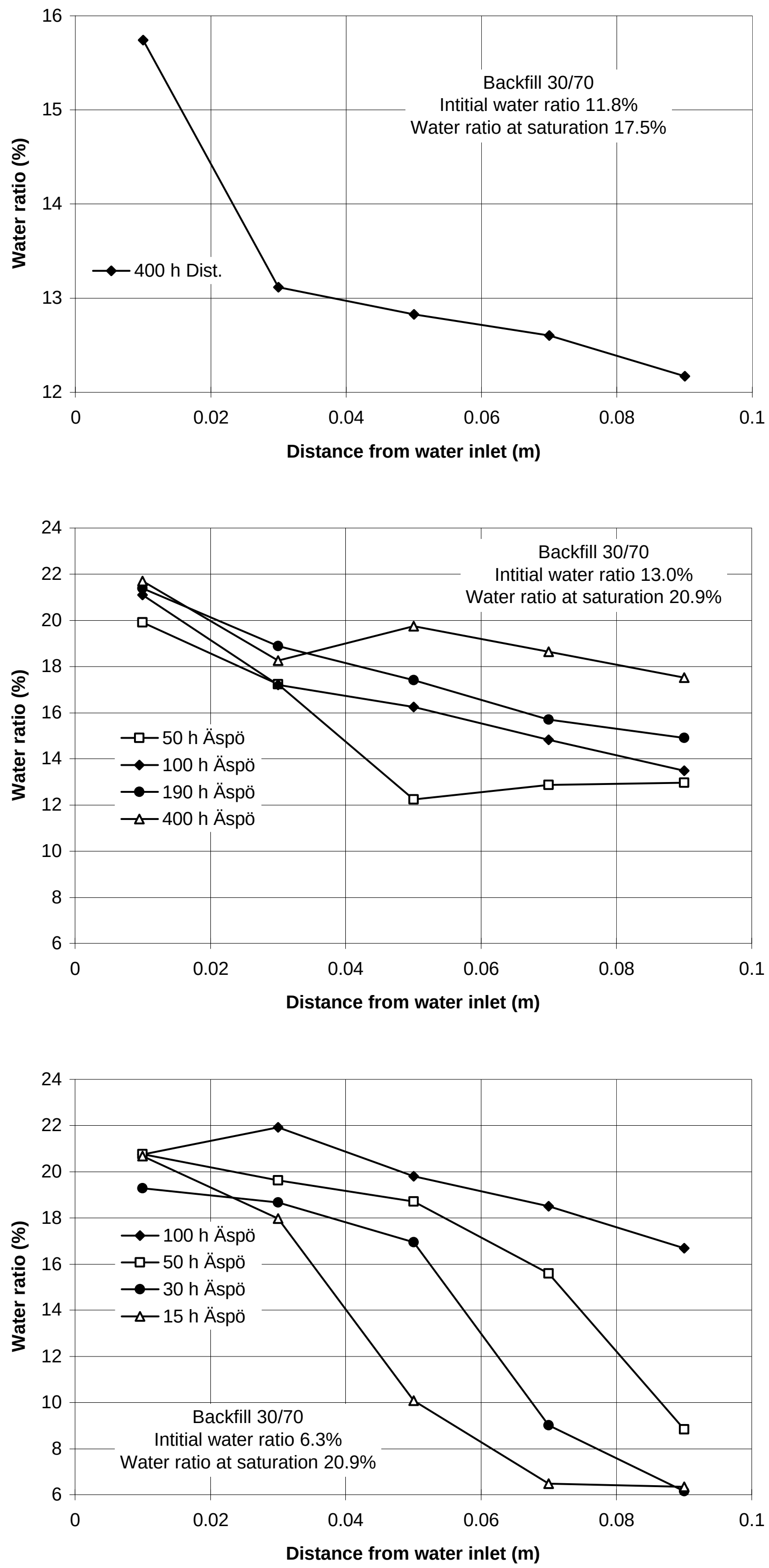


Figure 6-4. *Results from water uptake tests performed on 30/70 mixture. The initial densities of the material were* $r_d = 1.84\ g/cm^3$ *(upper) and* $r_d = 1.75\ g/cm^3$ *corresponding to 95% and 90% Proctor respectively. The tests were performed with both distilled water and Äspö water.*

6.4 CONCLUSIONS

The water uptake tests, that were made with backfill containing 0-30 % bentonite, were very consistent and yielded the following trends for all materials:

The water transport rate decreases with increasing bentonite content. This trend is logical since the hydraulic conductivity decreases with increasing bentonite content.

The water transport rate increases with increasing salt content. This is also logical with reference to the influence of the salt content on the hydraulic conductivity

The water transport rate was higher for backfill materials compacted at a low initial water ratio than for backfill compacted at optimum water ratio. This is a surprising observation. The reason may be that the hydraulic conductivity seems to be sensitive to mixing and compaction procedures as well as the amount of water added during mixing.

The water content distribution in the backfill during the water uptake process varies considerably between the salt free water and the salt Äspö water. The reason is not clear but the difference can be modelled by changing the relation between the hydraulic conductivity and the degree of saturation (Börgesson and Hernelind, 1998).

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