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Äspö Hard Rock Laboratory

Field compaction test of friedland clay at Äspö HRL

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September 2001

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Keywords: Friedland clay, water ratio, Proctor, in situ compaction, vibrating plate

ABSTRACT

Friedland clay has been tested as tunnel backfill at Äspö for determination of its applicability and compactability. Two test series were made, the first with clay material that turned out to be too fine-grained and dry for making it possible to bring the material on site and compact it without unacceptable dusting. Furthermore, the compaction of this material gave densities that were lower than expected although the obtained average values roughly correspond to the minimum required density. However, the variation was rather significant and indicates that a significant fraction of the compacted material had an unacceptably low density. The reason for the shortcomings is that the water ratio was too low and it was therefore recommended that Friedland clay material be prepared with a water ratio (ration between weight of water and weight of dry material) in the interval 10-12 % for further testing on a large scale.

A second test series was made on new more coarse-grained and moist material (average water ratio 12.9 %) that showed good compactability in the laboratory (dry density 1853 kg/m^3). The water ratio turned out to vary considerably (8-27 %) but insignificant dusting took place at the handling and compaction. The outcome of this test series was that the density was even a bit lower than in the first test series, which is believed to be due to the toughness of the now wetter clay material. Thus, it is concluded that the compaction energy provided by the field equipment was far too low to yield a sufficiently high density. Other techniques should be considered, like the use of rammers in *in situ* compaction, or precompaction of blocks, which are brought in place.

The work has been carried out as a joint project between SKB and Posiva.

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SAMMANFATTNING

Naturliga smektitiska leror som återfyllning av tunnlar och schakt i djupförvar kan utgöra alternativ till blandningar av bentonit och ballast. Tidigare undersökningar har visat att en representant för sådana leror, den tyska Friedland Ton, har lämpliga egenskaper för att fungera som tunnelåterfyllning både när det gäller den hydrauliska konduktiviteten och svällningstrycket förutsatt att torrdensiteten är minst ca 1500 kg/m^3. Denna densitet uppnås lätt vid Proctorpackning i laboratoriet och den här rapporterade undersökningen avsåg att visa om denna densitet kan uppnås också under fältförhållanden vid användning av den utrustning som tagits fram på Äspö för applicering och packning av återfyllningar. Laboratorietester har visat att man kan uppnå en torrdensitet av minst 1700 kg/m^3 för vattenkvoter (kvot mellan vatten vikt och vikt torr substans) mellan 8 och 16 % men dammbildning antogs kunna skapa problem för lägre värden än 10 %. Vattenkvoten hos det beställda materialet valdes därför till 10-12 % men den var endast 5 till 7 % hos det material som levererades till det första fälttestet. Det orsakade så kraftig dammbildning att packning i huvudsak bara kunde göras under ca 3 sekunder i varje läge.

Fälttestet omfattade anbringande och packning av två 0,3 m lager av granulerad Friedlandlera med efterföljande bestämning av densiteten med hjälp av gammastrålningsutrustning. De allmänna observationer som gjordes var att Friedlandleran i den form den levererades till Äspö inte kunde läggas ut och packas utan oacceptabelt stor dammbildning. Vidare gav packningen densitetsvärden som var lägre än förväntat även om de erhållna medelvärdena var av samma storleksordning som de erfordrade. För en serie av packade lager kan man förvänta att den slutliga torrdensiteten blir ca 1400 till 1475 kg/m^3 motsvarande 1890 till 1930 kg/m^3 vid vattenmättnad. Det ger en högre hydraulisk konduktivitet än det förutsatta högsta tillåtna värdet E-10 m/s, dvs 2E-10 to 3E-10 m/s, om grundvattnet har oceanernas salthalt. Det erforderliga svälltrycket för att stödja tunneltak och väggar, 100 kPa, kommer emellertid att utbildas för de densiteter som uppnåddes i Äspö.

Slutsatsen var att vattenkvoten var för låg för att eliminera dammbildning och för att kunna få upp materialet till kontakt med tunneltaket och det rekommenderades därför att Friedlandlera framställs med en vattenkvot av 12-15 % för fortsatt storskalig testning. Sådant material gav vid laboratoriepackning en torrdensitet av 1853 kg/m^3. En andra testserie i fält utfördes också och materialet hade här en medelvattenkvot av 12.9 %; dock varierade vattenkvoten signifikant mellan ca 8 och 27 %. Den uppmätta torrdensiteten varierade mellan 1220 och 1390 kg/m^3, dvs lägre än i den första testserien. Slutsatsen från den andra testserien är att packningsenergin hos den använda utrustningen inte var tillräcklig och andra metoder bör övervägas, t ex användning av stampar för kompaktering på plats, eller förkompaktering av block som lyfts in på plats.

Arbetet har utförts i samarbete mellan SKB och Posiva.

SUMMARY

Natural smectitic clays for backfilling tunnels and shafts in deep repositories may be an alternative to mixtures of bentonite and ballast. Earlier investigations have shown that a representative of such clays, the German Friedland clay, has suitable properties for serving as tunnel backfill with respect to hydraulic conductivity and swelling pressure provided that the dry density is at least about 1500 kg/m^3. This density is easily obtained by Proctor compaction in the laboratory and the presently reported study was planned to demonstrate whether this density can be obtained also under field conditions using the equipment developed for application and compaction of tunnel backfills at Äspö. The laboratory compaction tests showed that a dry density of at least 1700 kg/m^3 can be obtained for water ratios ranging from 8 to 16 % but dusting was estimated to cause problems at field compaction for lower water ratios than about 10 %. The required water ratio of the manufactured clay was therefore 10-12 % but for the material delivered to the first field test the water ratio was found to be only about 5 to 7 %, which caused so much dusting that compaction at one and the same spot could generally not be made for more than about 3 seconds.

The field test comprised application and compaction of two 0.3 m thick layers of granular Friedland clay with subsequent determination of the density by use of a gamma ray gauge.. The general observations made were that Friedland clay in the form it was delivered to the test site at Äspö could not be applied and compacted without unacceptable dusting. Furthermore, the compaction gave densities that were lower than expected although the obtained average values roughly correspond to the minimum required density. For a series of layers of Friedland clay of the investigated type one can expect the final dry density to be in the range of 1400 to 1475 kg/m^3 corresponding to 1890 to 1930 kg/m^3 at water saturation. This will yield a higher conductivity than the assumed maximum allowed value E-10 m/s, i.e. 2E-10 to 3E-10 m/s, if the groundwater salt content equals that of the oceans. However, the required swelling pressure to provide support to the walls and roof of a KBS-3 tunnel would be achieved with the densities obtained at the Äspö tests.

It was concluded that the water ratio was too low for avoiding dusting and for making it possible to bring the material up in contact with the tunnel roof and it was recommended that Friedland clay material be prepared with a water ratio in the interval 12-15 % for further testing on a large scale. Such material gave a dry density of 1853 kg/m^3 at laboratory compaction. A second field test was also conducted with material with an average water ratio of 12.9 % showing moisture variations in the interval 8 to 27 %. No dusting took place but the dry density was only 1220 to 1390 kg/m^3, which is less than in the first test series. The less effective compaction in the second series may be the toughness of the now wetter clay material, or possibly, application in too thin layers. Thus, it is concluded that the compaction energy provided by the field equipment was far too low to yield a sufficiently high density. Other techniques should hence be considered, like the use of rammers in *in situ* compaction, or precompaction of blocks, which are brought in place.

The work has been carried out as a joint project between SKB and Posiva.

1 SCOPE

Applying the criterion that the tunnel backfill in a KBS-3 repository should not be more permeable than the host rock, its conductivity should not exceed about E-10 m/s [1]. Furthermore, it should have a swelling pressure of at least 100 kPa for supporting the rock walls and roof.

The German Friedland clay fulfils these requirements provided that the dry density is at least about 1500 kg/m^3 and that the salinity of the groundwater does not exceed that of the oceans. This density is easily obtained by Proctor compaction in the laboratory and the presently reported study was conducted for investigating whether it can be obtained also under field conditions using the equipment developed for application and compaction of tunnel backfills at Äspö.

2 CLAY MATERIAL

2.1 General

The natural Friedland clay is industrially processed through drying and grinding by which granulated powder is obtained for commercial use. The material was manufactured by the German company DURTEC[1] and delivered in big-bags to the Äspö HRL. Because of the risk of dusting the required water ratio had been set at 10-12 % but the material delivered was found to have a water ratio of only 5.1 to 7.1 %, which caused considerable dusting.

Experience shows that effective compactability is obtained when the grain size distribution is of Fuller type. The granulometry should hence be parabolic in diagrams with linear ”weight % passing” and logarithmic grain size. The required largest grain size was 5 mm.

2.2 Grain (granule) size distribution

Friedland clay in dispersed form has an average content of clay-sized particles (<2 µm) of 57 %. The material used in the present investigation had the granulometric composition shown in Table 2-1.

Table 2-1. Grain (granule) size distribution of Friedland clay delivered for the present study. Data given by DURTEC GmbH.

Fractions, mm	Percentage of grain size representing the respective fraction
2-8	20.0
1-2	20.4
0.1-1	42.4
<0.1	17.2
Total	100

2.3 Mineralogy

The clay contains 45 % expandable minerals (montmorillonite and mixed-layer mica/montmorillonite), 24 % quartz, 5 % feldspars, 13 % mica, 11 % chlorite, and 2 % carbonates [2]. The average chemical composition is as follows:

SiO_2 57 %, Al_2O_3 18 %, Fe_2O_3 5.5 %, MgO_2 2 %, CaO 0%, Na_2O 0.9 %, K_2O 3.1 %.

Na is the dominant adsorbed cation according to the manufacturing company.

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[1] DURTEC, Ihlenfelder Strasse 153, 17034 Neubrandenburg, Germany.

2.4 Physical properties

2.4.1 General

General characterisation of clay backfills comprises *compactability, hydraulic conductivity* and *swelling pressure*. These properties have been determined in several laboratory investigations, which form the basis of the following condensed report.

2.4.2 Compactability

The results from Proctor compaction tests are shown in Figure 2-1, from which one concludes that the density of laboratory-compacted Friedland clay is not very sensitive to variations in water ratio (distilled water). Thus, the dry density does not vary beyond the range of 1750 to 1790 kg/m^3 when the water ratio is changed from 7 to 21 % by weight. These densities correspond to 2070 to 2130 kg/m^3 at complete saturation.

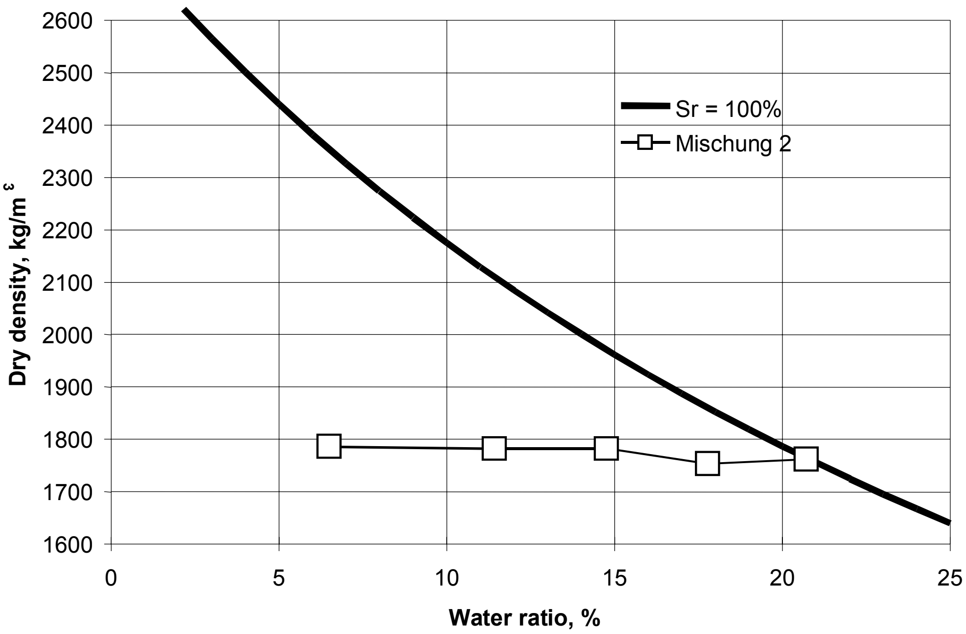


Figure 2-1. *Compaction tests (Test No 1, CT). (Mischung 2 represents the grain distribution in Table 2-1). The thick curve represents the theoretical maximum density (no voids), [2].*

2.4.3 Hydraulic conductivity

Saturation and percolation of Friedland clay with different solutions and concurrent recording of the flux has given the relationship between hydraulic conductivity and dry density in Figure 2-2. The hydraulic gradient was in the range of 20 to 200. It is noticed that there is no dramatic change in conductivity when the salinity is increased from that of ocean water to 20 % and that the conductivity does not exceed E-10 m/s for 3.5 % salt content of Ca-dominated water if the density at saturation is about 1950 kg/m^3 (dry density 1510 kg/m^3).

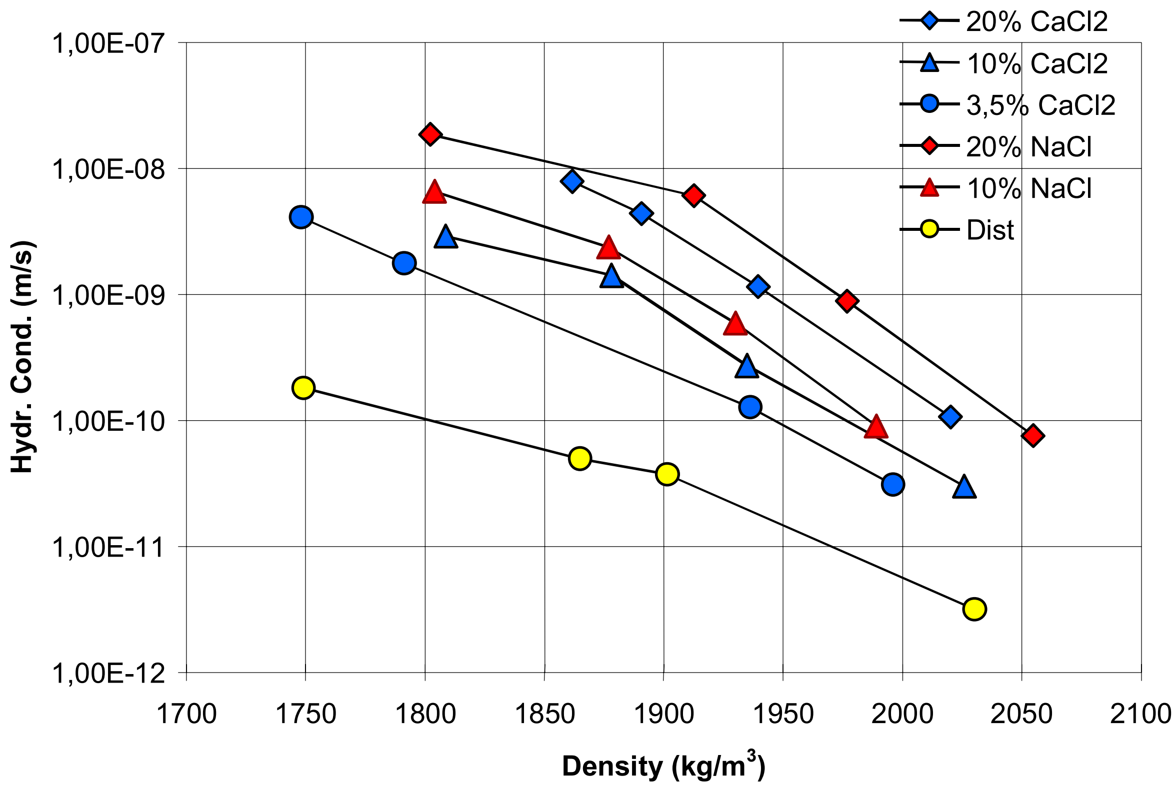


Figure 2-2. *Hydraulic conductivity tests on saturated samples [2].*

2.4.4 Swelling pressure

Figure 2-3 shows that the swelling pressure, which was recorded at the percolation experiments, exceeds the stipulated 100 kPa level for about 1850 kg/m^3 (dry density 1350 kg/m^3) and higher densities irrespective of the salt content of the porewater.

2.4.5 Conclusions

Applying the criterion that the hydraulic conductivity of tunnel and shaft backfills should not exceed the average bulk conductivity of the host rock the required conductivity is about E-10 at about 500 m depth [1].

The data in Figure 2-2 show that for groundwater salinity of commonly recorded orders of magnitude at a few hundred meters depth, i.e. 1 to 3 % with calcium as dominant cation, the hydraulic conductivity of the investigated natural clay is about E-10 m/s when the density is around 1950 kg/m^3 at saturation. For a groundwater salinity of 10 % the density required to give this conductivity should be about 2000 kg/m^3 (dry density 1590 kg/m^3), while the extreme case of 20 % salinity would require a density of 2050 kg/m^3 (dry density 1670 kg/m^3) to yield this conductivity.

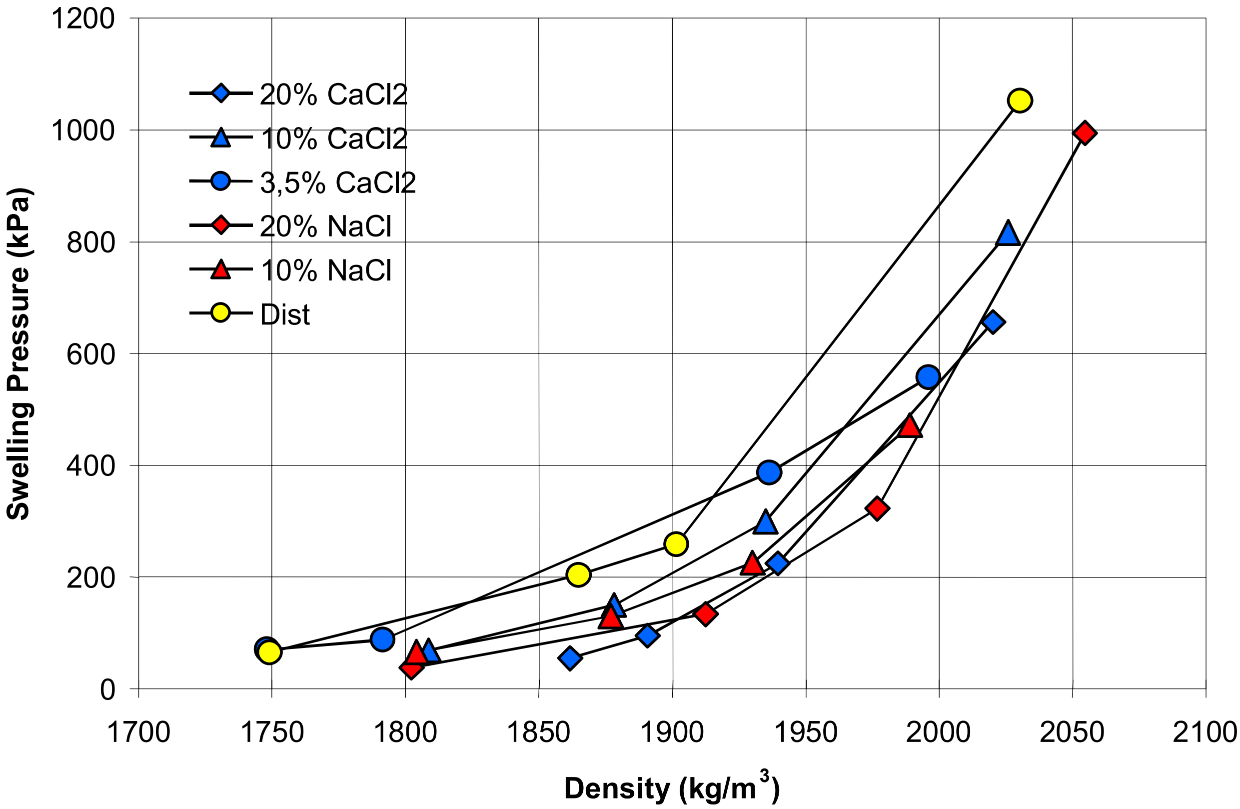


Figure 2-3. *Swelling pressure tests [2].*

For groundwater with a chemical composition corresponding to the oceans, i.e. with sodium as major cation, it is estimated that the density at water saturation should be at least 1950 kg/m^3, which corresponds to a dry density of 1510 kg/m^3.

3 EARLIER EXPERIENCE FROM APPLICATION AND COMPACTION TEST

3.1 On-ground test near Lund

A pilot compaction test of Friedland clay was performed and reported a few years ago, the material being very fine-grained (Figure 3-1) and having about 6 % water ratio [3]. This test was made by filling the air-dry powder within a steel frame anchored to ground and compacting the clay material with a 400 kg vibrating plate (Figure 3-2).

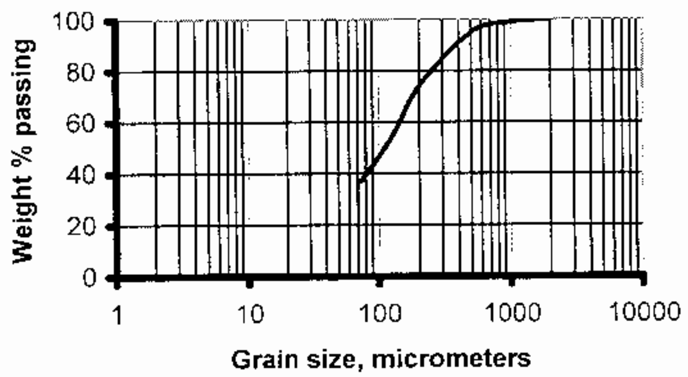


__Figure 3-1.__ Grain (granular) size distribution of Friedland clay in an earlier compaction test [3].

__Figure 3-2.__ Volumeter testing of the density of Friedland clay in earlier compaction test in a 1.5x1.5 m^2 steel frame using a 400 kg vibrating plate [3].

3.2 Results

The compaction lasted for 30 seconds after which the compression and density were measured. The initially 30 cm thick clay layer was compacted to a thickness of about 20 cm, yielding an average dry density of 1295 kg/m^3, which corresponds to a bulk density of 1815 kg/m^3 at complete water saturation. A second 10 cm thick layer was applied on top of the densified material and compacted in the same fashion. The dry density of the lower half of the resulting 26 cm layer was found to be 1630 kg/m^3, which corresponds to 2030 kg/m^3 after saturation (Figure 3-3). The average dry density of the entire 26 cm layer was 1450 kg/m^3, yielding a density of 1915 kg/m^3 after saturation. This test showed that the material was too dry and too fine-grained to be effectively compacted to a dry density on the same order that one can obtain at Proctor compaction in the laboratory, i.e. at least 1700 kg/m^3.

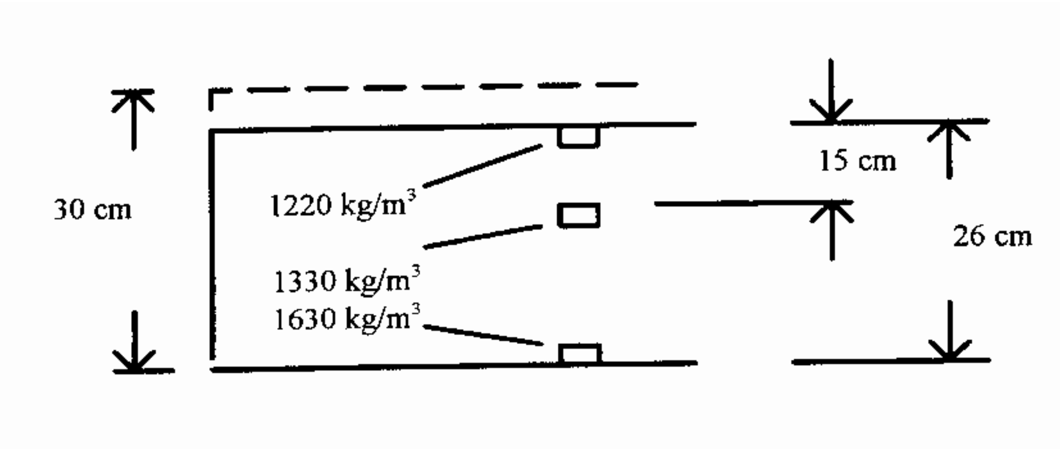


Figure 3-3. *Density distribution in the compaction test in the steel frame [3].*

4 APPLICATION AND COMPACTION TEST AT ÄSPÖ

4.1 Application

The application of the presently investigated material was made on a 35^o slope of earlier effectively compacted backfill consisting of a mixture of 30 % bentonite and 70 % crushed TBM muck. The Friedland clay material was applied by emptying the big bags close to the slope surface for minimising dusting and the material was then moved uphill by use of the blade of a tractor (”pusher”). A pilot test was made at the lower end of the slope using 30 s compaction time and more material was then applied and compacted to form a complete first layer, which had a thickness of about 20 cm after compaction and which was tested with respect to the density. A second layer with 30 cm thickness was then applied and compacted with subsequent determination of the density, after which a second compaction and measurement campaign was made. The rather long time of compaction in the pilot test was possible by applying textile mats on the surface for reducing dusting.

4.2 Compaction

The equipment for compacting backfills that has been worked out in conjunction with preceding backfilling tests and which was used also in the present experiment, consists of a tractor-carried rotary tilting unit to which a vibrating plate is attached (Figure 4-1). The force by which the vibrator is pressed against the soil is not known but sufficient to compact moist bentonite/ballast (30/70) material to an average dry density of about 1700 kg/m^3. In the present test the vibrations caused strong dusting and the time for compaction at each position had to be only 3 seconds.

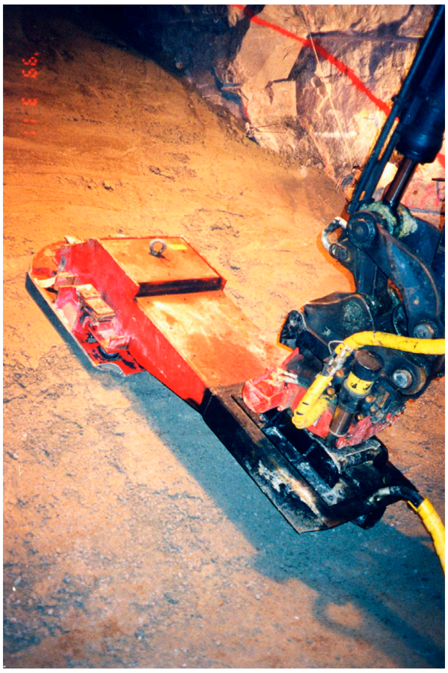


Figure 4-1. *Equipment used for compaction.*

4.3 Results

4.3.1 General

The material did not form a stable slope with higher angle than about 25^{o} and could not be moved up to come in good and stable contact with the roof of the drift. The vibrating plate tended to sink in the mass and this phenomenon together with the dusting clearly demonstrated that the material had no cohesion because the water ratio was too low.

4.3.2 Density

The density was determined by use of nuclear technique for which a gamma ray absorption (^{137}Cs) meter of type Campel Pacific MC-3 Portaprobe was utilised. It was calibrated before and after the tests and is concluded to give density values with an accuracy of +/- 50 kg/m^3. A rod was hammered down to form a hole for the measuring device and readings were taken at 5, 10 and 20 cm depth in 8-10 positions (cf. Figure 4-2) except in the preceding pilot test where only 3 positions were examined. The second layer was compacted in two sequences and the density determined in 10 positions (Figures 4-3 and 4-4).

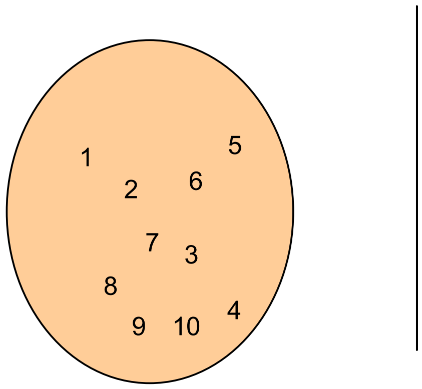


Figure 4-2. *Positions where the density was recorded. The view is perpendicular to the slope surface. First layer, after completion.*

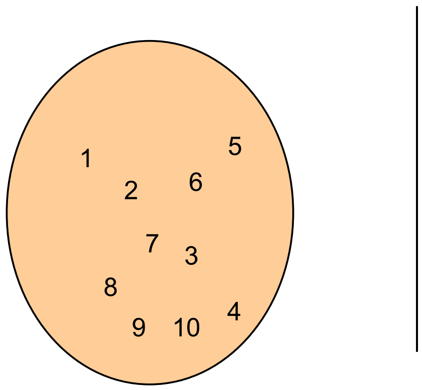


Figure 4-3. *Positions where the density was recorded. The view is perpendicular to the slope surface. Second layer, after first compaction sequence.*

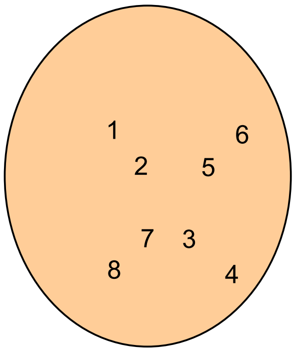


Figure 4-4. *Positions where the density was recorded. The view is perpendicular to the slope surface. Second layer, after second compaction sequence.*

The results are presented here as statistical data representing median values, quartiles and (lower) tenth percentile values except for the pilot test. Naturally, the recordings are too few to allow for an accurate analysis but the purpose here is to make the variation in density obvious. The complete data sheets are collected in appendix form in the report.

The data given for each depth represent the average density for the material located between the recording level, i.e. the surface and the respective depth value.

First layer, partially completed (pilot test)

Depth, cm	Recorded value, kg/m^3	Remarks
5	1490	Water ratio 7.6 %
10	1470	Water ratio 7.6 %
20	1490	Water ratio 7.6 %

First layer, after completion

Depth, cm	Median value, kg/m^3	Upper quartile, kg/m^3	Lower quartile, kg/m^3	Lower tenth per-centile, kg/m^3	Remarks
5	1420	1440	1380	1320	Water ratio7.1-7.6 % (one value 9.6 %)
10	1390	1400	1360	1310	Water ratio7.1-7.6
20	1440	1450	1430	1420	Water ratio7.1-7.6

Second layer, after first compaction sequence

Depth, cm	Median value, kg/m^3	Upper quartile, kg/m^3	Lower quartile, kg/m^3	Lower tenths percentile, kg/m^3	Remarks
5	1380	1400	1340	1300	Water ratio 5.1-7.1 %
10	1350	1380	1320	1300	Water ratio 5.1-7.1 %
20	1460	1490	1440	1430	Water ratio 5.1-7.1 %

Second layer, after second compaction sequence

Depth, cm	Median value, kg/m^3	Upper quartile, kg/m^3	Lower quartile, kg/m^3	Lower tenths percentile, kg/m^3	Remarks
-	-	-	-	-	-
10	1390	1420	1360	1330	Water ratio 6.6 %
20	1450	1470	1410	1380	Water ratio 6.6 %

4.4 Evaluation

4.4.1 General

- The density increased with increasing depth in both layers.
- The first layer was somewhat denser than the second one because it rested on a stiffer base, which caused less loss in compaction energy.
- The densities obtained in the present experiment were on the same order of magnitude as in the earlier field test. This indicates that the different grain size distributions did not affect the density significantly.
- Friedland clay in granulated form with a water ratio of less than about 7 % behaves like frictional materials with low specific gravity as demonstrated by the displacement caused by the compaction tool and by the low inclination angle of stable slopes.

4.4.2 Detailed observations

The following conclusions can be drawn from the experiments:

1. The evaluated average dry density expressed as the median value ranged from 1390 to 1460 kg/m^3, the highest figures representing the average density above 20 cm depth (1440-1490 kg/m^3) for which depth interval the lower quartile values varied between 1410 and 1440 kg/m^3. This means that about 75 % of the compacted material in this depth interval will have a density at water saturation of at least 1900 kg/m^3, while 25 % will have an average density at saturation of around 1880 kg/m^3. Less than 10 % will have an average density of 1870 kg/m^3. Furthermore, 25 % of the total mass above 20 cm depth will have an average density at water saturation of 1915 to 1940 kg/m^3.

2. Above 10 cm depth the average dry density in terms of the median value varied from 1350 to 1470 kg/m^3, i.e. somewhat lower than for the depth interval 0-20 cm, and for the interval 0-5 cm depth the median value was 1380 to 1420 kg/m^3 except in the more effectively compacted material in the pilot test where it was as high 1490 kg/m^3. The successive application and compaction of a series of layers will increase the density in the already applied material and it is expected on the basis of general experience that the shallowest material in each layer will be densified. For a series of layers of Friedland clay

of the investigated type one would expect the final dry density to be in the range of 1425 to 1475 kg/m^3.

3. Applying the criterion respecting the allowable minimum swelling pressure one finds that the requirement, i.e. a minimum pressure of 100 kPa, is fulfilled by Friedland clay with the densities achieved in the Äspö compaction experiments, provided that the groundwater salt content does not exceed that of the oceans (Figure 2-3).

4. As to the hydraulic conductivity it is concluded that the expected net dry density 1425-1475 kg/m^3, corresponding to 1900 to 1930 kg/m^3 at water saturation, will yield a higher conductivity than the assumed maximum allowed value E-10 m/s, i.e. 2E-10 to 3E-10 m/s, if the groundwater salt content equals that of the oceans (cf. Figure 2-2). The actual bulk conductivity may be higher than this because of the scale-dependent variation in homogeneity of the large backfill mass but this effect is believed to be compensated by the much lower hydraulic gradient in the repository than in the laboratory tests.

5 COMPLEMENTARY TEST SERIES

5.1 Test program

The test program comprised laboratory compaction at Intergrund AB, Lomma, Sweden, and field testing at Äspö.

5.2 Laboratory compaction

Material sent from the manufacturer DURTEC GmbH with a grain (granule) size distribution of a) 2-8 mm, 25 %, b) 1-2 mm, 25 %, and c) <1mm, 50 % and a water ratio of 14.4 % was compacted using ordinary modified laboratory compaction technique. The dry density was found to be 1853 kg/m3, i.e. well above the required value.

5.3 Field test

5.3.1 Grain size, water ratio

The grain size was not checked but it was noticed that the material was coarser than in the first field test and that the wettest material contained rather big chunks of coherent clay. The water ratio of material picked from four of the 16 delivered big-bags was determined and found to be 12.9 % as an average, the individual mean values being 26.6 % (still compactable material), 7.8 %, 23.6 %, 12.7 % and 14.8 %. Additional samples taken from the compacted clay showed much less variations, i.e. between 12.6 and 13.2 % (cf. Table 5-1).

5.3.2 Test conditions

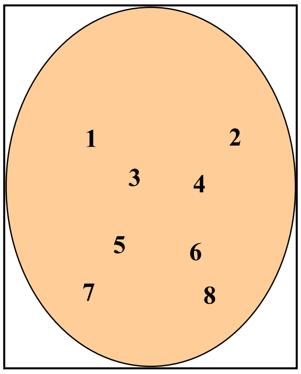
The same site was used as in the preceding main test. The slope on which the material was applied and compacted was prepared by removing the layer of rather soft clay material that covered very dense underlying backfill material of mixed bentonite and crushed TBM muck. The same equipment and procedures were used for application, compaction and density measurement as in the preceding test.

5.3.3 Test results

Field measurement in 8 positions gave the results summarised in Table 5-1.

Table 5-1. Densities, levels of measurement, and water ratio of the second test series. Locations are shown in the map below. All original data are given in the appendix of the second test series.

ID number	Dry density	Depth	Water ratio (w)
	kg/m^3	(cm)	(%)
1	1230	10	13,0%
2	1220	10	13,2%
3	1220	10	12,8%
4	1250	10	12,6%
5	1320	15	12,9%
6	1240	10	12,9%
7	1390	17,5	13,2%
8	1380	17,5	12,5%



5.3.4 Comments on test results and observations

It is obvious from Table 5-1 that the density was lower than in the preceding main test series. This may be explained by the toughness of the wetter material in the second test series causing better coherence and ductile aggregates that needed more compaction energy to break and move into dense layering. This is in contrast with the dryer material in the preceding test, in which crushing and internal movement of the grains required less energy. It is hence concluded that the compaction energy provided by the field equipment was far too low to yield a sufficiently high density.

Other major observations were:

- Insignificant dusting took place in the second test series, indicating that a water ratio of around 12 % is sufficient for avoiding this problem.

- Despite the relatively large variation in water ratio the small range of the density of compacted material shows that variations in water ratio is not a serious problem.

- A water ratio of more than 20 % does not make effective compaction impossible but it is believed that such high water ratio require very high compaction energies. A value in the interval 15-20 % may be at optimum.
- The material could not be pushed up to come in stable contact with the tunnel roof because of insufficient coherence.

6 CONCLUSIONS

The study shows that Friedland clay in the too dry form in which it was delivered to the test site at Äspö for the first, main test series could not be applied and compacted without unacceptable dusting. Furthermore, the compaction gave densities that were lower than expected although the obtained values roughly corresponded to the minimum required density, from the viewpoint of hydraulic conductivity and expandability. However, the variation was rather significant and the quartile and percentiles density values indicate that a significant fraction of the compacted material had an unacceptably low density.

The conclusion from the first test was that the water ratio was too low to avoid significant dusting and to make it possible to bring the material up in contact with the tunnel roof. It was believed that the water ratio range 12-15 % that had been required from the manufacturer should have eliminated dusting and given dry densities higher than 1500 kg/m^3. This was confirmed in a laboratory compaction test and it was therefore recommended that the manufacturer should prepare new Friedland clay material with the same grain size distribution as the material investigated in the laboratory test and with a water ratio in the interval 12-15 % for a complementary field test.

The complementary study was made with new material that was found to have an acceptable water ratio although the moisture was not homogeneously distributed. The test showed that dusting was eliminated but that the density was even lower than in the first test series. This may be due to the toughness of the wetter material but it may also be related to the small thickness of the applied layers. The impression is that the applied compaction method was not suitable and that other *in situ* techniques, like the use of rammers, could be more favourable and should be considered. Available experience should be summarised in the first place, and field tests should begin on a small scale. The technique of precompaction of blocks, which are brought to place in the tunnel should also be evaluated.

7 REFERENCES

1. **Pusch R, 1994**. Waste Disposal in Rock, Developments in Geotechnical Engineering, 76. Elsevier Publ. Co. ISBN:0-444-89449-7.

2. **Pusch R, 2001**. Experimental study of the effect of high porewater salinity on the physical properties of a natural smectitic clay. SKB Technical Report TR-01-07.

3. **Pusch R, 1998**. Backfilling with mixtures of bentonite/ballast materials or natural smectitic clay? SKB Technical Report TR-98-16.

4. **Gunnarsson D, Johannesson L-E, Sanden T, Börgesson L**, 1996. Field test of tunnel backfilling. SKB Progress Report HRL-96-28.

APPENDIX – RAW DATA (Clay Technology AB)

FIRST TEST SERIES, APRIL 2001

First Friedland clay test, Layer 1

The density was measured before the compaction took place

ID	Bulk density kg/m^3
1	1250
2	1320
3	1180

A seam of Friedland clay (approx 5000 kg) was placed at the foot of the inclined layer, and compacted by the vibrating plate.

After having compacted the clay during a time comparable to three passes with the plate, the density was measured at three places (IDs) at a depth of 20 cm.
The water content was measured later giving an average value of 7.6%.

ID	Bulk density kg/m^3	w %	Dry density kg/m^3
1	1640	7.6	1510
2	1510	7.6	1390
3	1530	7.6	1420

After these tests a filter mat was used in order to decrease the dust release

In order to test if it was possible to increase the density the material was compacted for one minute and the density was measured at three different depths

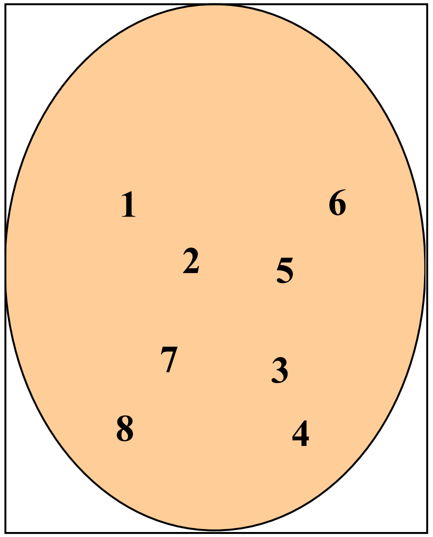
Depth cm	Bulk density kg/m^3	w %	Dry density kg/m^3
20	1620	7.6	1490
10	1590	7.6	1470
5	1610	7.6	1490

Friedland clay Layer 1

Coments:
It was not possible to make the clay stay in contact with the roof. No measurements with the penertrometer has thus been made.
The clay surface was compacted about three seconds per compaction sequence.

	Bulk density				Dry density		
ID	0-5 cm depth	0-10 cm depth	0-20 cm depth	Water ratio	0-5 cm depth	0-10 cm depth	0-20 cm depth
	(kg/m^3)	(kg/m^3)	(kg/m^3)	%	(kg/m^3)	(kg/m^3)	(kg/m^3)
1	1570	1510	1570	7.6	1450	1400	1450
2	1540	1520	1570	7.1	1430	1410	1460
3	1550	1490	1600	7.5	1430	1370	1480
4	1460	1400	1530	7.4	1350	1300	1420
5	1550	1520	1570	7.5	1430	1410	1460
6	1530	1510	1550	7.4	1420	1400	1430
7	1400	1440	1560	7.1	1300	1330	1450
8	1530	1530	1590	9.6	1380	1390	1440
Mean	1510	1490	1570	7.6	1400	1380	1450
Median	1540	1510	1570	7.4	1420	1390	1450

			Container mass	Container mass	Water ratio
ID	ID container	Container mass(g)	+ wet mass (g)	+ dry mass (g)	%
1	19	16.38	1092.48	1016.47	7.6
2	1,I	6.3	478.83	447.54	7.1
3	9,I	6.17	521.84	485.94	7.5
4	1	16.44	1021.32	951.87	7.4
5	13	16.16	869.6	810.38	7.5
6	8,I	6.39	508.15	473.43	7.4
7	7,I	6.34	649.57	606.78	7.1
8	5	15.99	737.79	674.7	9.6
Mean					7.6

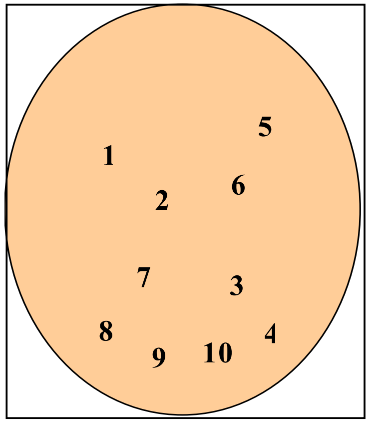


Friedland clay Layer 2, first compaction sequence

Coments:
It was not possible to make the clay stay in contact with the roof. No measurements with the penertrometer has thus been made.
The clay surface was compacted about three seconds per compaction sequence.

	Bulk Density				Dry density		
ID	0-5 cm depth	0-10 cm depth	0-20 cm depth	Water ratio	0-5 cm depth	0-10 cm depth	0-20 cm depth
	(kg/m^3)	(kg/m^3)	(kg/m^3)	%	(kg/m^3)	(kg/m^3)	(kg/m^3)
1	1380	1400	1600	7.1	1290	1300	1490
2	1550	1520	1560	6.8	1440	1420	1450
3	1450	1410	1580	5.1	1380	1340	1500
4	1420	1410	1540	7.1	1320	1310	1430
5	1490	1450	1550	7.0	1390	1340	1440
6	1520	1490	1590	6.9	1420	1390	1480
7	1470	1470	1620	6.6	1370	1370	1510
8	1410	1420	1580	6.6	1320	1330	1480
9	1480	1440	1580	6.6	1380	1340	1480
10	1490	1470	1540	6.6	1390	1370	1440
Mean	1470	1450	1570	6.6	1370	1350	1470
Median	1470	1440	1580	6.7	1380	1340	1480

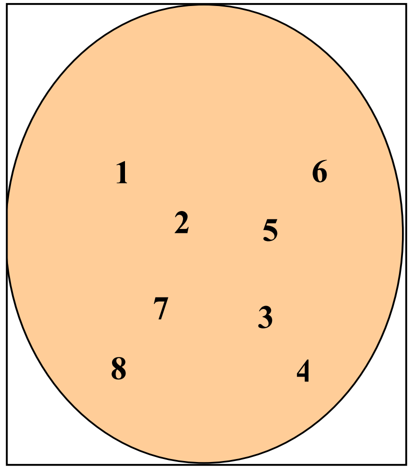
ID	ID container	container mass(g)	container mass	container mass	Water ratio
			+ wet mass (g)	+ dry mass (g)	%
1	9I	6.26	410.43	383.78	7.1
2	5I	6.32	380.1	356.29	6.8
3	7I	6.36	529.95	504.77	5.1
4	8I	6.41	349.58	326.86	7.1
5	5	16.2	773.21	723.91	7.0
6	4	16.39	951.49	891.52	6.9
8	1I	6.31	473.67	444.8	6.6
Mean					6.6



Friedland clay Layer 2, second compaction sequence

Coments:
Layer two was compacted with a second compaction sequence.
No samples for determining the water ratio were taken. An average water ratio from the samples from the first compaction sequence was used for calculating the dry density.

	Bulk Density			Dry density	
ID	0-10 cm depth	0-20 cm depth	w	0-10 cm depth	0-20 cm depth
	(kg/m^3)	(kg/m^3)	%	(kg/m^3)	(kg/m^3)
1	1570	1550	6.6	1470	1450
2	1510	1580	6.6	1410	1470
3	1470	1400	6.6	1370	1310
4	1480	1520	6.6	1380	1420
5	1470	1490	6.6	1370	1390
6	1510	1590	6.6	1410	1490
7	1470	1590	6.6	1370	1490
8	1460	1580	6.6	1370	1470
Mean	1490	1540	6.6	1390	1440



APPENDIX – RAW DATA (Clay Technology AB)

SECOND TEST SERIES, JULY 2001

ID	Dry density	Measurement depth	Water ratio (w)
	(kg/m^3)	(cm)	(%)
1	1230	10	13,0
2	1220	10	13,2
3	1220	10	12,8
4	1250	10	12,6
5	1320	15	12,9
6	1240	10	12,9
7	1390	17,5	13,2
8	1380	17,5	12,5