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Äspö Hard Rock Laboratory

Prototype Repository

Backfill of the tunnel in the Prototype Repository

Results of pre-tests. Design of material, production, technique and compaction technique

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April 2001

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Summary

The main requirements of the backfill in a deposition tunnel is to prevent the tunnel from being a major flow path for the water in the rock, to keep loose blocks of rock in place, to prevent too much upwards swelling of the buffer and to avoid that open slots between the backfill and the rock occurs.

These demands have guided the design of the backfill in the Prototype Repository. The tested backfill is a mixture of crushed rock (0-5 mm) and bentonite from Milos, which is Na activated and ground to a fine powder. The backfill has been tested both in laboratory and field tests. The field tests have included crushing of TBM-muck to ballast material with a maximum grain size of 5 mm, mixing the ballast with bentonite (30%) and water and compaction in inclined layers in a drift.

The laboratory results show that the bentonite has similar properties as MX-80. The hydraulic conductivity of the backfill with 0.7% salt in the mixing water is well below 10^{-9} m/s for any density. The dry density needs to be 1.6-1.8 in order to yield a swelling pressure of 100 kPa.

The crushing seems to be the key issue. The high water content and the large amount of fines in the TBM-muck resulted in major problems with crushing of the TBM-muck to 0-5 mm with traditional crushing because of clogging. The conclusion is that if the TBM-muck is to be crushed to 0-5 mm it must be dried or another crushing technique must be used.

The test with mixing in the proposed mixing station was successful and the technique seems very suitable.

The large scale handling, placement and compaction test showed that the handling and field compaction properties of 30/70 backfill is at least as good as for the backfill used in the Backfill and Plug Test. The average dry density was higher than 1.7 g/cm^3 and no separation of larger particles was observed.

The tests thus show that 30/70 mixture of the proposed components are well suited for backfill. However, if the problems with crushing of the specific TBM-muck to particles smaller than 5 mm cannot be overcome with reasonable costs, particles up to 20 mm should also be acceptable. Supplementary laboratory tests should be made on that backfill.

Sammanfattning

De huvudsakliga kraven på återfyllningen i en deponeringstunnel är att förhindra att tunneln blir en dominerande flödesväg för vatten, att hindra lösa block i tunneltaket från att falla ner samt att förhindra att bentonit bufferten sväller upp för mycket.

Dessa krav har styrt designen av återfyllningsmaterial för prototypförvaret. Det föreslagna återfyllningsmaterialet består av krossat berg (0-5 mm) och natriumaktiverad finmald bentonit från Milos. Återfyllningen har testats både i fält och i laboratorium. Fälttesterna inkluderade krossning av TBM-muck till ballastmaterial med en maximal kornstorlek av 5 mm, blanding med bentonit (30 %) och vatten samt inpackning i lutande lager i en ort i ÄHRL.

Laboratorietesterna visade att bentoniten har liknande egenskaper som MX-80. Återfyllningsmaterialets hydrauliska konduktivitet (med 0,7 % salt i blandnings vattnet) var under 10^{-9} m/s för alla testade densiteter. Torrdensiteten behöver vara 1,6 – 1,8 g/cm^3 för att ge ett svälltryck på 100 kPa.

Krossningen verkar vara huvudproblemet vid tillverkning av återfyllningen. Den höga vattenkvoten i kombination med den höga halten av finmaterial i TBM-mucken resulterade i stora problem med traditionell krossning eftersom utrustningen satte igen. Slutsatsen är att om TBM-mucken ska krossas till 0-5 mm så måste den vara torrare eller så måste en annan krossningsteknik användas.

Testen med den föreslagna blandningsstationen fungerade bra och tekniken verkar mycket lämplig.

Den storskaliga testen av hantering, inplacering och packning visade att återfyllningsmaterialets egenskaper i dessa hänseenden var lika bra eller bättre än återfyllningsmaterialet som användes i Backfill and Plug Test. Den genomsnittliga uppmätta densiteten var högre än 1,7 g/cm^3 och ingen seperation av större partiklar kunde observeras.

Testerna visar alltså att den föreslagna 30/70 blandningen är lämplig som återfyllningsmaterial. Om problemen med att krossa TBM-mucken till 0-5 mm inte kan lösas till en rimlig kostnad så kan emellertid även ett ballastmaterial med en kornstorleksfördelning mellan 0 och 20 mm vara acceptabel. Om detta material används så bör kompletterande laboratorietester göras.

Contents

1 Introduction

1.1 Background

The Prototype Repository is a full-scale simulation of a part of a repository with 6 deposition holes that will be equipped with canisters and filled with bentonite buffer and with a deposition tunnel that will be backfilled. The buffer, backfill and rock will be instrumented for measuring mainly thermal, hydraulic and mechanical processes.

The present study was initiated in order to choose the composition of the backfill and design the techniques to crush the rock, mix the components and apply and compact the backfill in the tunnel.

1.2 Experiences from previous tests

Several tests have been performed in earlier projects with the purpose to develop and test techniques for mixing backfill and place and compact it in a tunnel. Laboratory tests of different backfill materials have also been made. The following main experiences and conclusions have been made in these tests:

Field Test of Tunnel Backfilling (Gunnarsson et al, 1996)

This test was made in the Prototype tunnel and included crushing of TBM-muck, mixing with bentonite (0%, 10%, 20% and 30%) and filling and compaction of these mixtures in both inclined and vertical layers in the tunnel. Very valuable information was gained and a compaction technique for inclined layers developed. One conclusion was that compaction in layers inclined 35 degrees was the best way to handle both small amounts of water inflow and to make compaction close to the roof possible. Other conclusions were that techniques to handle inflow of large amounts of water had to be developed and that a special tool for compaction of the uppermost decimetres at the roof had to be designed.

Backfill and Plug Test (Börgesson, 1995; Gunnarsson et al, 2001)

This test is running in the tunnel excavated by blasting for the ZEDEX test. It includes backfilling with inclined compaction of 30/70 and 0/100 bentonite / crushed rock mixtures and subsequent measurement of the hydro-mechanical processes in the backfill during wetting and after completed water saturation as well as the interaction with the rock. Examples of experiences gained so far from this test are that the developed "roof compactor" worked sufficiently well (although problems with low density occur at irregularities of the roof), that the desired dry density 1.7 t/m^3 was achieved as an average and that some problems with separation and inhomogeneities of the backfill occurred although the behaviour of the backfill is not expected to suffer significantly from these phenomena.

Laboratory testing of backfill material (Börgesson et al, 1996; Johannesson et al, 1998)

Laboratory tests with the objectives to measure mechanical and hydraulic properties of mixtures of crushed rock and MX-80 bentonite with varying bentonite content have been made both on water saturated samples and unsaturated samples. Some important conclusions are that the influence of the salt content of the wetting water on the hydraulic properties is rather strong and that the spreading of results is large due to inhomogeneities in the structure that is revealed in the laboratory scale.

1.3 Strategy for choosing backfill material

The main functions of the backfill in the deposition tunnel is to prevent the tunnel from being a major flow path for the water in the rock, to keep loose blocks of rock in place and to prevent too much upwards swelling of the buffer. It is also desirable to avoid that open slots between the backfill and the rock occurs.

These functions have lead to the following demands on the backfill, which have guided the design of the backfill in the Prototype Repository:

- The hydraulic conductivity should not exceed $K=10^{-9}$ m/s (corresponding approximately to the average hydraulic conductivity of the rock around the Prototype Repository including all fractures).
- The swelling pressure of the backfill at the average dry density that is expected in the field should be at least 100 kPa after full water saturation
- The compressibility expressed as the compression modulus (oedometer modulus) at the average dry density that is expected in the field should not be lower than $M=10$ MPa in order to avoid an upwards swelling of more than 0.2 m. The choice of compressibility is based on preliminary calculations of the displacements of the interface between the buffer and the backfill, which showed that the displacement will be about 0.08 m with the E-modulus $E=30$ MPa and Poisson´s ratio $v=0.3$ (corresponding to $M=26$ MPa) (Börgesson and Hernelind, 1999).

The demands must be fulfilled at the chemical conditions that are expected in the repository, i.e. with site characteristic ground water (a salt content of about 0.7%).

Besides these demands the experiences from previous tests have yielded the following desires on the backfill for the Prototype Repository, which will result in a backfill that deviates somewhat from the backfill used in the previous tests:

- The ballast material of crushed rock should (if possible) have a maximum grain size of 5 mm instead of 20 mm (which was the limit in the previous tests). The reasons for decreasing the grain size are to reduce the risk of separation during mixing and placement and to reduce the inhomogeneities in the structure that was revealed in the laboratory scale.
- To use more finely ground powder of bentonite than the dry granule size distribution of MX-80. This is expected to yield a more homogeneous distribution of the clay fraction in the ballast pores.
- To use a Na-bentonite that has been converted from a Ca-bentonite by soda treatment.

2 Laboratory tests

2.1 General

A proposed composition of backfill has been tested in the laboratory with some basic tests, the single components separately as well as the mixtures. The backfill was composed according to the three desires presented in chapter 1.3.

In order to use a soda treated Ca-bentonite ground to a very fine powder a Greek bentonite from Milos was chosen. The bentonite is imported as raw material and treated by LKAB in Luleå. It is mainly used as furnace addition for production of iron pellets. For ballast material a product from the first test crushing of TBM-muck to 0-5 mm in *Svedala's crushing and screening test and research centre* was used.

2.2 Mixing water

In the Prototype Repository the backfill will be mixed with water that originates from the site during the actual mixing process at the production of backfill. As reference water for the laboratory tests, water taken from borehole KG0048A01 was used. The most important component of this water is the salt content. After analysis the following amount of different salts was added to distilled water and used in the tests:

NaCl: 4230 mg/l

$CaCl_2$: 1670 mg/l

This admixture corresponds to a salt content of 0.75%.

2.3 Bentonite material

The bentonite originates from Milos in Greece (Silver and Baryte Ores Mining Co). Some properties of the raw material determined by the supplier after addition of Soda are shown in Table 2-1.

Table 2-1. Properties of the Milos bentonite after processing (shipment 15/3 2001)

Quartz content	1.04 %
Silica content	51.4 %
K_2O	0.85 %
N_2O	2.90 %
Sulphur content	0.318 %
CaO	6.40 %

The bentonite is ground and dried in a facility in Luleå. It is grind to a fine powder with 90-95% of the dry particles smaller than 0.074 mm.

A number of basic laboratory tests have been made on the bentonite received in the autumn year 2000.

Natural water ratio

The average natural water ratio (per cent dry weight) determined as the water leaving the sample in 105 °C was 13.3% (average of 3 samples).

Liquid limit

The liquid limit has been determined with the cone method. Since the natural ground water at Äspö contains salt and the influence of salt is known to be rather strong at low bentonite densities, the liquid limit was also determined when the water used for mixing into the bentonite contained 0.7% and 1.2% salt with the same distribution of $CaCl_2$ and NaCl as the reference water. In order to compare the properties with the properties of MX-80 the same tests were made on MX-80. Figure 2-1 shows the results and reveals that the converted Milos bentonite has a higher water activity than MX-80 and that it is less sensitive to salt although the influence of salt in the water is still very strong.

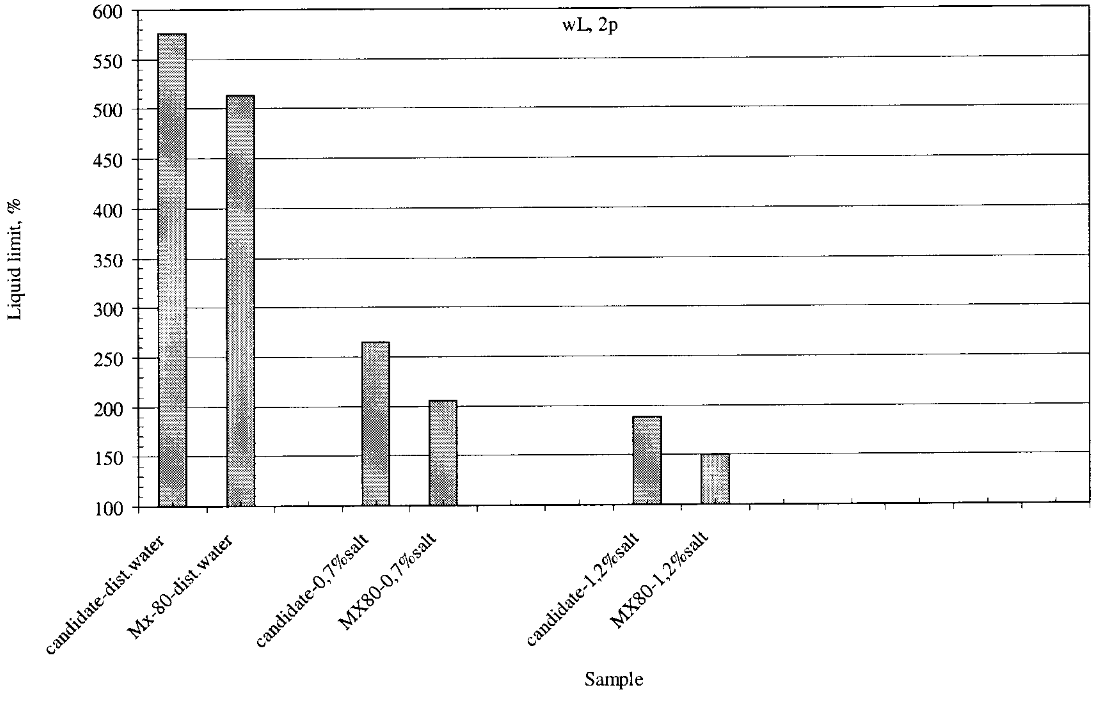

Figure 2-1. *Measured liquid limit of the Milos bentonite (candidate) at different salt contents in the mixing water and comparisons with MX-80*

Free swelling

The swelling ability has been investigated with swelling tests in which bentonite is strewed into a graduated measuring glass and allowed to swell freely in water (Karnland, 1999). The average result of 3 tests was a free swelling of 18 ml/g. This agrees well with results from corresponding tests on MX-80.

2.4 Ballast material

The rest products from the TBM boring is planned to be used in the Prototype Repository as ballast material. A test crushing was made by Svedala Svenska in *Svedala's crushing and screening test and research centre* and the material produced has been used for the laboratory tests. The grain size distribution is shown in Fig 2-2.

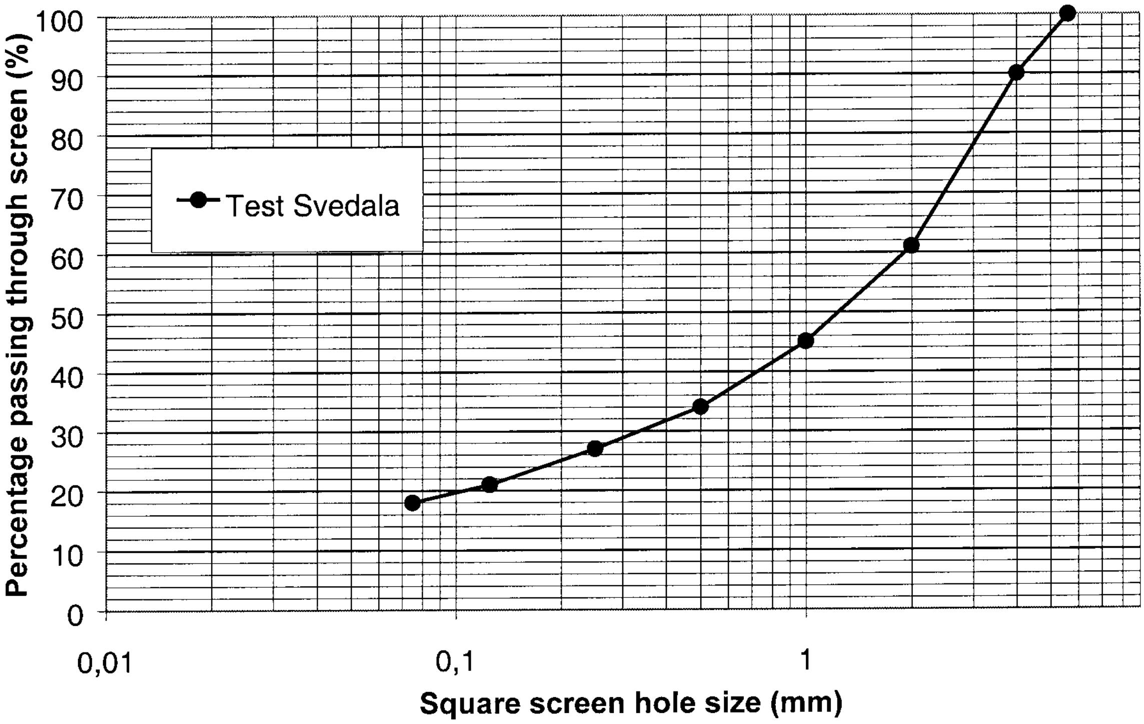

Figure 2-2. *Grain size distribution of the ballast material used in the laboratory tests.*

2.5 Backfill material

The following three types of laboratory tests were made on the proposed backfill:

- Laboratory compaction tests
- Hydraulic conductivity tests
- Swelling pressure tests

Laboratory compaction tests

The compaction tests were made as Modified Proctor tests with heavy weight (Fagerström, 1973). Figure 3-3 shows the results obtained for 20/80 and 30/70 bentonite / crushed rock mixtures. The results can be summarized according to Table 2-2.:

Table 2-2. Results of compaction tests

Mixture	Dry density at 100% Proctor Kg/m^3	Water ratio at 100% Proctor
20/80	2100	11%
30/70	2000	13%

The density at 100% Proctor is higher but also more sensitive to the water ratio in comparison with the material tested for the Backfill and Plug Test (Börgesson et al, 1996).

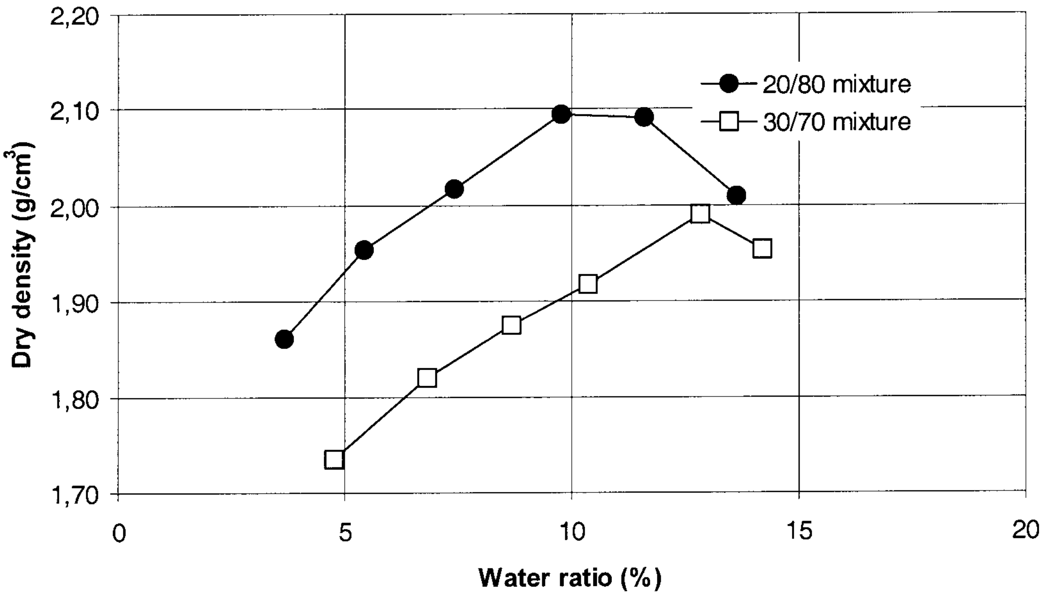

Figure 2-3. Results of compaction tests on two mixtures of bentonite and crushed rock.

Hydraulic conductivity tests

The hydraulic conductivity has been measured in oedometers with fixed sidewalls with the diameter 10 cm. The samples were compacted into the oedometers in 1 cm layers to the height 5 cm after mixing the backfill with the reference water to optimum water ratio. The samples were water saturated with the reference water by applying water in the bottom filter with a very low pressure and allowing air to dissipate through the upper filter. After completed wetting (3-8 weeks) a water pressure gradient was applied and the flow of water through the samples measured with time. When a steady water flow had been reached after about 1 week the hydraulic conductivity was evaluated. Table 2-3 shows the basic parameters and results of the tests. Fig 2-4 shows the hydraulic conductivity as a function of the dry density.

Table 2-3. Basic parameters[1)] and results of the hydraulic conductivity and swelling pressure tests.

Mixture	e	ρ_d g/cm^3	w	S_r	K m/s	σ_s kPa	u_b kPa	u_t kPa	
30/70	0.48	1.86	0.180	1.04	$2.0 \cdot 10^{-12}$	246	200	100	
30/70	0.66	1.70	0.228	1.02	$8.6 \cdot 10^{-12}$	106	150	100	
30/70	0.72	1.60	0.254	0.97	$2.1 \cdot 10^{-11}$	88	125	100	
30/70	0.84	1.49	0.292	0.95	$8.2 \cdot 10^{-11}$	56	125	100	
20/80	0.40	1.96	0.147	1.00	$1.4 \cdot 10^{-11}$	70	125	100	
20/80	0.50	1.83	0.174	0.96	$1.7 \cdot 10^{-10}$	139	25	0	
20/80	0.70	1.61	0.231	0.90	$4.3 \cdot 10^{-8}$	56	25	0	

1) e = void ratio; ρ_d = dry density; w = water ratio; S_r = degree of water saturation; K = hydraulic conductivity; σ_s = measured swelling pressure; u_b = applied water pressure in the bottom filter; u_t = applied water pressure in the top filter

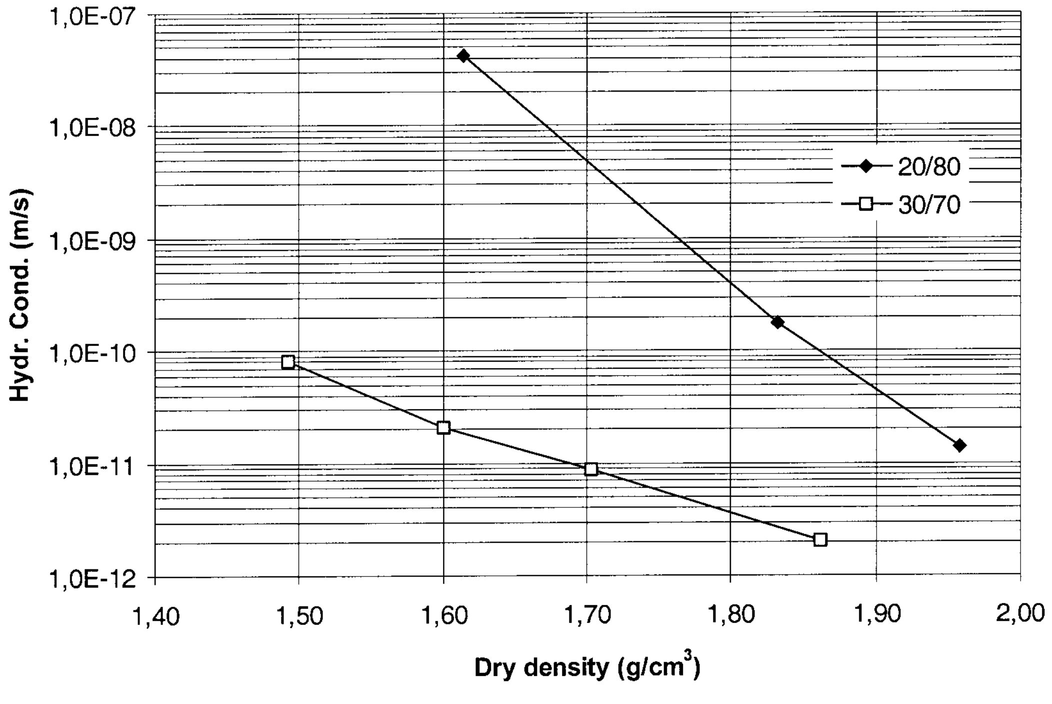

Figure 2-4. Measured hydraulic conductivity as a function of the dry density of backfill with 20% and 30% bentonite content.

The results show that the material deviates in hydraulic behaviour from the backfill used in the Backfill and Plug Test (Johannesson et al,1998) in the following way:

- The hydraulic conductivity is generally lower partly due to that that the salt content is 0.75% instead of 1.2% but also due to the difference in materials.
- The scatter is lower, probably due to the lack of particles larger than 5 mm and more homogeneous distribution of bentonite in the pores.

The results also show that 30/70 is acceptable in all density ranges and that also 20/80 is acceptable if the dry density is higher than 1.8 g/cm^3.

Swelling pressure tests

Since the upper filter is attached to a movable stamp the swelling force on the stamp could be measured by a force transducer applied between the stamp and a fixed lid in the cell. The increase in force with time was measured and the swelling pressure evaluated. The swelling pressure was shown in Table 2-3 together with the data from the hydraulic conductivity tests. Fig 2-5 shows the swelling pressure of 30/70 as a function of the dry density.

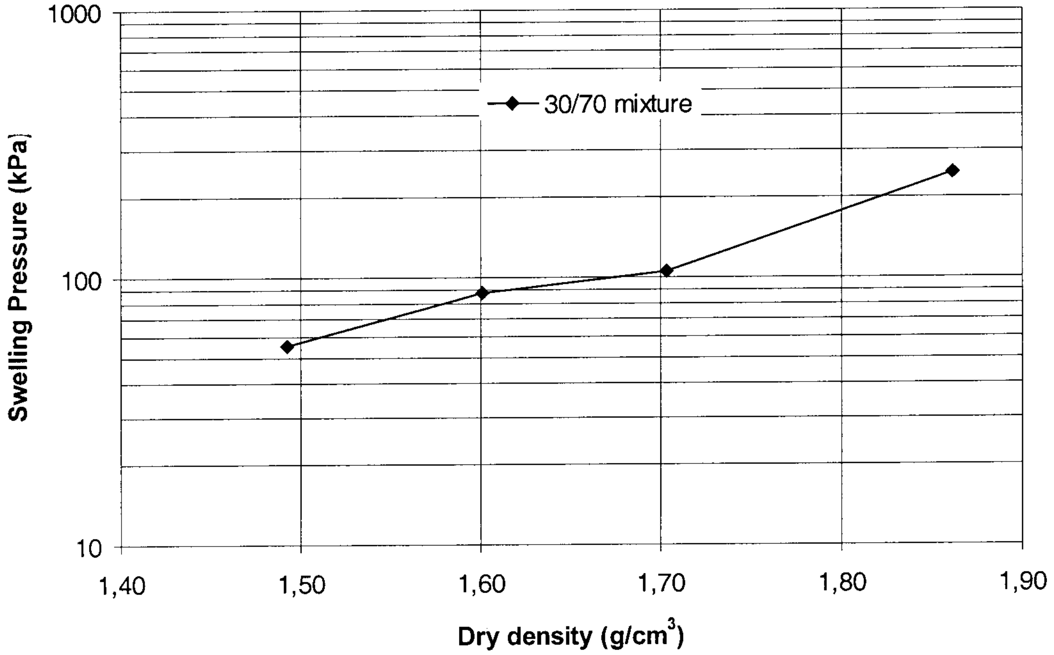

Figure 2-5. Measured swelling pressure as a function of the dry density of backfill with 30% bentonite.

The swelling pressure of 30/70 is lower than measured for the backfill used in the Backfill and Plug Test (Johannesson et al,1998) in spite of the lower salt content. The reason is probably the increased homogeneity in the new backfill, since the better distributed bentonite has a lower density in the pores of the ballast material. The dry density thus needs to be 1.7 g/cm^3 or higher in order to exceed 100 kPa. The swelling pressure of 20/80 is rather low and seems to suffer from a scatter caused by the low swelling potential. A new test is running but not yet finished.

2.6 Conclusions

The laboratory tests show that the proposed backfill material (grain size distribution of ballast according to Fig 2-2 mixed with finely ground powder of the Milos bentonite) is well suited for backfilling the Prototype Repository. 30% bentonite is required in order to yield the desired swelling pressure of 100 kPa when the reference mixing water is used. The tests should be supplemented with oedometer tests in order to confirm that the compressibility is similar to the compressibility of the backfill used in the Backfill and Plug Test (Börgesson et al, 1996).

3 Field tests for backfill production

3.1 Background

As a basis for the decision on which backfill material to use and as a preparation for the backfilling of the tunnel in the Prototype Repository some field tests of crushing TBM muck for ballast material, mixing the ballast material with bentonite and water and testing the compaction properties in full scale in Äspö HRL have been made. Chapter 3 deals with the backfill material production, i.e. crushing and mixing procedures, while chapter 4 treats the compaction tests.

3.2 Scope

The scope of these tests of backfill production is to manufacture approximately 50 tons of backfill material consisting of 30 % bentonite and 70 % crushed rock with the grain size 0-5 mm. This includes the crushing of TBM-muck to 0-5 mm and mixing the product with the sodium activated calcium bentonite from Milos, Greece.

3.3 Crushing

3.3.1 General

The TBM muck had been crushed to 0-20 mm for previous tests in the summer of 1995 (Gunnarsson et al, 1996). This could be done without problems. In the summer of 2000 a small amount of TBM muck (about 50 kg) was crushed in *Svedala's crushing and screening test and research centre*. This small amount of TBM-muck was dried by spreading it in a thin layer on a floor indoors. The grain size distribution of this crushed material was presented in Fig 2-2. This material was mixed with bentonite in Clay Technology's laboratory and used for the laboratory tests described in chapter 2.

The crushing to 0-5 mm in a larger production scale showed to be more problematic. The reason was the high amount of fines (15-20 % < 0,075 mm) in combination with the high water ratio (5%), which made the material stick to the material pockets and clog the screen that was used for separating the fines before the actual crushing. This made it necessary to try some different way of crushing the material.

3.3.2 Intended equipment and method

65 tons of TBM-muck was transported from the Äspö HRL to Svedala´s test plant in Dalby in the south of Sweden in order to test crushing and mixing and then use it for the field compaction test. The crusher was a Hydrocone 3000.

The planned crushing procedure was the following:

1. The fraction < 5 mm is sorted out and stored separately (final product 1)
2. The fraction > 5 mm is crushed in a Medium Course (MC) crushing chamber

3. The fraction < 5 mm from the second crushing is sorted out and stored separately (final product 2)
4. The remaining fraction > 5 mm is crushed in Medium Fine (MF) crushing chamber in a closed circuit until all the material is < 5 mm (final product 3).

The three products were planned to be stored and transported separately and mixed proportionally in the mixing with bentonite.

This procedure was tested week 46 last year (2000). The material stuck in the pockets and had to be removed with high-pressure water. About 20 tons of the originally 65 was used for testing and was lost. It was concluded that this technique was not feasible.

3.3.3 Alternative equipments and methods

The material could thus not be crushed as planned. To be able to use the intended crushing equipment it was necessary to lower the water ratio of the material. The material was moved into a barn and placed in a 50 cm thick layer on the floor. A permeable geo-textile was placed under the TBM-muck and two 9 kW portable dryers were used for keeping the RF above the TBM-muck low. The material was left in the barn for three weeks. During this time the water ratio did not change noticeable and it was concluded that this method was much too slow. Two other methods were considered:

1. Wet crushing: The fines in the material are washed out and the coarse material can then be crushed. This means that practically all of the fines (<0,075 mm) are removed from the original TBM-muck.
2. Drying by the use of a big tumble dryer of the kind that is used in asphalt plants: This method also results in a loss of fine material. The loss of fines can be controlled with variation in temperature and feeder speed. These kinds of tumble dryers cannot handle material courser that 25 mm. This fraction will have to be sorted out before the drying.

The second method was chosen. A dryer installed in a nearby asphalt plant in Dalby operated by NCC was used.

A flow chart for the new crushing method is show in Fig 3-1. A lot of material was lost during all the operations necessary to perform the crushing according to Fig 3-1. The weights of the final crushing products are presented in Table 3-1:

Table 3-1. The weight of the crushing products

Crushing product Number:	Weight (ton)
1	3.4
2	6.7
3	13.5
Total	23.7

The final amount of crushed TBM muck was thus reduced to 23.7 tons. The theoretical grain size distribution obtained if the three products are presented as *"Test crushing in Dalby"* in Fig. 3-2. The product crushed in the beforehand mentioned *Svedala crushing and screening test and research centre* is presented as *"Test crushing in Svedala"*

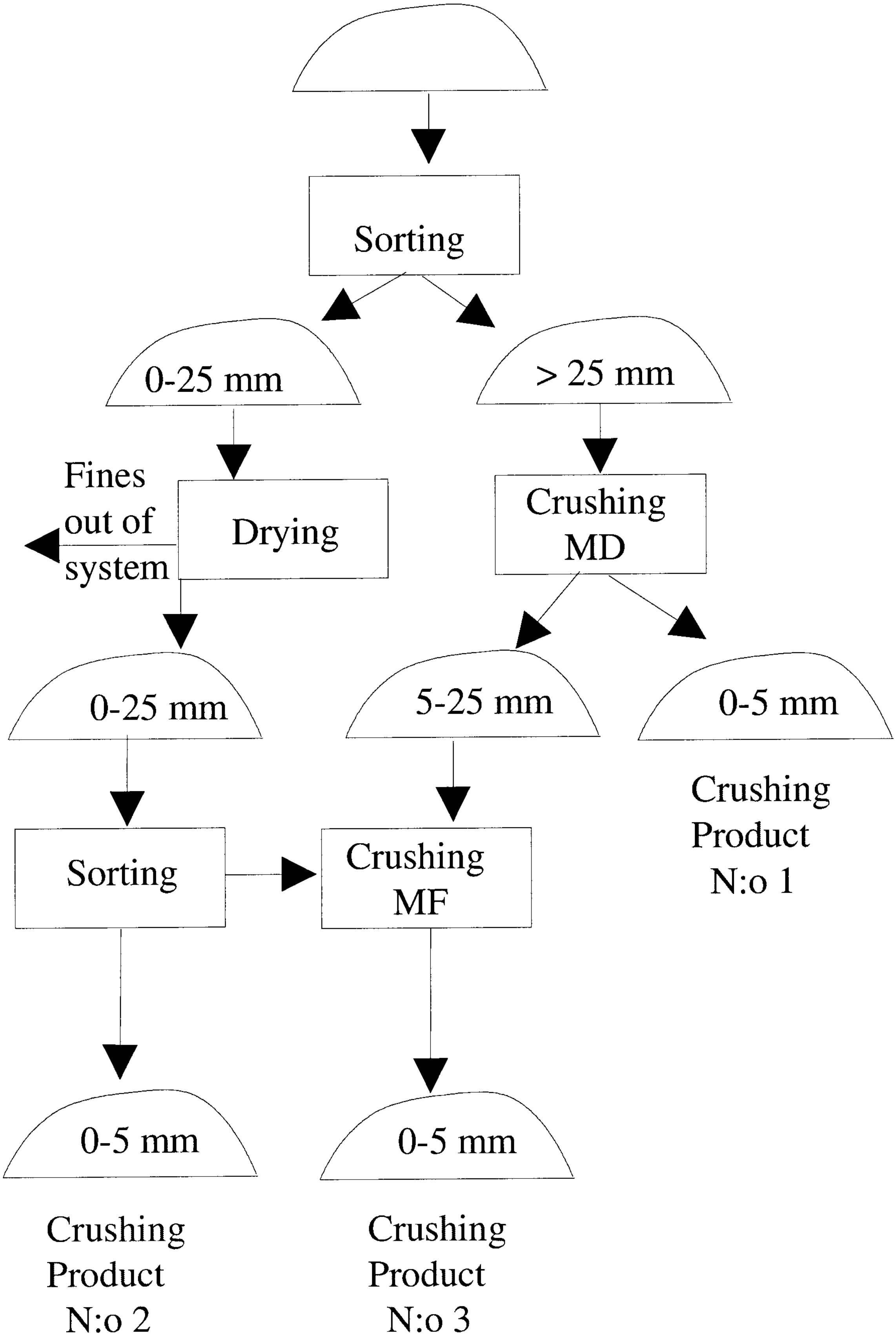

Figure 3-1*. Material flow for the crushing*

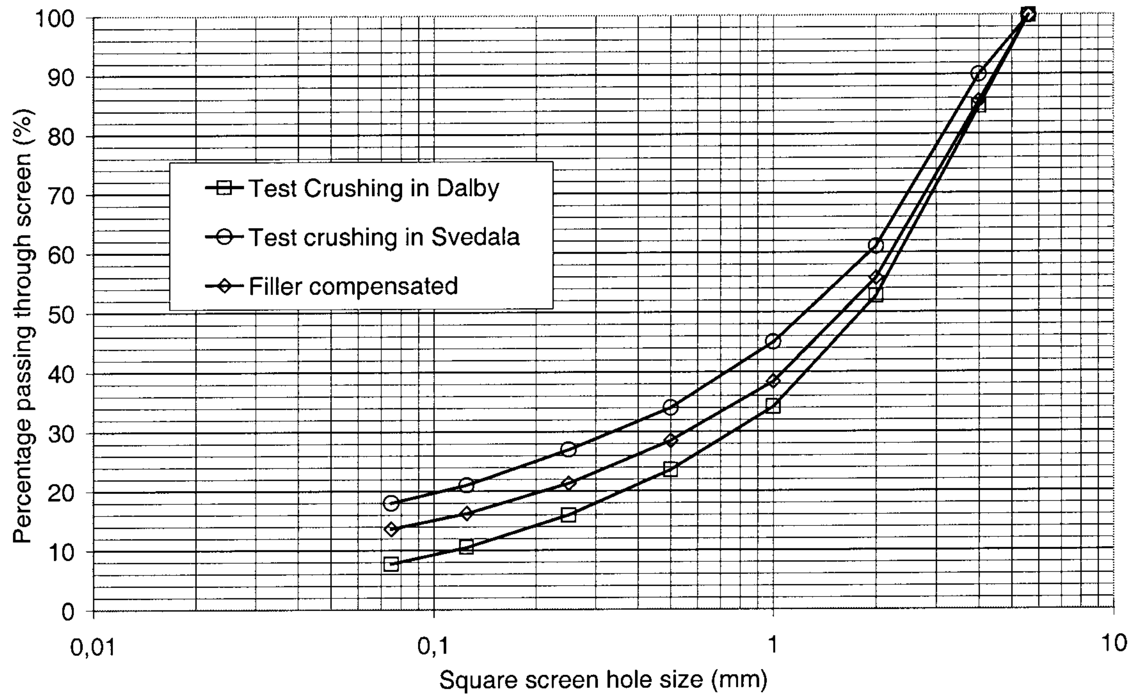

Figure 3-2. Grain size distributions

3.3.4 Conclusions

The high water ratio of the material makes it very difficult to crush to 0-5 mm with traditional cone or jaw crushers. These crushing techniques are based on the fines being removed before the crushing. The high amount of fines in combination with the high water ratio immediately makes a 5 mm sieve clog. If the fines are not removed they form aggregates that cannot be crushed. This causes high strain on the bearing axes of the crusher and might cause the crusher to break down. Sorting out fine material is also necessary in a continuous crushing procedure where cone or jaw crushers are used.

The alternatives are to decrease the water ratio of the material or to use a different crushing technique.

3.4 Mixing

3.4.1 General

The mixing station that was used is a Tecwill Cobra C80 and is operated by NCC Ballast and was situated in Huddinge south of Stockholm. The water ratio of the produced 30/70 was adjusted using 0,8 % salt water that was prepared on site by NCC. The crushed material from the test crushing (23.7 tons) and the bentonite were transported to the mixer and the mixed material was then transported to Äspö HRL for the compaction tests.

Since the amount of fines in the crushed material was lower than expected a fraction from a nearby crushing plant that contained much fines was added in the mixing. The theoretical grain size distribution curve obtained if all of the crushed rock fractions that form the ballast are mixed is also presented as "*Filler compensated*" in Fig 3-2.

The amount of filler compensated crushed TBM-muck was not enough for the planned three layers of 30/70 material. In order to manufacture enough backfill material for three layers locally crushed rock was also mixed with bentonite. The main purpose of producing this material was not to investigate what density could be achieved but to use it for practising the compaction technique. The two types of 30/70 mixtures were transported and stored separately.

3.4.2 Equipment and method

The mixing station is originally a concrete mixer but has only been used for mixing crushed rock and bentonite for covering refuse dumps. It consists of four ballast pockets, a silo for material in powder form (normally cement and in this case bentonite), the mixing jar and a control room. The mixer is a paddle type with two individually driven sets of paddles rotating in opposite directions. Water is added through four pipes with holes resulting in the water being sprayed into the jar.

The mixing was made in the following steps:

1. The dry components (different rock fractions from the crushing and the bentonite) were mixed for two minutes.
2. Water was added by sprinkling.
3. Mixing for two more minutes

The receipt for one mixing round is shown in table 3-2.

Table 3-1. Receipt for one ton of 30/70. Amount of material in kg.

TBM 3	TBM 2	TBM 1	Filler	Bentonite	Water	Tot
318	168	111	41	294	67	1000

The mixed 30/70 material was stored in a tent by the mixing station and kept from freezing. It was then transported in covered containers to Äspö HRL were it was stored in tents that were also heated to keep the material from freezing.

3.4.3 Evaluation of mixing technique

Despite some practical problems due to freezing and electrical malfunction the mixing worked well. The mixer seemed efficient, the rotating speed of the two in opposite directions rotating sets of paddles was high and the water was effectively sprinkled over the material. This resulted in a product that appeared very homogeneous in grain size distribution and water ratio. The water ratio of the material was measured as a part of the compaction test and it was rather homogeneous. The variation in the measured water ratio in backfill layer 2 is presented in Fig. 3-3.

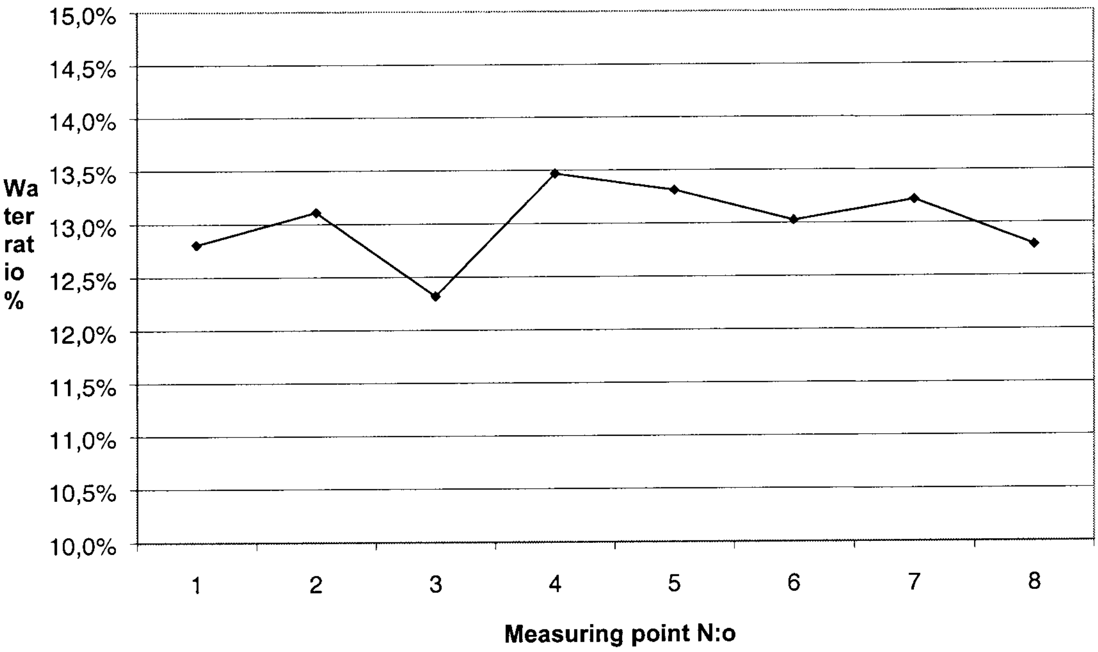

Figure 3-3. The variation in water ratio in layer 2

4 Field test of backfill compaction

4.1 Scope

The main purposes of the test were

- to test the field compaction properties of the proposed backfill material, i.e. to confirm that the intended densities can be achieved in field
- to test a test a new carrier of the vibrating plates with operators
- to test the drainage system that will be used for handling the water in the Prototype Repository

The latter test was caused by the large inflow of water that occurs in the Prototype tunnel. In order to be able to make a successful backfilling this water needs to be drained off.

Three 20 cm thick 30/70 layers with the inclination 35 ° were compacted and the density and water ratio measured. The first two layers consisted of 30 % bentonite and 70 % crushed granite with grain size 0-5 mm from Gladö kvarn, Huddinge (type 1). The ballast of this backfill type was used as substitute due to the lack of sufficient quantities of crushed TBM muck. The third layer consisted of 30 % bentonite and 70 % crushed TBM muck (type 2). Type 2 was described in chapter 3. The compaction tests were performed in the "TASM" niche in the Äspö HRL. The drainage system that will be used in the Prototype repository was also tested.

4.2 Equipment and technique

4.2.1 Backfilling equipment

The same compaction equipment as used in the Backfill and Plug Test was used for the compaction tests. The compaction cycle is shown in Figs 4-1a and b and the technique is further described in the report on the installation of the Backfill and Plug Test (Gunnarsson et al, 2001).

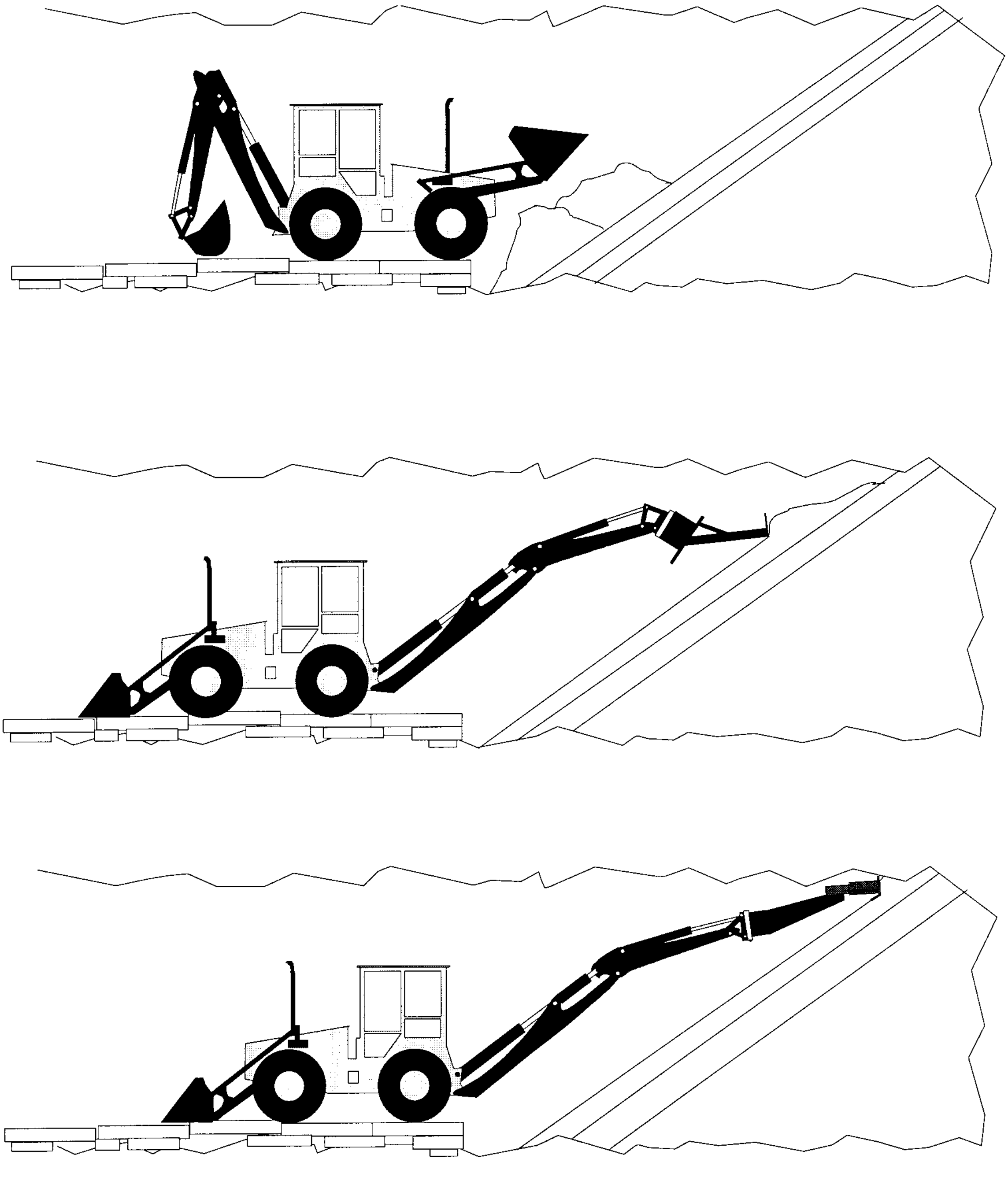

Figure 4-1a. *The backfilling of one layer (placement, pushing in place and compaction at the roof)*

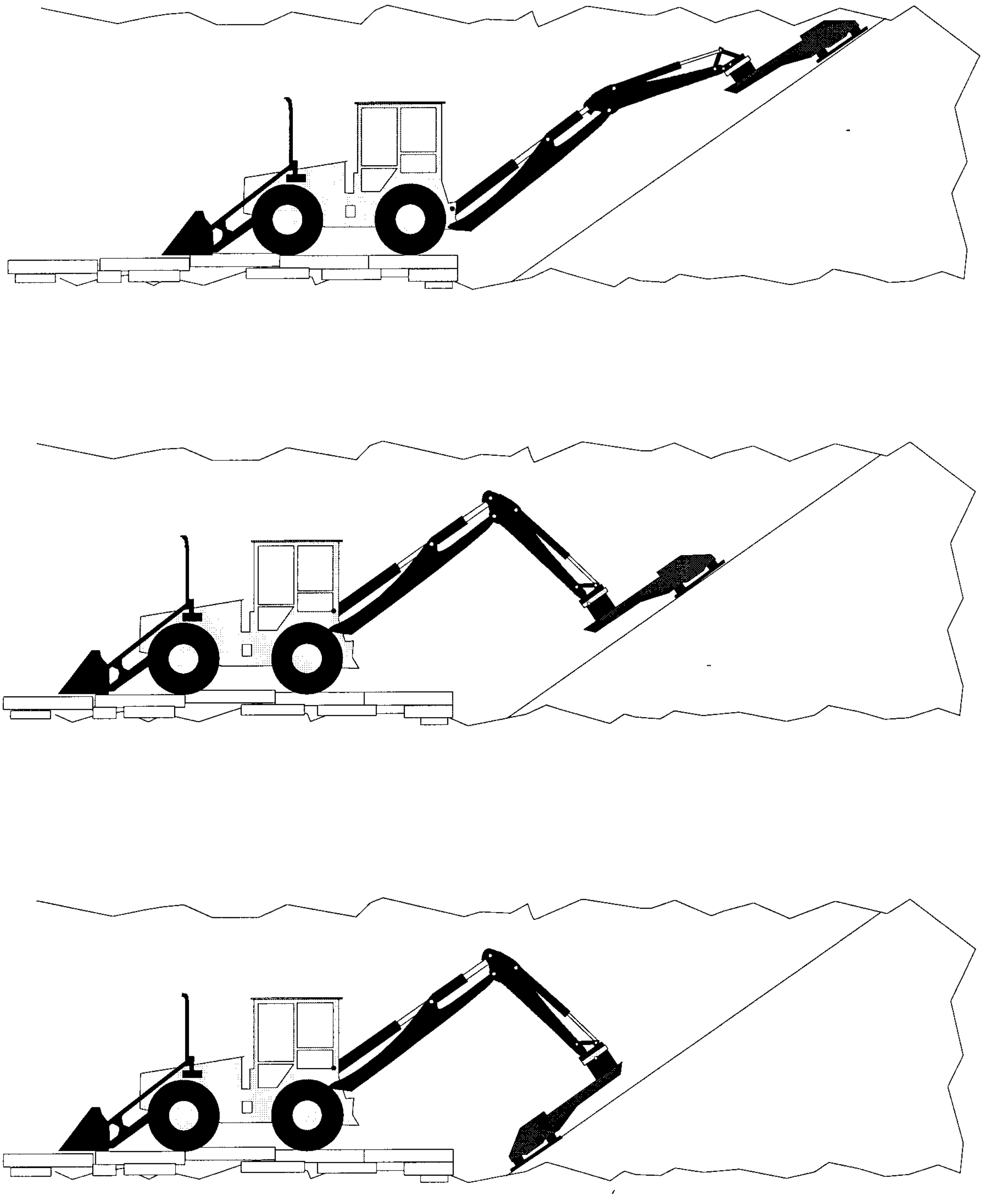

Figure 4-1b. The backfilling of one layer (compaction with the slope compactor)

4.2.2 Equipment, methods and scope for measuring density

Two different types of nuclear gauges have bee used for determining density in the layers. A *Campel Pacific MC-3 Portaprobe* (referred to as gauge A) was used on every layer. This gauge measures the average density of the layer. A *Campel Pacific MC-s-24 Direct Readout Strata Density / Moisture Gauge* (referred to as gauge B) was used for determining the density at different depths. These methods are described further by Gunnarsson et al (1996).

A penetrometer (*Controls model T165*), was used for indicating the density at the roof. The measuring principle is based on a rod being pushed into the material and the maximum required force registered. The force can then translated into a dry density. The penetrometer calibration is presented in Appendix 1.

The standard measurements for one layer were 8 measurements with gauge A and about 70 measurements with the penetrometer according to Fig.4-2.

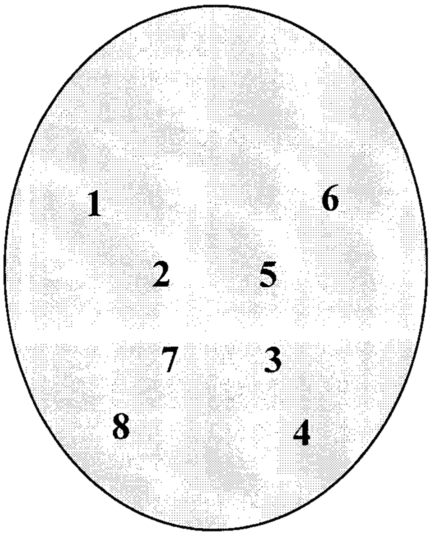

Figure 4-2. *The standard measurements for one layer*

4.3 Measured densities

4.3.1 Density of 30/70 backfill of Type 1 in layers 1 and 2

Layer 1

The average density measured with Gauge A on layer 1, using a measuring depth of 150 mm, was 1,71 g/cm^3 if the four measurements that were made about 0.5 from the walls were excluded. The average of the measurements close to the walls were 1.57 g/cm^3. Four passes with the vibrating plate were made on this layer. Normally one extra pass of the vibrator is made along the walls. This was not made for this layer, which can explain the low density close to the walls. The compaction technique is not uncomplicated and it is expected that it takes some time for the driver of the carrier to master the technique. It was expected that the density of the first layer was low.

To determine the density of the material at the roof penetrometer measurements were made. The measurements were made in an array 10 cm from the roof with a spacing of 10 cm between the measuring points. The penetrometer measurements are not very accurate and mainly give an indication of the density at the roof. The results are presented in Fig 4-3.

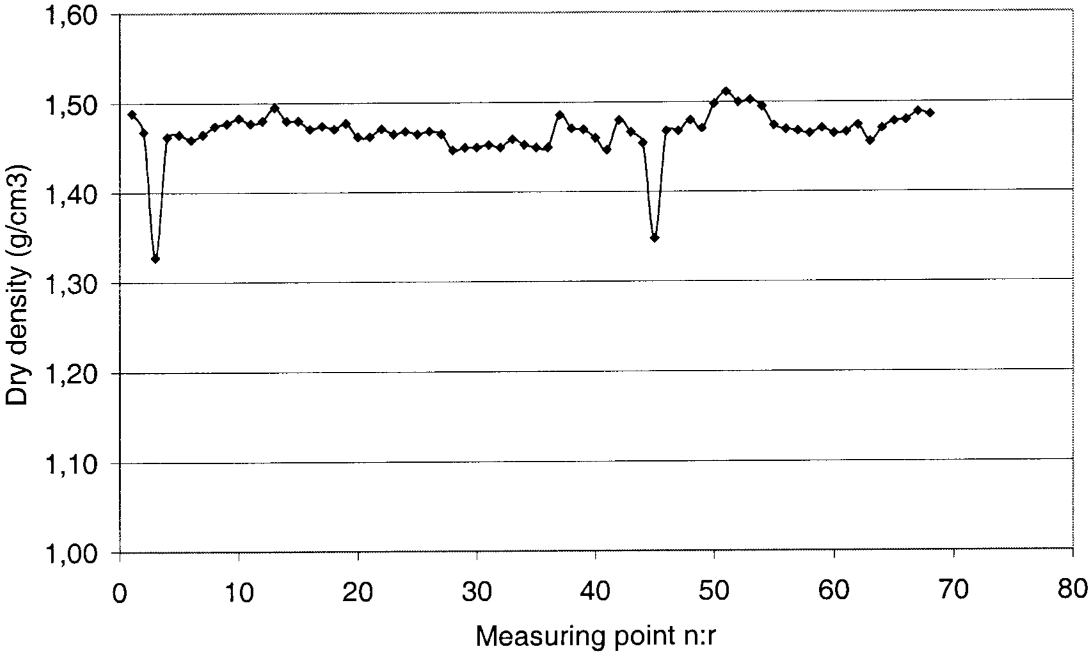

Figure 4-3. *Results from the penetrometer measurements at the roof in layer 1.*

Layer 2

Four passes with the vibrating plate over the entire surface and one pass along the walls were made on this layer. The average density measured with gauge A using a measuring depth of 150 mm was 1,80 g/cm^3. There was no significant difference between the densities measured in the centre of the layer and the ones made close to the walls. During the compaction of the material at the roof the roof compactor broke down before the compaction was complete. This affected the density in some part at the roof as can be seen in the results from the penetrometer measurements in Fig 4-4.

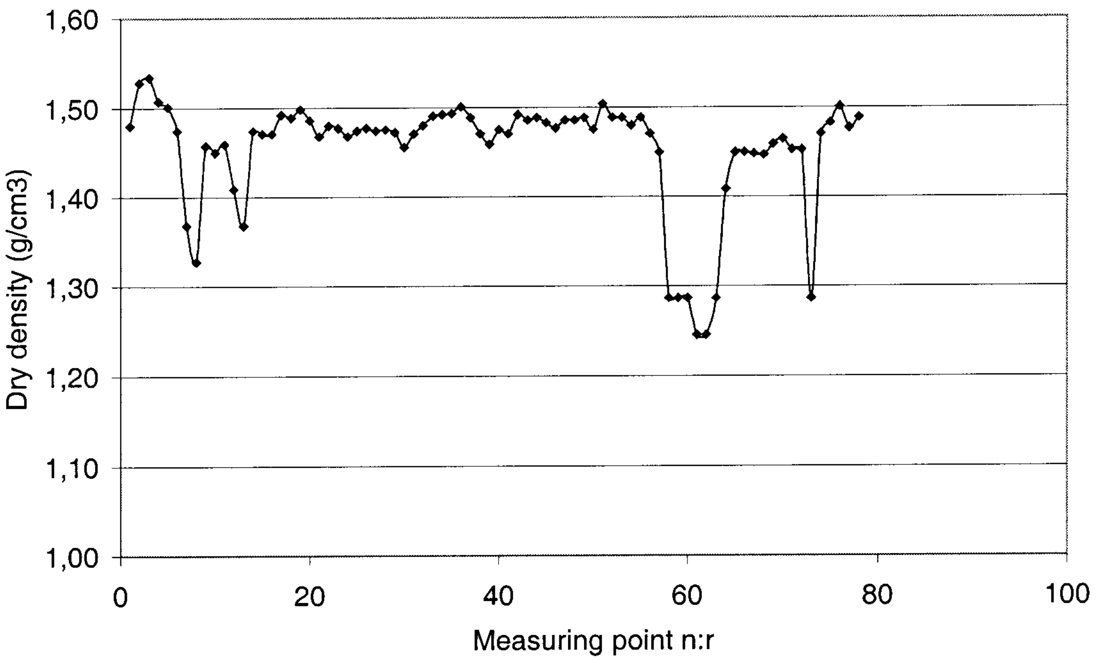

***Figure 4-4.** Results from the penetrometer measurements at the roof in layer 2.*

4.3.2 Density of 30/70 backfill Type 2 in layer 3

Since this type of backfill material has the same composition as the suggested backfill for the Prototype Repository more measurements were made and the results are presented more in detail. The amount of material was not enough for one entire layer (see chapter 3). The layer was compacted to 20 cm and covered 2/3 of the previous layer. The material could thus not be compacted towards the roof and hence no measurements at the roof have been made.

The layer was compacted with four passes with the vibrating plate. Measurements with nuclear gauge A was made in the positions showed in Fig. 4-5. Measurements were made at the depths 5, 10 and 20 cm in each point. Measurements were made with nuclear gauge B in two points (denoted B1 and B2 in Fig 4-5). In these points the density was measured at every 5 cm down to a depth of 40 cm. Penetrometer measurements were made 10, 20 and 30 cm from the rock along the left wall according to Fig 4-5.

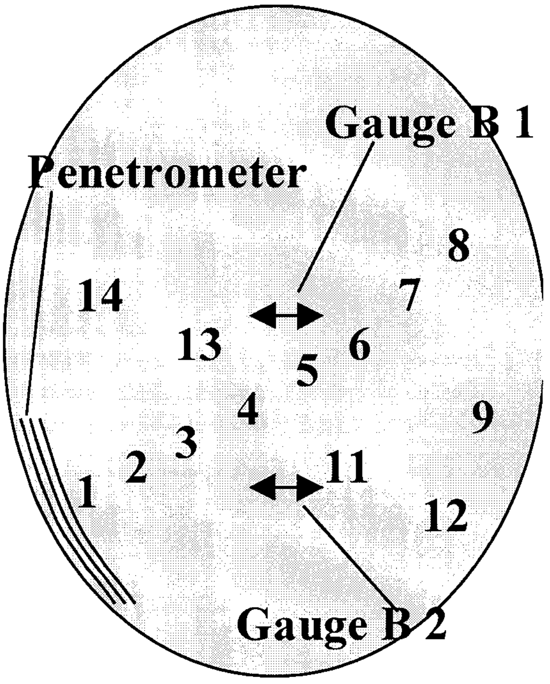

Figure 4-5. Scope of the measurements made on layer 3

Density measurements made with gauge A

The density measurements are presented in Fig. 4-6. The average density of the measurements made at 20 cm depth was 1,70 g/cm^3. If measurement 9, which was made as close as possible to the permeable mat, is excluded the average density rises to 1,72 g/cm^3.

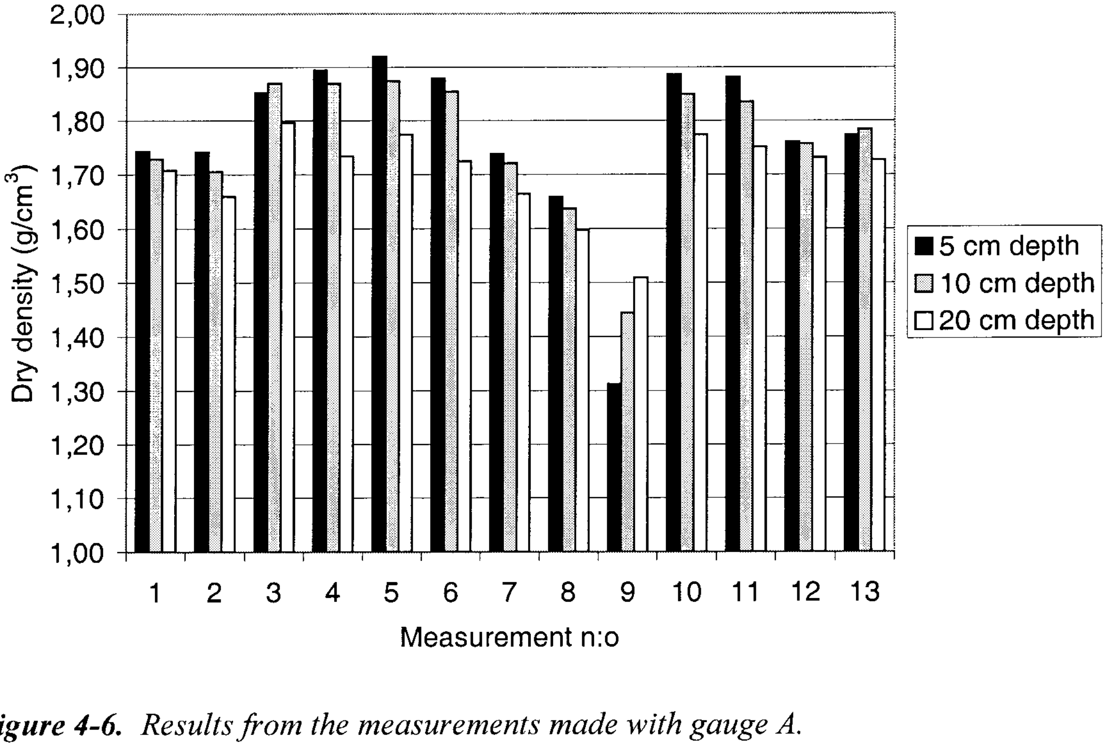

Figure 4-6. Results from the measurements made with gauge A.

Density measurements made with Gauge B

The results from the measurements made with Gauge B are presented in Fig. 4-7. The measured densities mainly agree with the results obtained with Gauge A. The variation with depth measured at location B1 is typical for compacted bentonite/crushed rock profile. The density is high in the surface and then decreases through the thickness of the compacted layer. The measured density in the top of the underlying layer is high and also decreases with depth. One measurement made at 150 mm depth in section B2 does not correspond to what was expected. This reading is probably incorrect. The most probable cause is that the person doing the readings has misread the figures on the display.

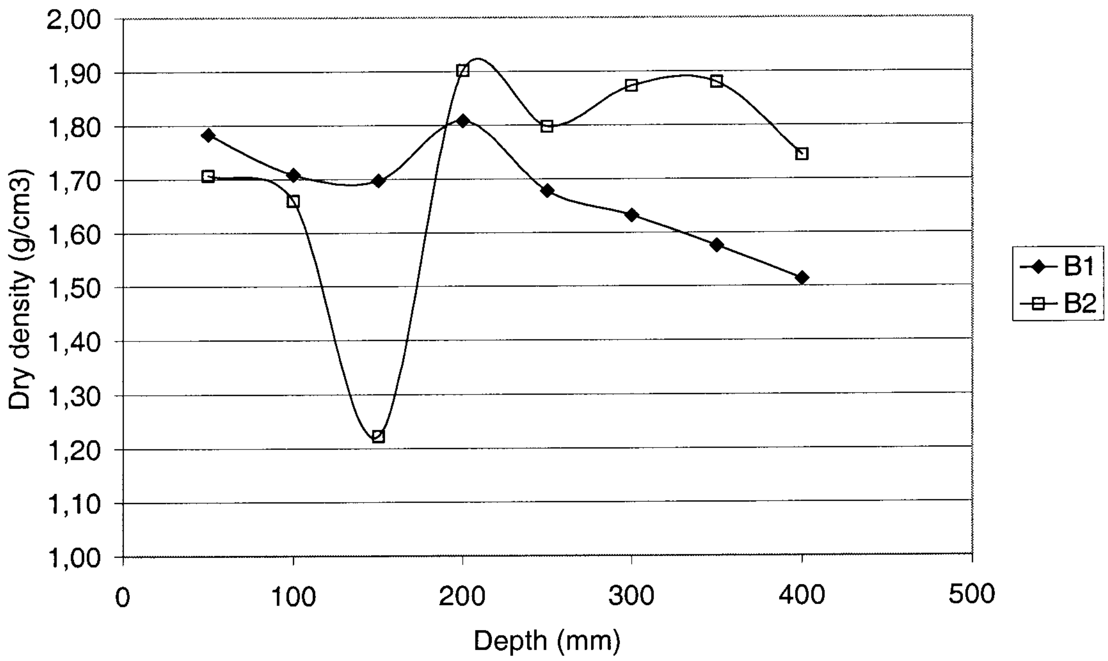

Figure 4-7. Density measurements made with Gauge B.

Penetrometer measurements

Penetrometer measurements were made along the left wall with a spacing of 10 cm. One array was made 10 cm, one 20 cm and one 30 cm from the rock surface. The first array consisted of 26 measurements, the second of 25 and the third of 8. The results show that there is a low-density zone close to the wall of the tunnel. As seen in Fig 4-8 the measured dry density 10 cm from the wall is about 1,45 g/cm^3. 20 cm from the rock the average measured dry density is 1,46. 30 cm from the rock the average measured dry density is slightly higher. The average of these three values is 1,47 g/cm^3. In measurement 4 and 5 in the arrays 10 and 20 cm from the wall there is a dip in measured density. This was probably induced by an irregularity in the rock wall.

The density is thus rather low since it is not higher than the density measured in the roof in layers 1 and 2. The reason is not clear. It may be caused by the fact that the new driver of the carrier was too careful and did not fulfil the compaction close to the wall. However, the results of the calibration of the penetrometer are doubtful. Additional calibration is required.

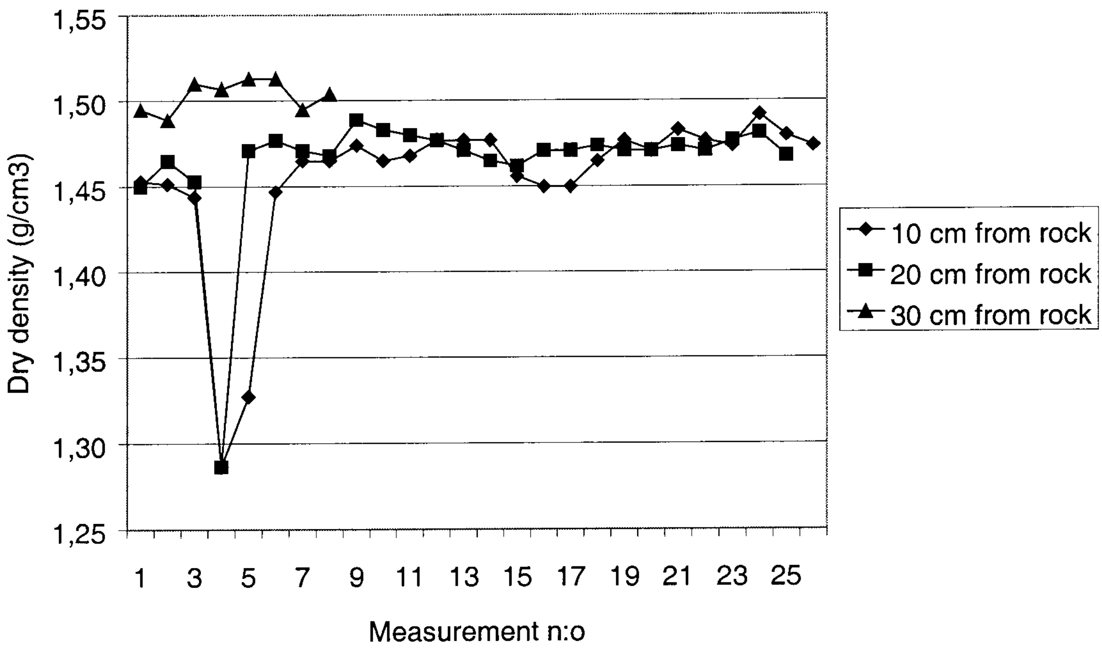

Figure 4-8. Results from penetrometer measurements in layer 3.

4.4 Drainage system

In order to test the drainage system that will be used in the Prototype Repository a strip of the drainage mat was mounted in the tunnel (see Fig 4-9). Since the rock surface was uneven a plane concrete surface was cast on the right hand wall. The mat was then attached to this surface. A tube simulating inflow was led into the mat. Another tube led water from the mat in the same way as planned for the drainage system in the Prototype Repository. The mat was placed so that the backfill layers intersected it.

The drainage system worked well. It seemed completely tight and did not leak any water. It did however affect the density in the nearby backfill material as seen in Fig4-6. If the slope compactor or the roof compactor is pushed against the mat during compaction the result is most probable that the permeable mat breaks. The driver of the carrier was very careful around the mat and as a result the material close to the mat was not compacted as well as material close to the rest of the walls. In the Prototype Repository there might be a conflict between compaction of material close to the walls and not ripping the mat, which might result in leakage of water from the mat and thus affect the water ratio of the backfill material. However a broken of the mat will be covered with backfill during the succeeding layers and the leakage time will not be very long. Temporary repairing of the mats may also be required.

Figure 4-9. *The drainage mat*

4.5 Conclusions

4.5.1 Density

The conclusion refers mainly to the density of the third layer.

The general conclusion is that it is possible to achieve an average dry density of 1.7 g/cm^3 or higher with the actual material and compaction equipment. It is however necessary to determine the compaction time needed, i.e. the number of passes of the slope compactor, and the extent of extra compaction needed towards the roof and walls of the tunnel. Such tests should be made in the prototype tunnel in the beginning of the backfilling phase.

The effect of instruments, cables and drainage mats on the compaction work is not considered. The drainage mat seems to reduce the density.

4.5.2 Handling of backfill material in the field

Both types of 30/70 backfill showed very good characteristics in the field:

- No separation was observed
- There were no practical problems transporting the material

- The material could be handled with the pushing tool without any problems.
- The pushing of material towards the roof worked well. The cohesion made the material stay in place for the compaction.
- The compaction worked well both at the roof and over the rest of the layer surface. The compacted surface was hard and even (see Fig 4-10).

Figure 4-10. *The compacted surface at the roof.*

4.5.3 Drainage system

The drainage system worked well but there is a risk that it might rip and start to leak during compaction. It will also decrease the density of the backfill material next to the mat.

5 Conclusions and design of material, production technique and compaction technique

A mixture of crushed rock (0-5 mm) and bentonite from Milos Na activated and ground to a fine powder has been tested both in laboratory and field tests. The results show that a mixture with 30% bentonite is well suitable for backfill material in the Äspö Prototype Repository.

The laboratory results show that the bentonite has similar properties as MX-80. The hydraulic conductivity of the backfill with 0.7% salt in the mixing water is well below 10^{-9} m/s for any density. The dry density needs to be 1.6-1.8 in order to yield a swelling pressure of 100 kPa. The hydraulic conductivity is thus lower and the swelling pressure is also lower than for the backfill used in the Backfill and Plug Test. This is an expected result of that powder bentonite is used instead of the slightly granulated MX-80.

The crushing seems to be the key question. The high water content and the large amount of fines in the TBM-muck resulted in big problems with traditional crushing to 0-5 mm because of clogging. The conclusion is that if the TBM-muck is crushed to 0-5 mm it must be dried or another crushing technique must be used. Both alternatives are costly.

The test with mixing in the proposed mixing station was successful and the technique seems very suitable.

The large scale handling, placement and compaction test showed that the handling and field compaction properties of 30/70 backfill is at least as good as for the backfill used in the Backfill and Plug Test. The average dry density was higher than 1.7 g/cm^3 and no separation of larger particles was observed.

The tests thus show that 30/70 mixture of the proposed components are well suited for backfill. However, if the problems with crushing of the specific TBM-muck to particles smaller than 5 mm cannot be overcome with reasonable costs, particles up to 20 mm should also be acceptable. Supplementary laboratory tests should be made on that backfill.

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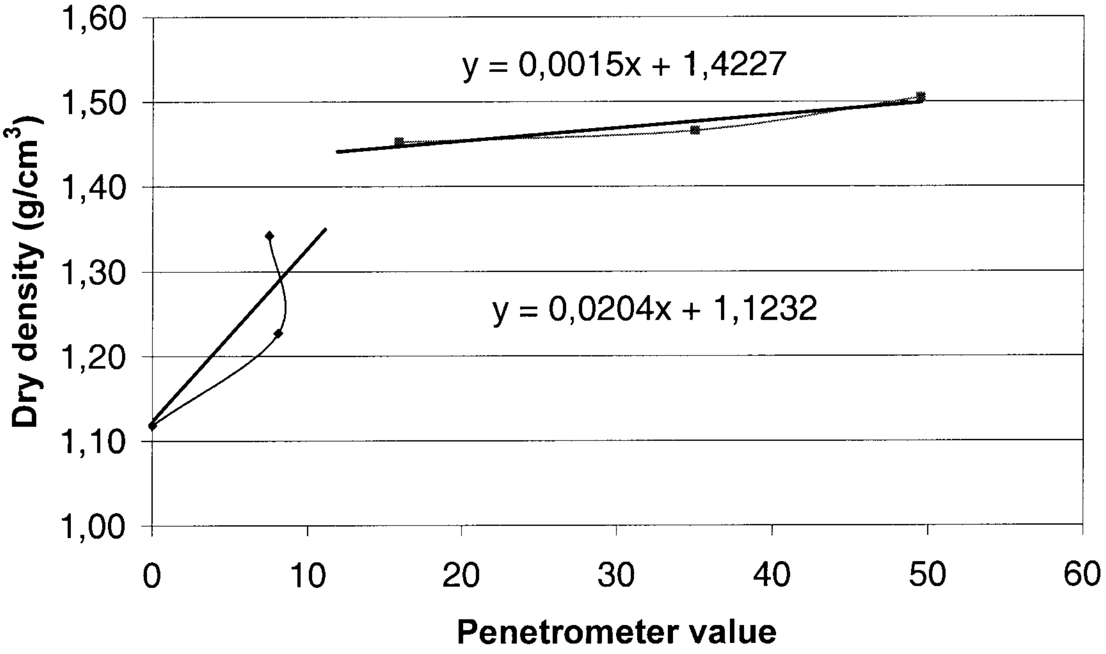
APPENDIX 1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Dry density (g/cm3)
Penetrometer value