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Backfilling with mixtures of bentonite/ballast material or natural smectitic clay?

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October 1998

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ABSTRACT

Comparison of the performance of backfills of mixed MX-80 and crushed rock ballast, and a natural smectitic clay, represented by the German Friedland clay, shows that the latter performs better than mixtures with up to 30 % MX-80.

Considering cost, Friedland clay prepared to yield air-dry powder grains is cheaper than mixtures of 30 % MX-80 and crushed ballast.

Both technically and economically it appears that the Friedland clay is a competitive alternative to mixtures of 30 % MX-80 and crushed ballast. However, it remains to be demonstrated on a full scale that Friedland clay ground to a suitable grain size distribution can be acceptably compacted on site.

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SAMMANFATTNING

Rapporten beskriver en jämförelse mellan egenskaperna hos fyllningar bestående av blandningar av MX-80 bentonit/ballast där ballasten består av krossat TBM-material, samt naturligt lermaterial representerat av Friedlandlera från Tyskland.

Mikrostrukturella modeller för blandningar som förutsätter att MX-80-kornen bevaras gäller inte eftersom de bryts ned. Lerkomponenten fyller största delen av utrymmet mellan ballastkornen t.o.m. vid så låg halt av MX-80 som 10 % men homogeniteten och densiteten varierar starkt. Blandningar med 30 % MX-80 räcker för att åstadkomma erforderligt stöd för berget och motstånd mot expansion av bufferten i deponeringshålen och för att göra fyllningen mindre permeabel än omgivande berg. I alla dessa avseenden är emellertid den naturliga leran överlägsen.

Ballast av krossat TBM-berg innehåller mycket finkornig debris som häftar vid kornen och skapar strömningsvägar som ökar genomsläppligheten.

Både tekniskt och ekonomiskt utgör den undersökta Friedlandleran ett konkurrenskraftigt alternativ till blandningar med 30 % MX-80. Det återstår emellertid att visa att packningsbarheten hos lämpligt granulerat material är acceptabel.

SUMMARY

The report presents the outcome of a comparison of the performance of backfills of mixed MX-80 and crushed rock ballast, and a natural smectitic clay, represented by the German Friedland clay.

Microstructural models for mixed backfills implying that the MX-80 grains are preserved do not work since the grains break down. The clay component of bentonite/ballast mixtures fills the large majority of the space between the ballast grains even at 10 % MX-80 content but the homogeneity and density vary strongly. Mixtures with 30 % MX-80 compacted to an achievable density is just about sufficient to provide the required rock support and resistance to upward expansion of buffer in the deposition holes and to make the backfill tighter than the surrounding rock. In all these respects the investigated natural clay is superior.

Grains of crushed TBM muck as ballast have very fine rock debris attached to them which forms more or less continuous coatings that provide flow paths and hence raises the bulk hydraulic conductivity.

Both technically and economically it appears that the Friedland clay is a competitive alternative to mixtures of 30 % MX-80 and crushed ballast. However, it remains to be demonstrated on a full scale that Friedland clay ground to a suitable grain size distribution can be acceptably compacted on site.

1 INTRODUCTION

The KBS3 concept is based on the principle that engineered barriers consisting of canister, clay buffer and tunnel backfill provide the required isolation of the highly radioactive waste, while the nearfield rock offers mechanical confinement and the farfield rock long migration paths for escaping radionuclides. The present report concerns the tunnel backfill, the primary function of which is to moderate upward expansion of the buffer clay in the deposition holes and to provide support to the tunnel roof and walls for maintaining the stability of the rock. If the compressibility of the backfill is high, the clay buffer will expand upwards and become softer and more permeable in its upper part. The nearfield rock will also be affected by the upward movement because the rock close to the floor will be lifted, which may make natural flatlying fractures expand and propagate. This increases the axial hydraulic conductivity of the tunnel floor. These mechanisms are illustrated in Figure 1, [1]. An additional function of the backfill is to seal off the tunnels so that they will not serve as major hydraulic conductors.

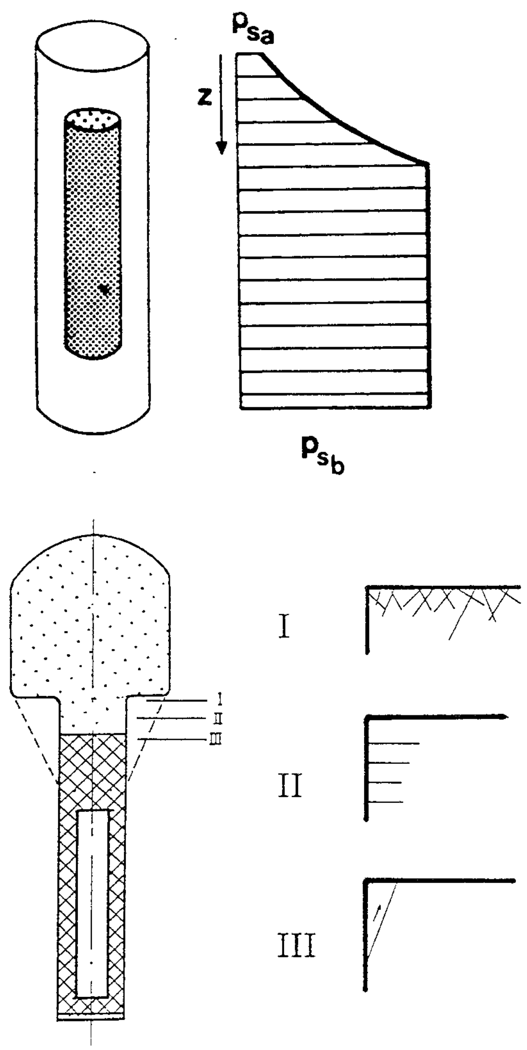


Figure 1. *Schematic illustration of cases where upward expansion of the buffer may affect the rock. Uppper: Softening of top part of the buffer. Lower: Influence on the stability of the rock (I=blast-disturbance, II="discing", III=wedge).*

2 CRITERIA

2.1 General

2.1.1 Presently applied conditions

The backfill in tunnels and shafts of a KBS3 repository should fulfil the following criteria:

1) It must cause only limited upward expansion of the buffer.

2) It must support the roof and walls of the tunnels so that rock fall and major changes in the hydraulic performance of the nearfield rock will not take place.

3) It must not serve as a major hydraulic conductor in the repository.

2.1.2 Quantification

The first criterion implies that the backfill must be dense and have a low compressibility. Upward expansion of the buffer takes place until equilibrium is established between the swelling pressure of the buffer and the effective contact pressure mobilized in the overlying backfill. A preliminary measure of the maximum allowable displacement of the interface between the buffer and backfill is 20 cm.

The second criterion means that the swelling pressure of the backfill should be 100 kPa for preventing rock fall (blocks with 3 m height) from the roof and for establishing a tight backfill/rock contact.

The third criterion, i.e. that the backfill should not be an important hydraulic conductor, means that it should be less permeable than the surrounding rock. This condition may not be applied in due time since it is still not known whether a combination of permeable backfill in the form of crushed rock and strategically located, very tight plugs provide the same limited groundwater flow as very tight clayey backfills. The plug-based concept is not considered here.

Additional parameters of less importance are practicality in handling, transport and application, and cost.

2.2 Preparation

The raw material must be available in very large quantities, at least 1 000 000 tons, with very small variations in composition and guaranteed accessibility through purchase or options. Furthermore, it must be possible to obtain or prepare the backfill material so that the mineral composition and granulometry vary within very small intervals. This means that both the individual components of clay backfill mixtures and the mixtures must be currently checked. If natural material with suitable composition is chosen as backfill it must fulfil specified conditions as to acceptable variations in composition.

2.3 Application

The backfill material must be effectively compactable by use of ordinary techniques available to contractors. The presently investigated techniques using blades for moving the backfill material to form inclined layers in the tunnel and vibrating plates for lateral compaction should be applicable [2,3].

2.4 Cost

At this stage economical aspects are not of major importance in finding and developing technique for safe disposal of radioactive waste. However, if there are two or more equally scored backfill materials, cost may be a decisive parameter.

3 CANDIDATE MATERIALS

3.1 Principle of selection

Backfill of KBS3 type, i.e. mixtures of MX-80 bentonite and non-clay ballast, is a given candidate. A competing candidate material group is represented by natural smectitic clay and the Friedland clay from the Neubrandenburg area in Mecklenburg-Vorpommern, Germany, is taken as a representative of this type of material. Major reasons for this choice are the large amount of accessible material and extensive use of Friedland clay for environmental protection and also the fact that the clay is very well characterized and has been used used as raw material in advanced tile manufacturing on an industrial scale for decades.

3.2 KBS3 tunnel backfill

3.2.1 General

An important principle applied in preparing fills for compaction is that the grain size distribution should be of Fuller type, which means that smaller grains fit into the voids of larger grains and that the grain size curve is parabolic in diagrams with linear "weight % passing" and logarithmic grain size. Long experience has led to the general recommendation that water should be added in the preparation of the fill to yield maximum dry density (optimum water content). However, it is also known that mixing of air-dry components yields a dry density that may be even higher than the density at optimum water content and this principle was used for the bottom bed of the big SFR concrete silo in the Forsmark repository. The major advantage of not using water is that one source of error in obtaining a large quantity of homogeneous fill is eliminated. Practical and economic advantages are the shorter time and lower cost of preparing the backfill. Since dry mixing was successfully applied when preparing the 1.5 m thick bottom bed for the SFR silo this method is considered in the report.

According to the basic concept, the KBS3 tunnel backfill is a mixture of 10-20 % MX-80 bentonite with about 10 % water content, and ballast material with Fuller-type gradation and very low water content [3]. Backfill with 20 % bentonite is proposed for compensating the lower density near the roof. The Stripa BMT project conducted about 15 years ago showed that the basic concept is feasible and that the backfill performs acceptably when the groundwater is poor in electrolytes.

Geochemical investigations in more recent time have shown that the groundwater at 500 m depth and deeper down may be rich in electrolytes. Thus, the Äspö groundwater is strongly brackish or even more electrolytic with Ca as major cation. Since this implies less expandability and higher hydraulic conductivity of the clay component, present considerations indicate that backfills with higher bentonite content may be required. In fact, backfills with 30 % MX-80 mixed with ballast are presently in focus.

The ballast material component of backfills in KBS3 tunnels was originally defined as a mixture of three sand/silt fractions of glacial origin. In recent time, ground TBM muck or blasted rock has turned out to be Fuller-graded, and is now considered as major ballast candidate.

The report contains important physical data, i.e. swelling pressure and hydraulic conductivity of a number of investigated KBS3-type backfills with bentonite clay and glacial and crushed rock as ballast components. This is made for demonstrating that only backfill with 30 % MX-80 clay fulfils the criteria. Only this latter backfill type with crushed rock as ballast component is used for comparison with backfill prepared from Friedland clay.

3.2.2 Gradation

MX-80 has a content of clay-sized particles (<2 μm) of 80-90 %, while ballast of glacial origin contains few particles of this sort. Crushed rock contains a few percent of clay/silt-sized particles. The grain size distribution of MX-80 and crushed rock is shown in Figure 2.

The granulometry of the 10/90 and 30/70 bentonite/ballast mixtures of air-dry conditions are shown in Figures 3 and 4. The diagrams also show the grain size distribution of the mixtures assuming effectively dispersed MX-80 after hydration.

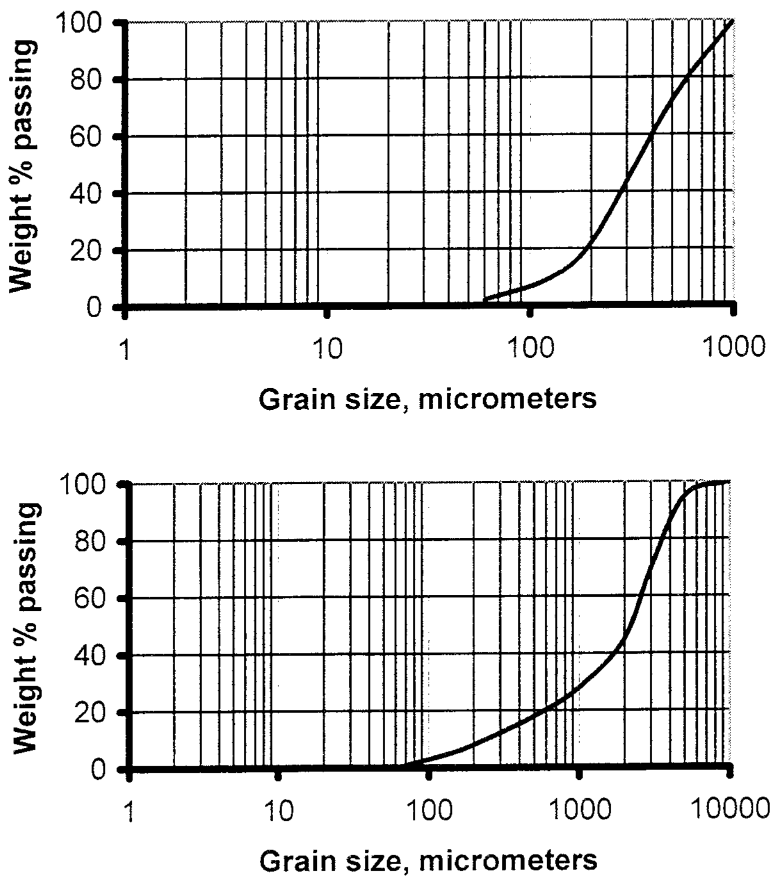


Figure 2. Grain size distributions. Upper: MX-80. Lower: Crushed rock.

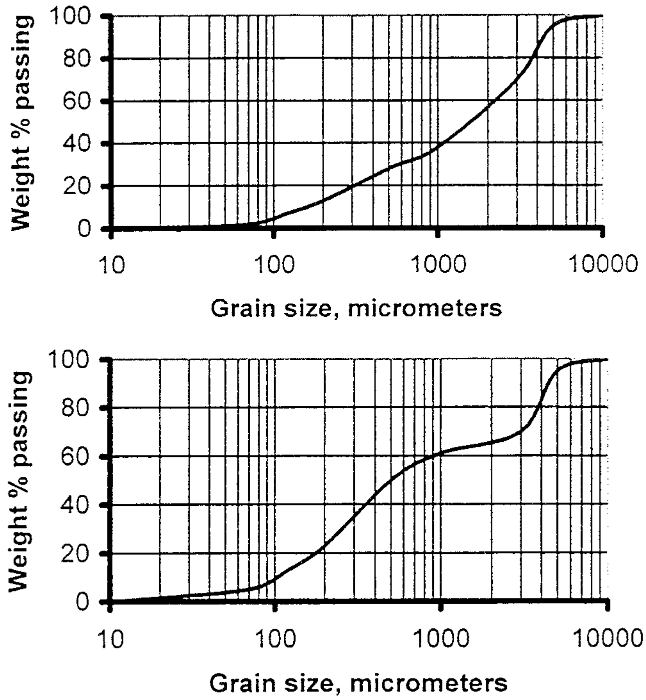


Figure 3. *Grain size distribution of mixture of air-dry MX-80 and crushed rock. Upper: Clay-to-ballast ratio 10/90. Lower: Clay-to-ballast ratio 30/70.*

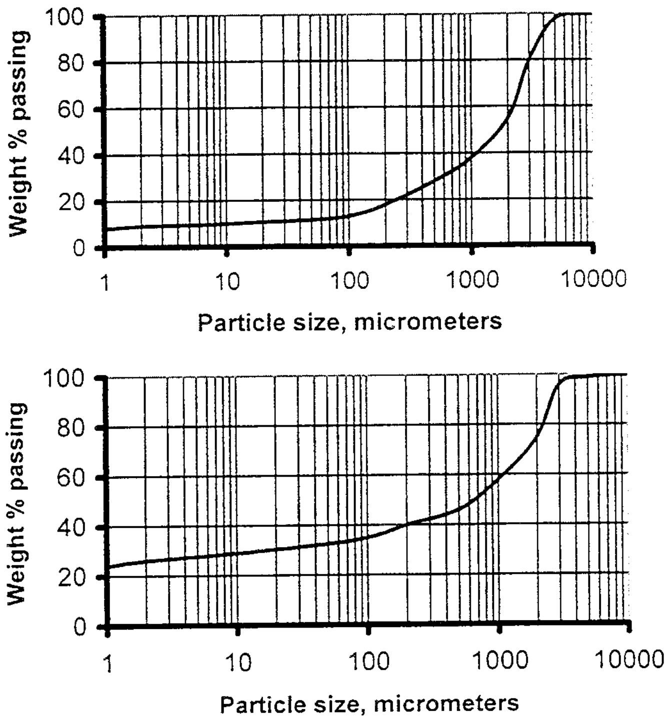


Figure 4. *Grain size distribution of water saturated, homogeneous mixture of MX-80 and crushed rock. Upper: Clay-to-ballast ratio 10/90. Lower: Clay-to-ballast ratio 30/70.*

3.2.3 Mineral composition

MX-80

Bulk MX-80 contains 65-75 % montmorillonite, 10-14 % quartz, 5-9 % feldspars, 2-4 % mica and chlorite, 3-5 % carbonates and chlorite, and 1-3 % heavy minerals [4].

The chemical composition is as follows [4]:

SiO_2 61-65 %, Al_2O_3 22-25 %, Fe_2O_3 1-7 %, MgO 1-2 %, CaO 0-0.6 %, Na_2O 0-1 %, K_2O 0-3 %.

Crushed rock

Granite commonly contains 10-30 % (weight %) quartz, 10-50 % feldspars, 10-20 % heavy minerals and 1-5 % mica. The dominant rock type at Äspö, the Äspö diorite, holds about 10 % quartz, some 15-25 % K-feldspars (orthoclase + microcline) and 5-10 % biotite, while the fine-grained granite holds about 40 % K-feldspar and a few percent biotite. The so-called Ävrö granite holds about 15-20 % quartz, 25-35 % K-feldspars and about 5 % biotite [4]. The content of pyrite is about 1 %.

3.2.4 Stress/strain properties

Compactability

The Stripa BMT project gave comprehensive information on the compactability in the laboratory and in-situ of mixtures of MX-80 and well graded ballast of glacial origin to which a small amount of feldspar-rich filler had been added [5]. Laboratory (Proctor) compaction tests showed that the optimum water content was 14 % yielding a dry density of 1920 kg/m^3 (2200 kg/m^3 at saturation) for 10 % bentonite mixtures, and 1820 kg/m^3 (2150 kg/m^3 at saturation) for 20 % bentonite mixtures. These values were not reached in the field tests, in which a 400 kg Dynapac plate vibrator was used to compact 0.15-0-3 m thick horizontal layers of 10 % bentonite material in 10-15 runs. Here, the average dry density was 1710-1750 kg/m^3, which corresponds to an average density at saturation of 2090 kg/m^3.

Almost "ideally" graded mixtures of 10 % MX-80 or 20 % MX-80 and crushed Romeleåsen (granite) ballast were Proctor-compacted in the laboratory in a pilot study for the current Äspö tests and it was found that the density was very sensitive to even small changes in water content [3]. Thus, for the 10 % bentonite mixture the optimum water content was 10 %, yielding a dry density of 2020 kg/m^3 (2230 kg/m^3 at saturation), the corresponding values being 9 % and 1870 kg/m^3 (2180 kg/m^3 at saturation) for the 20 % bentonite mixture. A water content of 0-2 % of these mixtures gave almost the same densitites at the respective optimum water content but a change by only 2 % units up or down from the optimum water content reduced the dry density by more than 10 %.

Proctor compaction tests of 10 % MX-80 and 90 % crushed TBM muck for the Äspö experiments showed, in contrast to the tests with Romeleåsen ballast material, that the optimum water content was low (7 %) and that slight changes in water content did not make the density deviate much from the maximum value 2160 kg/m^3 (2360 kg/m^3 at saturation), [6]. For 20 % MX-80 mixtures the optimum water content was still about 7 % and the dry density about 2060 kg/m^3 (2300 kg/m^3 at saturation). For 30 % MX-80 mixtures the same dry density, about 1930 kg/m^3 (2215 kg/m^3 at saturation), was obtained irrespective of the water content.

Field compaction of mixtures of 10, 20 and 30 % MX-80 and crushed TBM muck was made at Äspö as part of a comprehensive pilot test series of backfilling [6]. For the 10 % mixture that was slope-compacted by use of a specially designed 700 kg vibrating plate machine the dry density ranged between 1630 and 2150 kg/m^3, the majority of the denser part having the average dry density 2060 kg/m^3 (2300 kg/m^3 at saturation). For the 20 % mixture there was considerable variation in density, i.e. between about 1390 and 2100 kg/m^3 (1875-2325 kg/m^3 at saturation). The average dry density of the denser part of the 20 % MX-80 backfill was about 2000 kg/m^3 (2260 kg/m^3 at saturation). For the 30 % mixture the dry density ranged from 1250 to about 1850 kg/m^3 (1790-2165 kg/m^3 at saturation). The average dry density of the denser part of the 30 % MX-80 backfill was about 1650 kg/m^3 (2040 kg/m^3 at saturation).

Considering both the Stripa and Äspö tests it is concluded that compaction with vibratory plate equipment and applying the backfill in 0.15-0.20 m layers gives considerably lower densities than obtained by laboratory Proctor compaction. The following average densities that can be obtained in the larger part of a compacted backfill using vibrators are concluded to be:

* Dry density=2160 kg/m^3 (2360 kg/m^3 at saturation) of mixtures of 10 % MX-80 and 90 % crushed TBM muck. With well graded glacial silt/sand/gravel ballast the average dry density is 1920 kg/m^3 (2210 kg/m^3 at saturation).

* Dry density=2060 kg/m^3 (2300 kg/m^3 at saturation) of mixtures of 20 % MX-80 and 80 % crushed TBM muck.

* Dry density=1700 kg/m^3 (2070 kg/m^3 at saturation) of mixtures of 30 % MX-80 and 70 % crushed TBM muck.

Compressibility

The compressibility of fully water saturated backfill overlying the buffer clay in the deposition holes is the major parameter that determines how much the buffer in the deposition holes will expand upwards. Tests of MX-80/ballast mixtures have been performed and reported both for the Stripa and Äspö backfills. The compressibility is expressed in terms of the compression modulus number *m*, which is given for a number of laboratory tests in Table 1. SB represents mixtures of sand and bentonite while RB stands for mixtures of crushed rock and bentonite. "Forsmark" represents compression tests on the bottom bed material of the SFR silo, while BMT represents mixtures used for backfilling the Stripa BMT tunnel.

***Table 1.** Compressibility in terms of the modulus number m.[3,7].*

Backfill type	Bentonite content, %	Dry density, kg/m^3	*m*, MPa
SB (Forsmark)	10	2150	200
SB (BMT)	10	1910	199
SB (BMT)	10	1790	167
SB (BMT)	10	1650	105
RB (Simpevarp)	15	1900	160
RB (Simpevarp)	15	1600	60
RB (Simpevarp)	15	1300	20
RB (TBM crush)	30	1830	5

Using *m*-values specified in Table 1 for estimating the compression of the backfill under a buffer swelling pressure of about 5 MPa, one finds that the interface between the buffer clay and a very well compacted backfill with 10 % MX-80 and a dry density of 2150 kg/m^3 (2355 kg/m^3 at saturation) in a 5 m high tunnel will be displaced by about 10 cm. For a backfill with 30 % MX-80 and a dry density of 1830 kg/m^3 (2150 kg/m^3 at saturation) the corresponding displacement would be at least 50 cm. However, the compression will be counteracted by an increased effective pressure in the backfill and already at 30 cm displacement the compression of the backfill in the deposition hole and in the lowest part of the tunnel would have increased the dry density by as much as 300 kg/m^3. This generates an effective pressure of at least 1 MPa that largely balances the pressure exerted by the expanded buffer. For comparison of the performance of backfills with higher clay content a better measure of the ability of the backfill to resist compression is the relationship between swelling pressure and density.

3.2.5 Swelling pressure

The swelling pressure of bentonite/ballast mixtures is known to depend very much on the distribution of the clay in the voids of the ballast and on the density of the clay component and the ballast grain system, as well as on the porewater chemistry. Typical data for saturation with distilled water and brackish and salt water are given in Table 2.

No data have been reported for mixtures of 30 % MX-80 and crushed TBM muck, but assuming that they behave like the SB mixture investigated in the Stripa BMT project, it is expected that the swelling pressure is on the order of 500 kPa when the dry density is 2100 kg/m^3 (2320 kg/m^3 at saturation). Since the expected in-situ density at saturation is (conservatively) only 2070 kg/m^3, the swelling pressure of the backfill when saturated with distilled water will probably not exceed 200 kPa. When saturated with salt, Ca-dominated water the swelling pressure is not expected to exceed 100 kPa at this density, which means that the pressure criterion is still fulfilled.

Table 2. *Swelling pressure p_s of saturated backfill materials [3,4,7]. SB represents mixtures of sand and bentonite while RB stands for mixtures of crushed rock and bentonite.*

Backfill type	Bentonite (MX-80) content	Dry density, kg/m^3	Density at saturation, kg/m^3	p_s, kPa Distilled water	p_s, kPa saline solution
SB (Forsm.)	10	2150	2355	400	-
SB (BMT)	10	2100	2325	170	20
SB (BMT)	10	1750	2110	150	-
SB (BMT)	20	1580	1995	200	-
SB (BMT)	20	1420	1895	100	-
SB (Forsm.)	30	1590	2000	250	-
SB (Forsm.)	30	1750	2110	450	-
SB (Forsm.)	30	1825	2150	600	-
SB (BMT)	30	2100	2325	500	200
SB (Forsm.)	30	2100	2325	650	-
RB (Romele)	10	2180	2375	575	-
RB (Romele)	20	1590	2000	70	-

The relationship between density at saturation with distilled water and swelling pressure for 30 % MX-80 and 70 % ballast is shown in Figure 5, from which one finds that the swelling pressure approaches 0.8 MPa when the density is raised beyond 2400 kg/m^3.

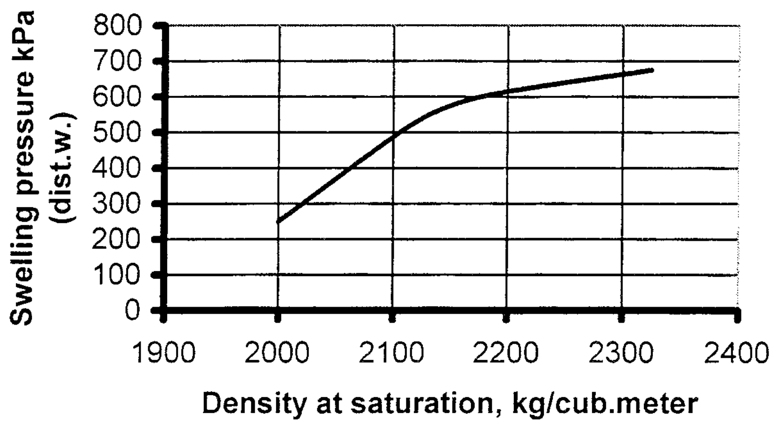


Figure 5. *Relationship between density and swelling pressure for backfill consisting of 30 % MX-80 and crushed TBM muck.*

3.2.5 Hydraulic conductivity

Table 3 is a compilation of published conductivity data. It indicates that mixtures of 10 % MX-80 with a density at saturation that can be obtained in practice in tunnels, i.e. about 2200 kg/m^3, has a hydraulic conductivity that is in the range of 10^{-10} to 10^{-8} m/s when percolated with distilled water. Percolation with strongly brackish or ocean water gives ten times higher values. Mixing of 30 % MX-80 and 70 % ballast to yield the achievable density 2070 kg/m^3, gives an average conductivity of about 10^{-11} m/s at percolation with distilled water and 10^{-10} m/s when percolated with strongly brackish water.

Table 3. *Hydraulic conductivity (K) of bentonite/ballast materials [3,4,9].*

Backfill type	Bentonite (MX-80) content	Dry density, kg/m^3	Density at saturation, kg/m^3	*K*, m/s Distilled water	*K*, m/s Salt water
SB (Forsm.)	10	1900	2200	3.4×10^{-10}	
SB (Forsm.)	10	1980	2250	1.2×10^{-10}	
SB (Forsm.)	10	2140	2350	1.1×10^{-10}	
SB (BMT)	10	1790	2130	10^{-9}	3×10^{-9} (2 % NaCl)
RB (Romele)	10	1870	2180	10^{-8}	
RB (Romele)	10	1970	2240	9×10^{-10}	
RB (Äspö)	10	2000	2260	2×10^{-11}	4×10^{-11} (Äspö)
RB (Romele)	20	1760	2110	10^{-11}	
RB (Romele)	20	1880	2180	10^{-11}	
RB (Äspö)	20	1730	2090	4×10^{-11}	
RB (Äspö)	20	1980	2250	2×10^{-11}	3×10^{-11} (Äspö)
SB (Forsm.)	30	1510	1950	1.1×10^{-11}	10^{-10} (1 % $CaCl_2$)
SB (BMT)	30	1750	2100	10^{-10}	10^{-9} (2 % NaCl)
RB (Äspö)	30	1870	2190	4×10^{-12}	
RB (Äspö)	30	1850	2100		6×10^{-11}

3.3 Friedland clay backfill

3.3.1 General

The natural Friedland clay is industrially processed through drying and grinding by which air-dry granulated powder is obtained for commercial use like the MX-80 bentonite. A suitable grain size distribution should be of Fuller type like for MX-80/ballast mixtures. The grain size curve of the air-dry material should hence be parabolic in diagrams with linear "weight % passing" and logarithmic grain size. The grain size of the presently investigated material was somewhat too small to be ideal for field handling and compaction.

The report contains important physical data, i.e. swelling pressure and hydraulic conductivity of the investigated Friedland clay.

3.2.2 Gradation

Friedland clay in dispersed form has an average content of clay-sized particles (<2 μm) of 57 %. Air-dry clay powder with a number of grain size distributions can be obtained by using different grinding equipments. The air-dry material used in the present investigation had the granulometric composition shown in Figure 6. Figure 7 shows the particle size distribution in dispersed form.

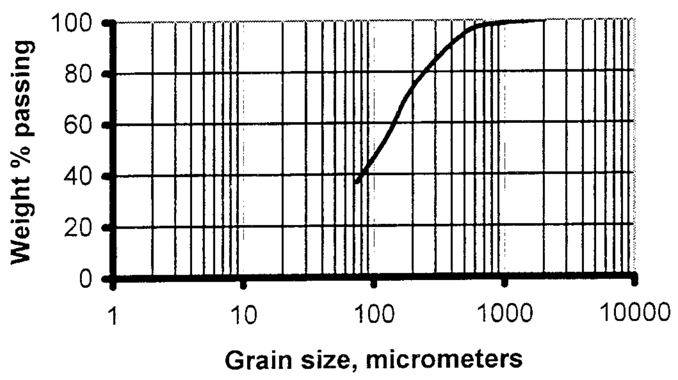


Figure 6. Grain size distribution of the investigated Friedland clay in air-dry form.

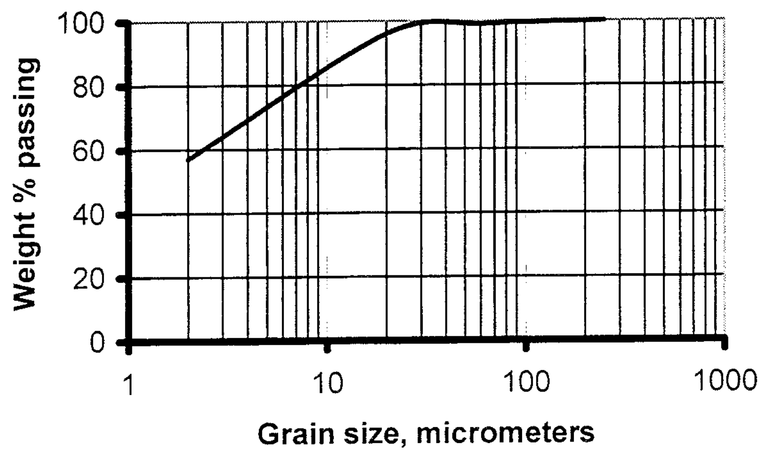


Figure 7. Grain size distribution of water saturated, dispersed Friedland clay.

3.3.3 Mineral composition

Bulk Friedland clay contains as an average 45 % expandable minerals (mica/montmorillonite), 24 % quartz, 5 % feldspars, 13 % mica and 11 % chlorite, and 2 % carbonates) [4].

The average chemical composition is as follows [4]:

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

Na is the dominant adsorbed cation according to the manufacturing company DURTEC, Ihlenfelder Strasse. 153, 17034 Neubrandenburg, Germany.

3.3.4 Stress/strain properties

Compactability

Information on the compactability of air-dry powder has been obtained by performing plate vibrating tests [9]. The field experiment was made to simulate the compaction of tunnel backfill by use of a vibrating plate. A rigid form of steel was welded and anchored to the concrete base so that a 1.5x1.5 m^2 open pit was formed in which the dry powder was applied in 10 and 20 cm layers. They were then compacted by a 400 kg vibrating plate with 0.75x 0.75 m^2 bottom plate for about 30 seconds after which the compression was measured. Finally, samples were dug out for determination of the density. Figures 8 a and b illustrate how the work was performed.

Figure 8 a. *Field test arrangement. Pit construction.*

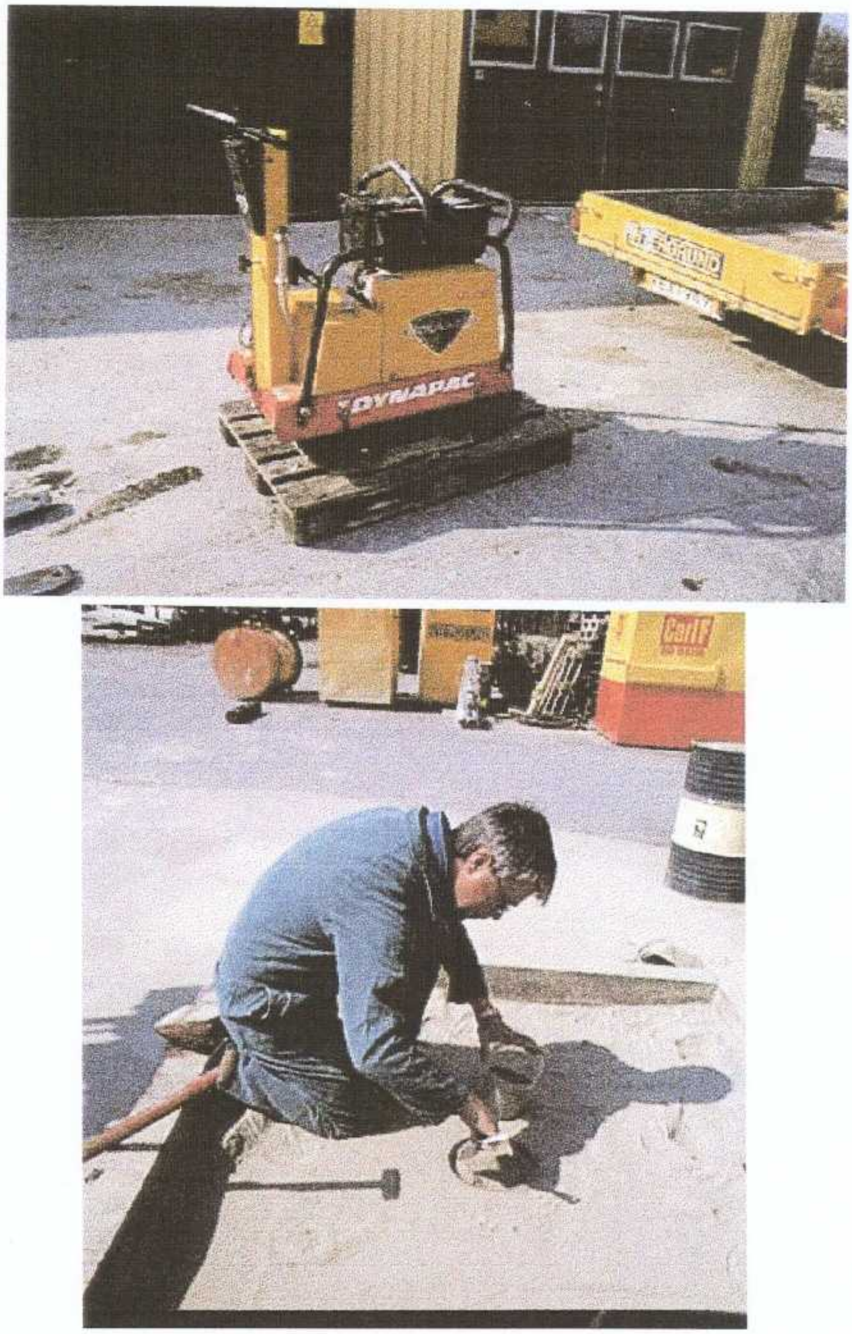


Figure 8 b. *Field test arrangement. Upper: 400 kg vibrating plate. Lower: Volumeter for determination of density (Intergrund AB).*

A 20 cm layer of air-dry, very fine-grained Friedland clay, which has a density of 1010 kg/m^3 in powder form, was compacted to an average dry density of 1295 kg/m^3, corresponding to 1815 kg/m^3 at water saturation. A second 10 cm thick layer was applied on top of the first one and compacted in the same fashion, which gave a dry density of 1220 kg/m^3 (1770 kg/m^3 after saturation). Sampling after the field test gave a dry density of the lower half of the 26 cm thick layer of 1630 kg/m^3, corresponding to 2030 kg/m^3 after saturation. The average dry density of the entire 26 cm bed was 1450 kg/m^3, which corresponds to 1915 kg/m^3 after saturation (Figure 9).

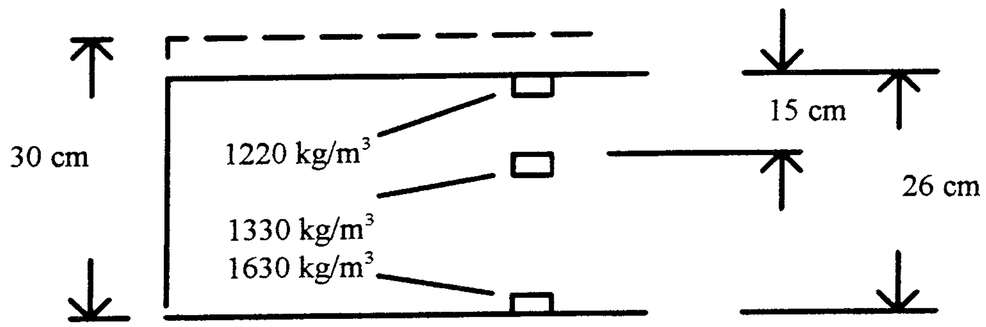


Figure 9. Density distribution in a profile through the center of the bed.

Compressibility

No compression tests for determination of the parameter *m* have been performed. As stated earlier in the text the relationship between density and swelling pressure is a more suitable measure of the displacement of backfill overlying the buffer in the deposition holes. It is believed that the dry density of the backfill will be 1600 kg/m^3 (2000 kg/m^3 at saturation), using somewhat coarser material and compaction by heavier equipment developed for the Äspö field tests. This yields a swelling pressure of at least 600 kPa for 3.5 % $CaCl_2$ as pore liquid as reported below. The pressure increases to about 2 MPa if the compression yields a density of 2100 kg/m^3 (dry density 1750 kg/m^3). This corresponds to a displacement of the buffer/backfill interface of about 0.25 m assuming compression of 3 m backfill.

3.2.5 Swelling pressure

The swelling pressure of Friedland clay as a function of density is illustrated by the diagram in Figure 10 and Table 4. The laboratory technique was the same as in the corresponding investigation of mixtures of MX-80 and ballast material.

The swelling pressure increases moderately and rather linearly when the density at saturation is raised from 1800 to about 1950 kg/m^3 for clay with distilled water or 3.5 % $CaCl_2$ as pore solution. For further increase in density to 2100 kg/ m^3 the swelling pressure increases strongly and rapidly. It should be noted that the strong electrolyte does not appreciably affect the swelling pressure. For the density 2000 kg/ m^3 that is expected to be achieved in the tunnels, the swelling pressure is concluded to be about 1 MPa when the clay is saturated with distilled water and

The diagram demonstrates that the hydraulic conductivity at percolation with distilled water drops from more than 10^{-10} m/s to less than 10^{-12} m/s when the density at saturation is raised from 1600 to 2100 kg/m^3. For 3.5 % $CaCa_2$ solution the conductivity drops from 10^{-9} m/s to about 10^{-12} m/s when the density at saturation is raised from 1750 to 2100 kg/m^3. For the density 2000 kg/ m^3 that is expected to be achieved in the tunnels, the hydraulic conductivity is concluded to be about $5x10^{-12}$ m/s when the clay is saturated with distilled water and about $2x10^{-11}$ m/s when saturated with 3.5 % $CaCl_2$ solution.

The diagram is almost of textbook type, showing a strong decrease in hydraulic conductivity with increasing density, and a consistently higher conductivity of the clay when percolated with salt Ca-rich solution. For densities in the range of 1700-1900 kg/m^3 the influence of the electrolyte content is smaller than for montmorillonite-rich clays because collapse of clay gels in the space between denser particles and aggregates is less extensive in clays with mixed-layer minerals.

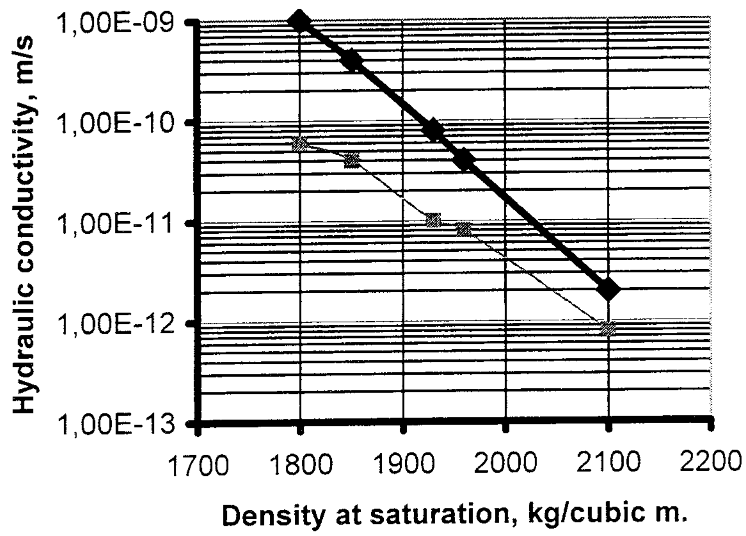


***Figure 11**. Hydraulic conductivity of Friedland clay as a function of the density at saturation. Thin curve represents distilled water, thick curve $CaCl_2$ solution.*

***Table 5**. Hydraulic conductivity (K) of Friedland clay.*

Dry density, kg/m^3	Density at saturation, kg/m^3	*K*, m/s Distilled water	*K*, m/s $CaCl_2$ solution
1750	2100	$8x10^{-13}$	$2x10^{-12}$
1520	1960	$8x10^{-12}$	$4x10^{-11}$
1475	1930	10^{-11}	$8x10^{-11}$
1320	1830	$4x10^{-11}$	$4x10^{-10}$
1190	1750	$6x10^{-11}$	10^{-9}
900	1570	$2x10^{-10}$	-

4 MICROSTRUCTURAL ASPECTS

4.1 Theoretical microstructural modeling using FEM

Finite element technique (FEM) has been applied for modeling the microstructural evolution of bentonite/ballast backfills [9]. It was based on the assumption that the bentonite grains are equal and spherical with 1 mm diameter and that the ballast grains are also spherical but with 2.4 mm diameter. The weight ratio bentonite to ballast was 1 to 10. In 2D the structural arrangement was as shown in Figure 12.

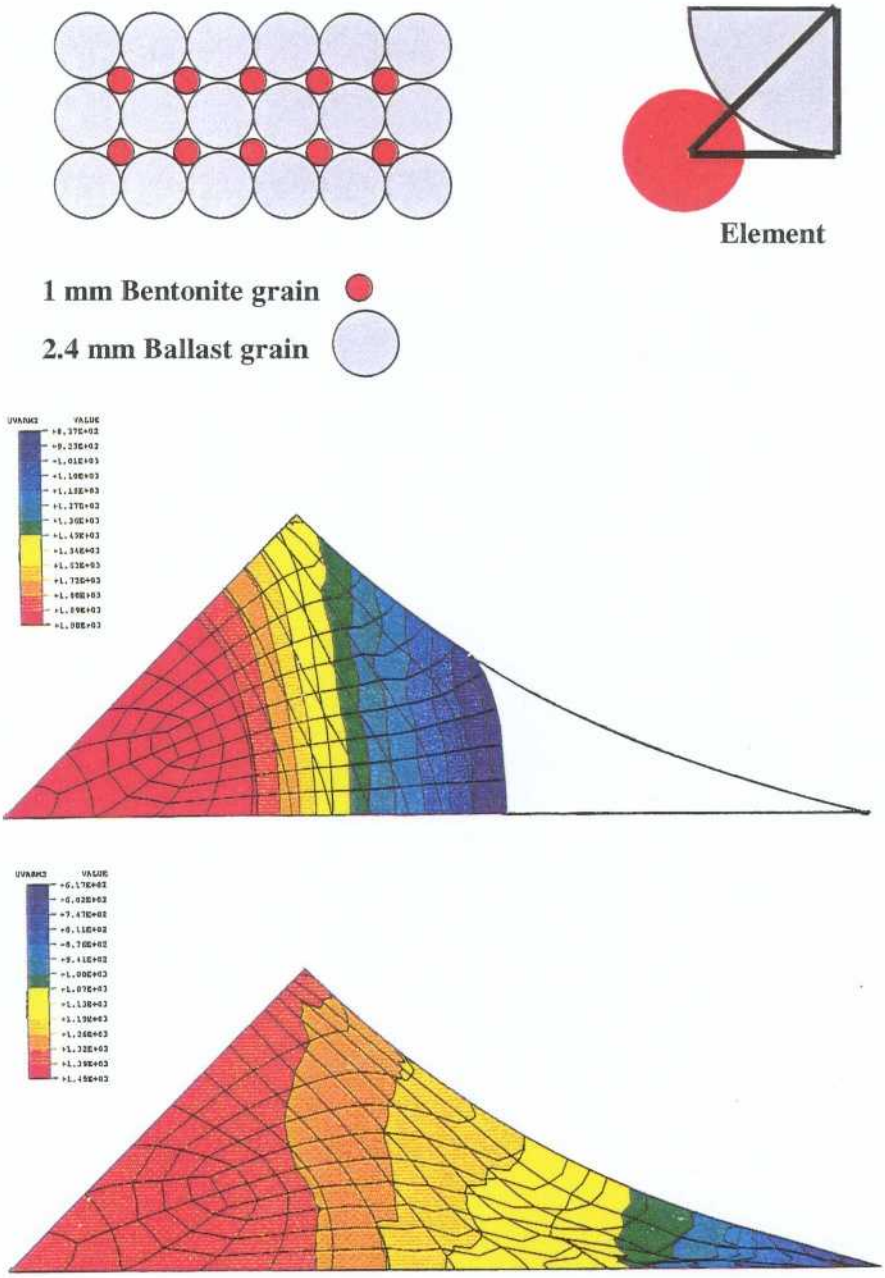


***Figure 12**. Bentonite/ballast mixture with 10 % bentonite. Upper: Geometry. Lower: Void ratio distribution at equilibrium (white and blue: very soft, red: dense.*

Calculations using ABAQUS and a material model assuming modified Drucker-Prager plasticity, "porous elasticity", porewater pressure related to density-dependent suction (swelling pressure with negative sign) and hydraulic conductivity related to the void ratio show that the bentonite grains will expand to fill 75 % of the initially water-filled void in the element in 20 seconds. After infinite time the unfilled parts, which are located at the contacts of ballast grains, represent about 0.5 % of the initial void (Figure 12). These isolated open voids do not contribute much to the bulk conductivity but the outer parts of the bentonite grains are soft (e=1.6-3.5) and permeable and cause a rather high bulk conductivity ($K>10^{-9}$ m/s). The expandability and swelling pressure of 10/90 backfills are almost nil even at 2100 kg/m^3 at saturation.

Increasing the bentonite content to 15 % and using fine-grained bentonite (0.5 mm) the microstructural model in Figure 13 is obtained. The ballast grains are still in contact but the voids have been reduced from about 1 mm maximum diameter to about 0.5 mm. The density of the clay filling in the ballast voids is somewhat higher but the net bulk hydraulic conductivity is not significantly reduced ($K>10^{-10}$ m/s). The expandability and swelling pressure of 15/85 backfills are insignificant. The latter is in the range of 50-200 kPa for a density at saturation of 2100 kg/m^3.

Not until the bentonite content is raised to about 30 % the hydraulic conductivity K is significantly reduced and the swelling pressure p_s appreciably raised: K down to 10^{-11} m/s and $100<p_s<400$ kPa for a density at saturation of 2000 kg/m^3. The ballast grains are then not in contact anymore but float in the clay matrix. The homogeneity and density of the clay matrix are then the sole conductivity-controlling parameters except for the porewater chemistry.

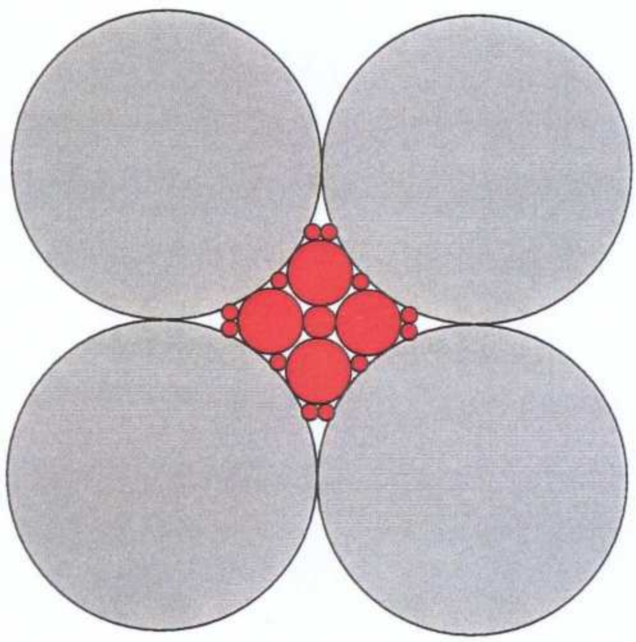


Figure 13. *Microstructural model in 2D of MX-80/ballast mixture with 15 % fine bentonite.*

4.2 3D improved model

4.2.1 Mixing

Bentonite and ballast particles smaller than 1 mm in fact determine the microstructure. Mixtures of MX-80 grains and crushed rock ballast can be approximated to consist of two grain sizes, 400 μm and 100 μm, the largest representing the ballast and the smallest the bentonite. A 10/90 bentonite/ballast mixture contains about 8 times as many bentonite grains than ballast grains, while for a 30/70 mixture this ratio is 24.

Preparation and compaction of mixtures, air-dry or wetted, imply strong agitation by which bentonite grains undergo abrasion and break into fragments. The size of the bentonite grains after such agitation ranges from a few micrometers to a tenth of a millimeter in the finer part of the mixtures. The rotation and sliding of clay and ballast particles caused by vibratory movement and a large number of cyclic pressurizing bring them into dense layering. These processes invalidate FEM calculations based on the assumption that the initial bentonite grains are unaffected.

4.2.2 Influence of bentonite content

Freshly prepared air-dry bentonite/ballast fills have the structure in Figure 14 before compaction.

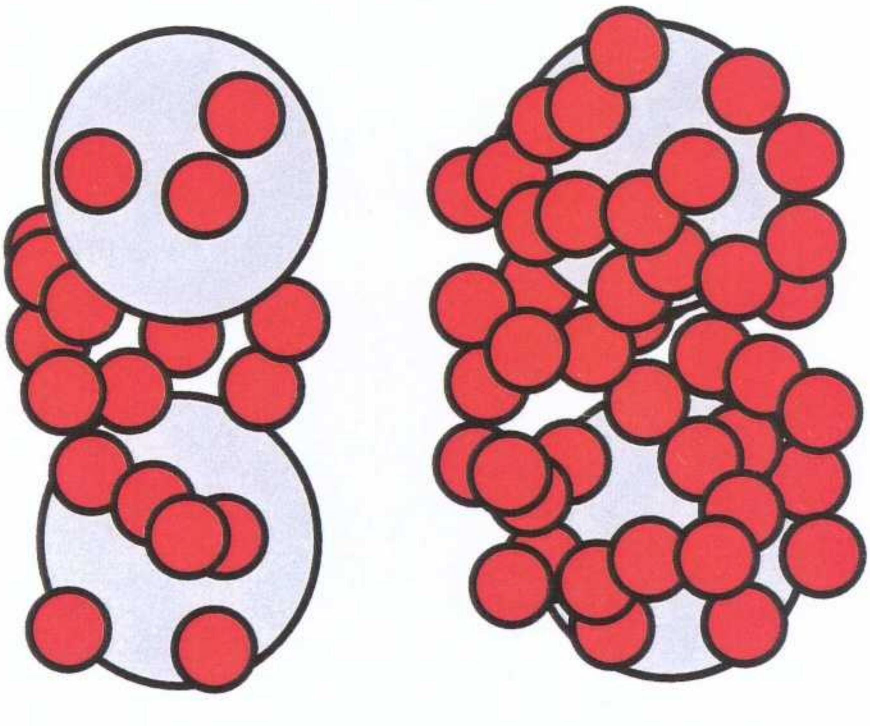


Figure 14. *Soft bentonite/backfill mixtures with 400 μm ballast grains and 100μm bentonite grains. Left: 10/90 clay/ballast mixture. Right: 30/70 mixture.*

4.2.3 10/90 backfill

Mixed condition

An undisturbed unit cell of 10/90 backfill with cubical symmetry contains 1/8 of a 400 μm diameter ballast grain and 1 bentonite grain and it has 200 μm edge length (Figure 15). The volume of the bentonite-containing void in the unit cell is 3.8×10^6 μm^3 (porosity of ballast system 0.38). The dry bulk density of the backfill microelement will be 1500 kg/m^3 (1945 kg/m^3 after saturation).

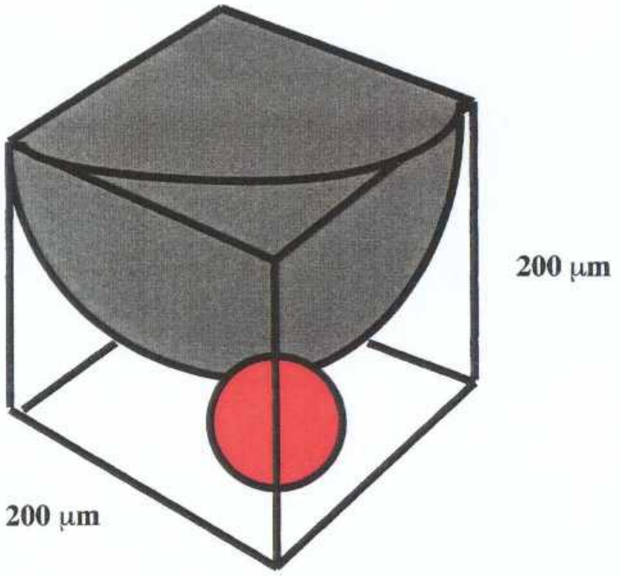


Figure 15. *"Undisturbed" unit cell of 10/90 backfill prior to compaction. The diameter of the large ballast grain is 400 μm. The red bentonite grain is 100 μm.*

Compaction

Assuming the bentonite to behave as a Mohr/Coulomb material, compression under 1 MPa pressure or combination of 0.1 MPa pressure and vibration-induced shearing, will break a 100 μm diameter bentonite grain into at least 8 fragments with a volume of 6×10^4 μm^3 (Figure 16). They will be moved into the voids between the ballast grains and also form coatings (cutans) of these grains.

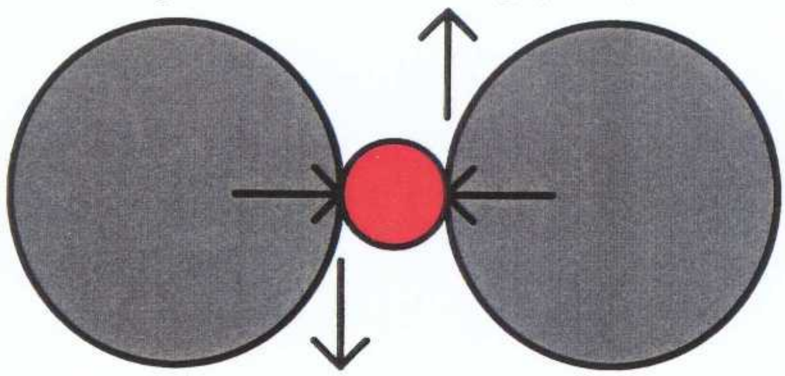


Figure 16. *Load conditions of bentonite grain in compacted bentonite/ballast backfill.*

Assuming that compaction yields a dry density of 1750 kg/m^3 (2100 kg/m^3 at water saturation) the volume of the unit cell is decreased by 15 %. Uniaxial compression gives a shortening of the unit cell by 30 μm and a reduction of the volume of the bentonite-containing void in the unit cell to 2.6x10^6 μm^3 in conjunction with relative movement of neighboring ballast grains and change of the cubical symmetry.

The fragments originating from the bentonite grain in the unit cell occupy a volume of 5x10^5 μm^3, which hence means that about 2.1x10^6 μm^3 remains open and water-filled. Taking the assumed 8 fragments to be disc-shaped with 10^4 μm^2 base their thickness is about 6 μm, i.e. 6x10^4 Å, which means that they consist of about 100 stacks of 5 smectite lamellae with 1 interlamellar hydrate layer in Na montmorillonite. Two more hydrate layers can hence be formed, by which the smectite stacks expand by 20 % and occupy a space of 6x10^5 μm^3, still leaving 2x10^6 μm^3 open. Repeated stress impact in the course of the compaction and hydration-induced stresses will make the fragments move and break up into individual stacks of lamellae, which will reorganize. For pH>5 a "repulsive" (unstable) gel consisting of a cardhouse of fully expanded stacks of lamellae will hence form spontaneously [10]. The average density of the gel will be 1540 kg/m^3, which corresponds to a hydraulic conductivity of about 10^{-11} m/s at percolation with distilled water and 10^{-8} m/s at percolation with 3.5 % $CaCl_2$ solution.

Applying conventional mathematical expressions for the net average hydraulic conductivity of soil with varying permeability it should be 10^{-12} m/s at percolation with distilled water and 10^{-9} m/s at percolation with 3.5 % $CaCl_2$ solution. These values are much lower than experimental data, which demonstrates that the clay gel is not homogeneous.

Very effective compaction can possibly bring the bulk dry density up to 1900 kg/m^3 (2200 kg/m^3 at saturation). The volume of the bentonite-containing void in the deformed unit cell is then reduced from 2.6x10^6 μm^3 to 2.3x10^6 μm^3 and since the now numerous fragments originating from the bentonite grain in the unit cell still occupy a volume of 5x10^5 μm^3, about 1.8x10^6 μm^3 void space remains open. The average density of the gel will then increase from 1540 to 1630 kg/m^3, which corresponds to a hydraulic conductivity of about 10^{-12} m/s at percolation with distilled water and 10^{-10} m/s at percolation with 3.5 % $CaCl_2$ solution, yielding a bulk conductivity of 10^{-13} m/s at percolation with distilled water and 10^{-11} m/s at percolation with 3.5 % $CaCl_2$ solution. These values are also lower than experimental data.

4.2.3 30/70 backfill

Mixed condition

In backfill with 30 % bentonite the clay forms a matrix that controls the bulk hydraulic conductivity and swelling pressure. The microstructural evolution is largely determined by the interaction of bentonite grains and a unit cell of the backfill is therefore of the type shown in Figure 17. For modeling it is required to take the grain size variation of the bentonite into consideration, which explains that two grain diameters appear, i.e. 350 and 100 μm. The bigger grain is taken to be 400 μm, which makes the geometries of the 10/90 and 30/70 backfills identical.

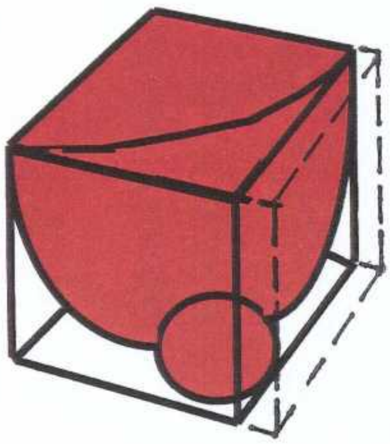


Figure 17. *Unit cell of clay component in 30/70 backfill. The diameter of the big bentonite grain is 400 μm and that of the small one 100 μm.*

Compaction

Assuming that compaction with plate vibrators yields a dry density of 1750 kg/m^3 (2100 kg/m^3 at water saturation), the volume of the unit cell is decreased by 15 %. Like the 10/90 backfill uniaxial compaction gives a shortening of the unit cell by 30 μm and a reduction of the volume of the void in the unit cell to $2.6x10^6$ μm^3 in conjunction with relative movement of the grains and change of the cubical symmetry (Figure 17).

Unlike the 10/90 backfill the big grain is deformed plastically, which makes the small grain deform less and remain coherent although strongly deformed (Figure 17). The main difference between the two cases is that both grains expand and produce a clay gel with higher density than in the 10/90 case. The stress/strain behavior of grain systems of this typer has been modeled by use of the BEM code BEASY [11]. In principle, the central parts of the grains remain dense while their outer parts soften but to a smaller extent than in the 10/90 case (cf. Figure 18).

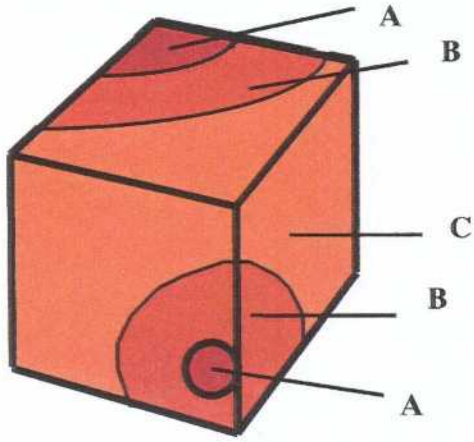


Figure 18. Schematic picture of hydrated unit cell of 30/70 mixture. A) Core with original grain density. B) Intermediate zone with slightly reduced density. C) Intermediate zone with reduced density.

The density of the gel, which will consist of nearly fully expanded stacks of lamellae with $3x10^{-6}$ μm^3 free water between them, will have a density of 1890 kg/m^3. It has a hydraulic conductivity of about $2x10^{-13}$ m/s at percolation with distilled water and 10^{-12} m/s at percolation with 3.5 % $CaCl_2$ solution, yielding a bulk conductivity of $6x10^{-14}$ m/s at percolation with distilled water and $3x10^{-12}$ m/s at percolation with 3.5 % $CaCl_2$ solution. These values are also lower than experimental data by about 2 orders of magnitude, which demonstrates that the clay gel is not homogeneous.

4.2.4 Friedland clay

The grain size of the investigated finely ground air-dry Friedland clay is significantly smaller than that of the clay component of 30/70 MX-80/ballast and the ratio between the numbers of small and big clay grains that make up a representative generalized microstructural unit cell is higher due to the flatter grain curve (Figure 19). This means that the voids between the big grains would be more effectively filled with small grains and the remaining voids hence smaller for any bulk density value. However, the higher content of montmorillonite in MX-80 forms stronger, denser and more homogeneous gels of coagulated stacks of lamellae that have been released from dispersed grains and the average density of the clay is therefore probably similar in the two backfill types.

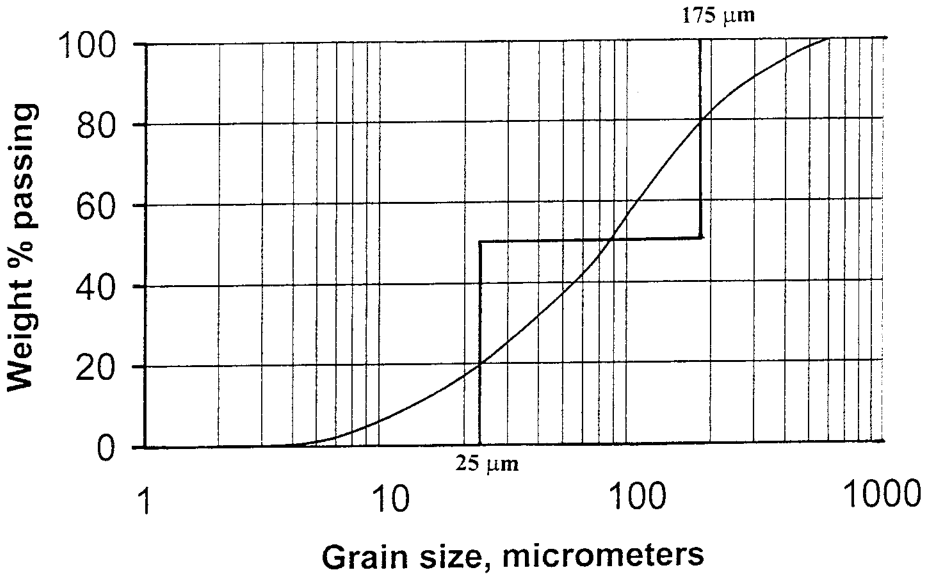


Figure 19. Grain size distribution of the investigated Friedland clay with two grain sizes selected for microstructural modeling.

In contrast to the MX-80 grains, those in Friedland clay contain less expandable minerals (about 50 %) that may not be equally represented in all grains. This would imply that the clay gel formed by coagulation of dispersed grain fragments is more heterogeneous and permeable than in backfills of 30/70 mixtures. However, since the space between the grains is smaller than in such mixtures matured Friedland clay is still assumed to be at least as homogeneous as 30/70 backfills.

5 MICROSCOPY

5.1 Preparation

5.1.1 Material samples

Mixtures of MX-80 and crushed TBM muck with weight ratios 10/90 and 30/70, and Friedland clay were investigated. The mixed materials were intensely stirred and then poured in a metal cell with 10 mm diameter and 30 mm length. These samples were compressed to a dry density of 1900 kg/m^3 (2200 kg/m^3 at saturation) in the cell and end caps screwed on in order to support the filters that were put in contact with the samples at the ends of the cell. The air-dry Friedland clay powder was compacted to a dry density of 1450 kg/m^3 (1900 kg/m^3 at saturation).

5.1.2 Preparation for microscopy

The cell was submerged for 24 hours in a solution consisting of 85 % by weight of butyl methacrylate and 15 % methyl methacrylate to which 2 % 2.4-dichlorbenzoylperoxide (EMW) catalyst had been added [12]. Polymerization was obtained by heating to 60°C for 15 hours. Experience shows that the monomer is absorbed by expanding clay minerals similar to water, i.e. both in interlamellar space and on basal surfaces of the smectite stacks [13]. Hence, the distribution and constitution of the clay component of the various backfill materials can be assumed to represent those in water saturated materials.

After polymerization the stiff soil specimens were extruded from the cell and thin sections (30 μm) prepared by grinding in the fashion used in petrology. For the Friedland clay also ultrathin sections (300-700 Å) were prepared by use of an ultramicrotome equipped with diamond knives.

5.2 Microscopy

5.1 Techniques

Ten thin sections were examined and photographed at magnifications ranging between 10 and 100 x using ordinary light. These graphs were then digitalized by scanning, and variations in density vizualised by ascribing different colors to different features. For Friedland clay transmisson electron microscopy (TEM) was also applied. Due to the large amount of ballast grains of quartz and feldspar ultrathin microtome sections could not be prepared from the clay/ballast mixtures.

Legend for optical micrographs of 10/90 and 30/70 backfills as well as of the Friedland clay:

Brownish matrix represents bentonite.

Grey/yellow objects represent larger ballast grains.

Black/dark brown zonation and discrete very small objects represent rock debris.

5.3 Results

5.3.1 Microscopy

Typical micrographs are shown in Figures 20-25. The following comments are valid:

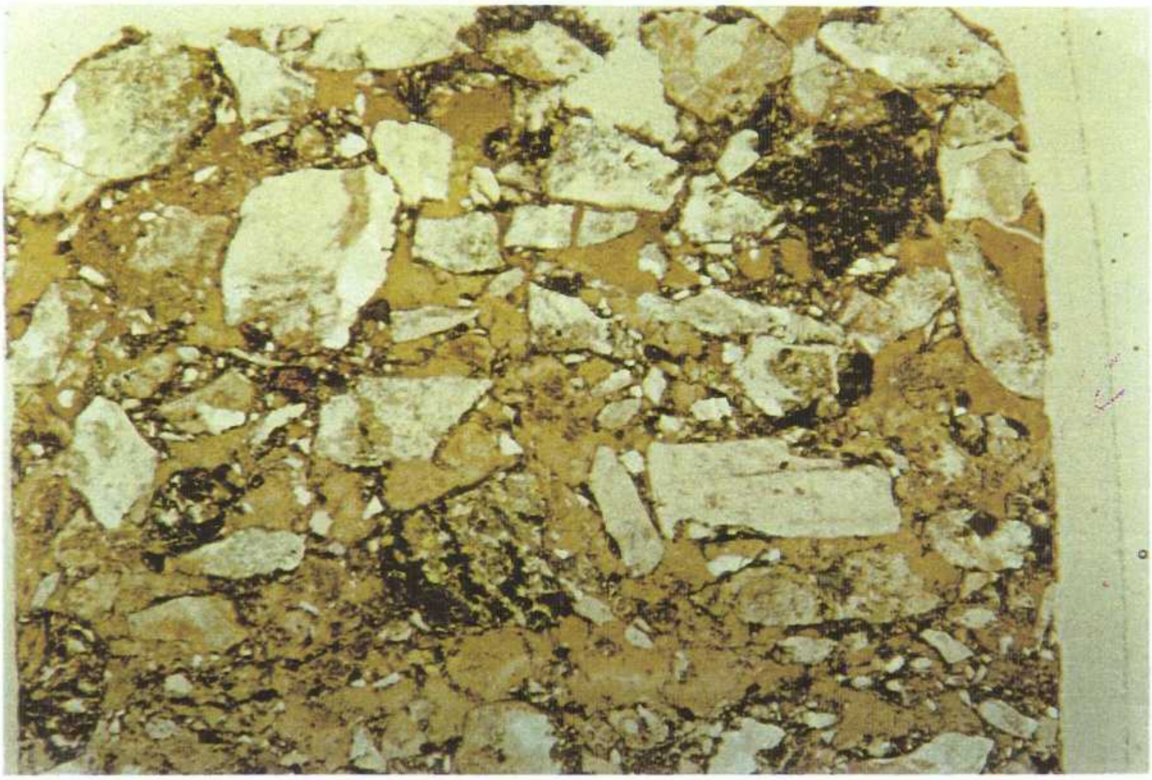
5.3.2 10/90 bentonite/ballast mixture

At low magnifications (10 x) the degree to which the MX-80 clay fills the voids between the rock grains appears to be high but local unfilled parts can be seen (Figure 20 and 21). The clay density varies and is estimated to range between about 1100 and 1700 kg/m^3.

At 100 x magnification a number of narrow voids between ballast grains can be seen that appear to be incompletely filled with clay (Figure 20). They appear as white areas representing the acrylate embedment with very small particles fixed in it. These minute particles are believed to be rock debris from the crushing operation and they are assumed to have been attached to the big rock grains before and in the mixing operation. Many of them remained at these grain surfaces also during and after the mixing as demonstrated by Figure 21.

The presence of clay gels with very low density and the locally incomplete filling and also high frequency of debris grains, of which many had a size of a few hundreds of a millimeter to a few micrometers, are concluded to increase the hydraulic conductivity to a significantly higher value than would have been obtained for a soil with the voids uniformly filled with MX-80 clay with the theoretically derived values 1500-1600 kg/m^3.

a



b

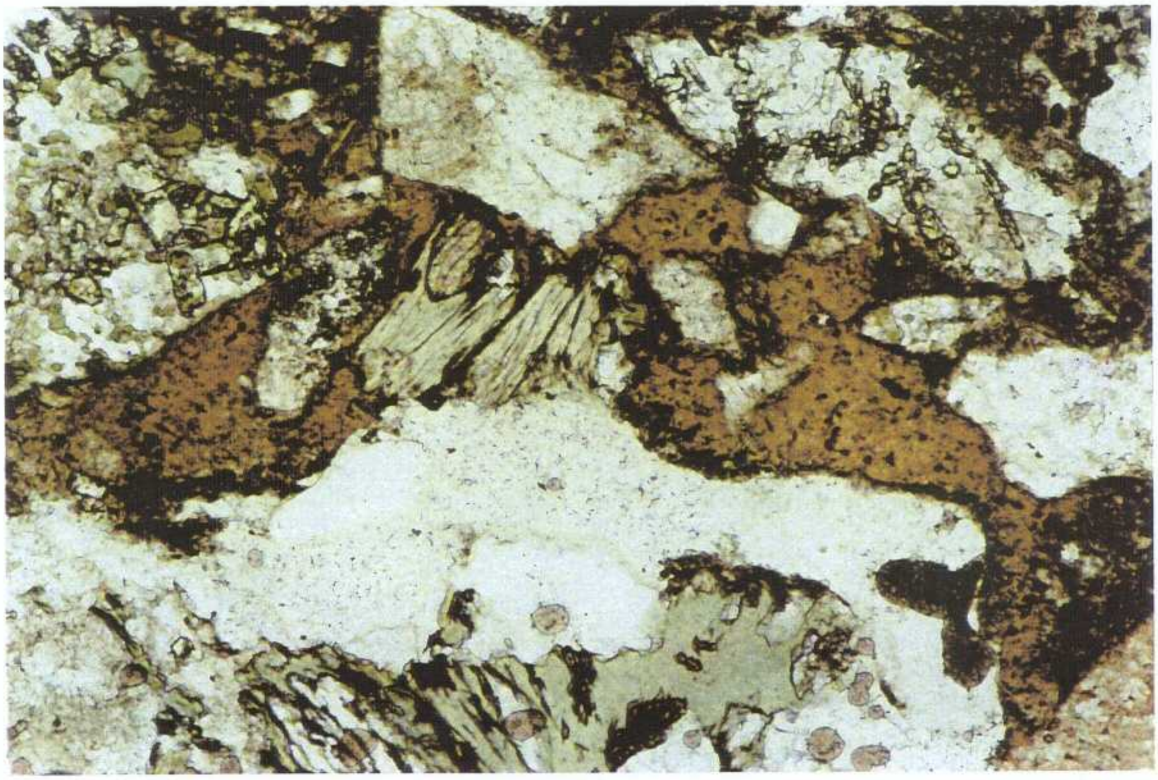
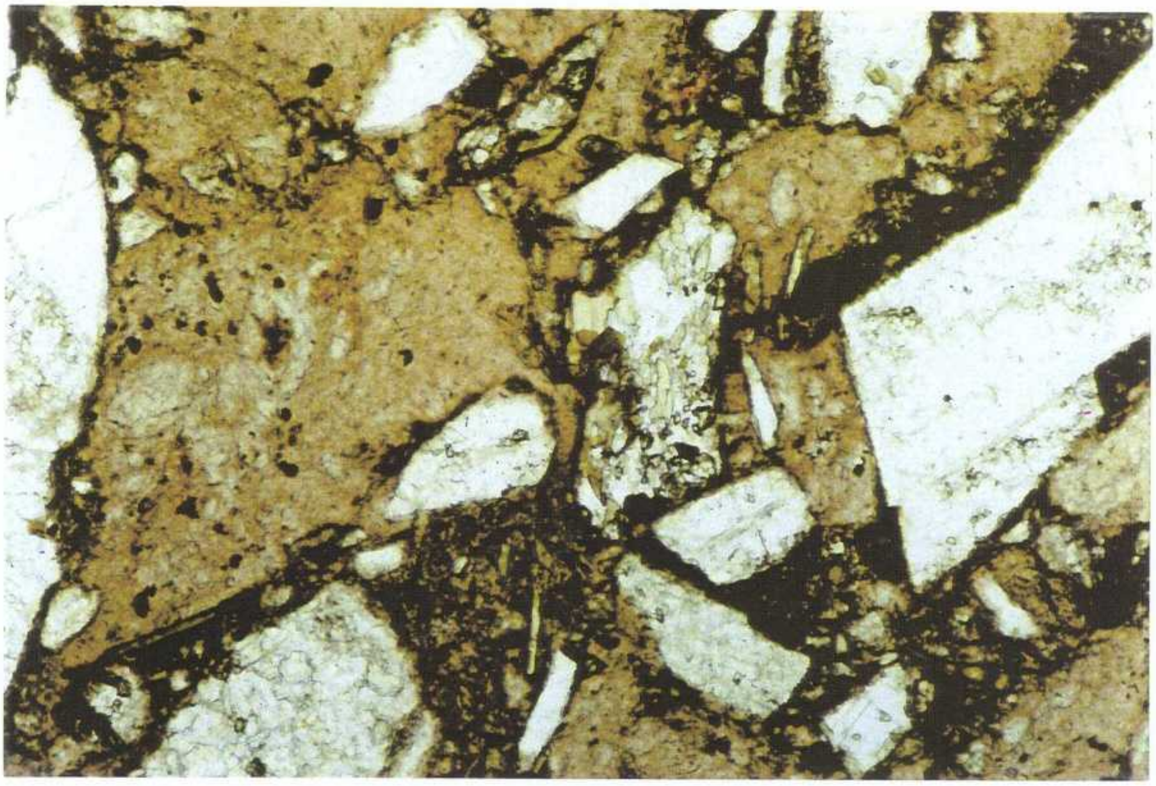


Figure 20. *Micrographs of 10/90 MX-80 and crushed rock ballast. Upper: 10 x magnification. Lower: 100 x magnification.*

a



b

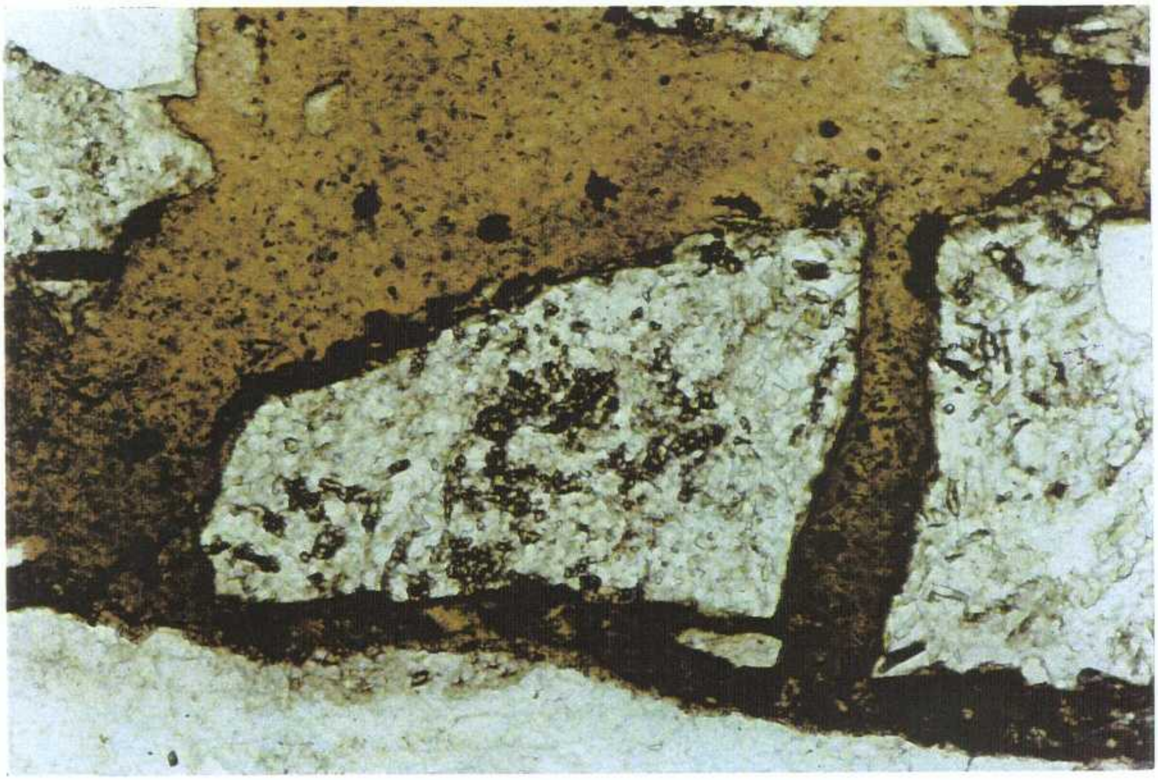


Figure 21. *Micrographs of 10/90 MX-80 and crushed rock ballast. 100 x magnification.*

5.3.3 30/70 bentonite/ballast mixture

An interesting observation is that many of the rock grains, which have low degrees of sphericity and roundness, contain fractures while staying coherent. These fractures are open and imply some hydraulic conductivity of the ballast component. However, where the fractures caused breakage of the grains in the mixing operation (Figure 23), clay could get in and fill openings with an aperture of around 200 μm. It is estimated that this primarily took place by small bentonite fragments entering the voids in the mixing operation.

At low magnifications (10 x) the degree to which the bentonite fills the voids between the rock grains is very high (Figure 24a) and the clay density is estimated to range between about 1400 and 2000 kg/m^3. In contrast to the 10 % bentonite backfill material, one finds no empty voids between the rock grains at 100 x magnification. The clay component hence fills up all voids that can be seen.

As in the bentonite-poor mixture, a high number of minute rock-forming mineral particles are observed in the clay but more frequently attached to the big rock grains.

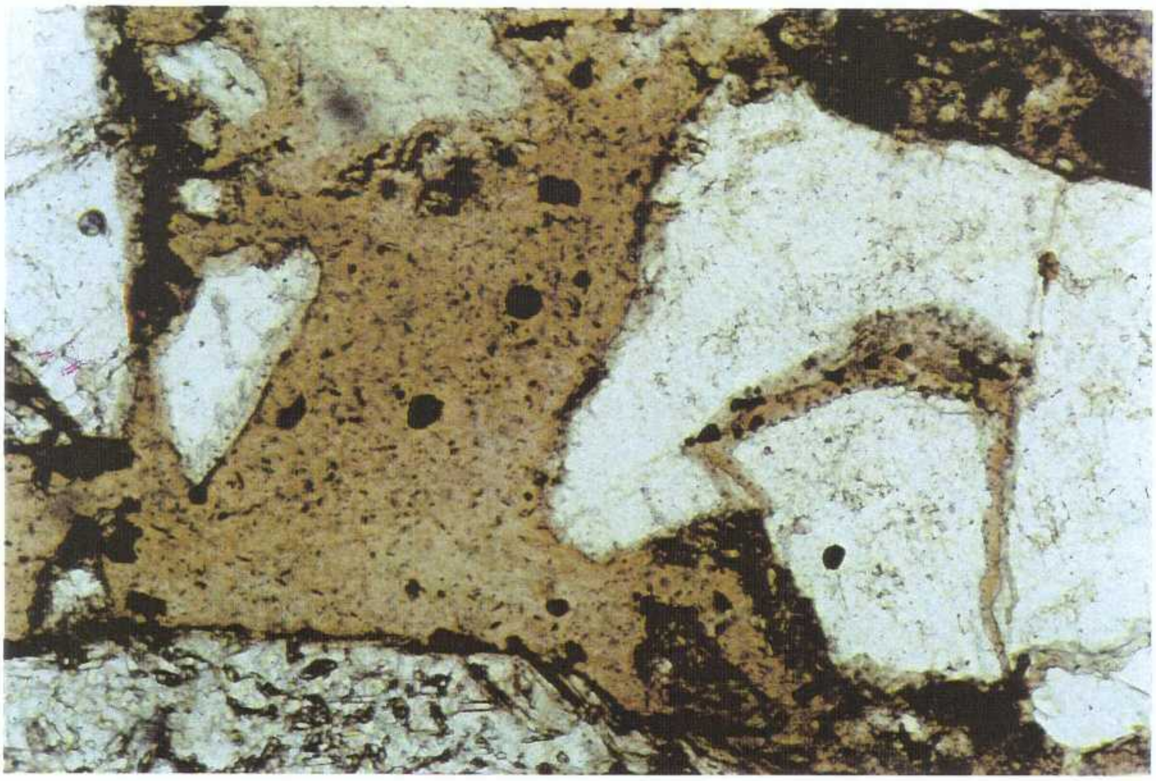


Figure 23. *Micrograph of 30/70 MX-80 and crushed rock ballast. 100 x magnification.*

a

b

Figure 24. *Micrographs of 30/70 MX-80 and crushed rock ballast. Upper: 10 x magnification. Lower: 100 x magnification.*

5.3.4 Friedland clay

Light microscopy

The appearance of the micrographs is quite different from those of the mixed backfills. Thus, one finds from the representative micrographs in Figures 25 and 26 obtained by use of light microscopy that the soil matrix is much more fine-grained and homogeneous although there are discrete silt and sand grains. These are rounded, which made them slide and rotate in the compaction processes without causing pockets into which clay could not readily move. Some local lense-shaped zones of clay with low density are seen.

An interesting observation is that the clay is dominated by flow structures, which indicate that large shear strain was induced by the compaction. It is believed that comprehensive breakage of the original grains took place in this process and that the major homogenization factor was not strong expansion of such grains, like in the case of MX-80 grains in mixtures, but fragmentation and subsequent moderate expansion of the fragments.

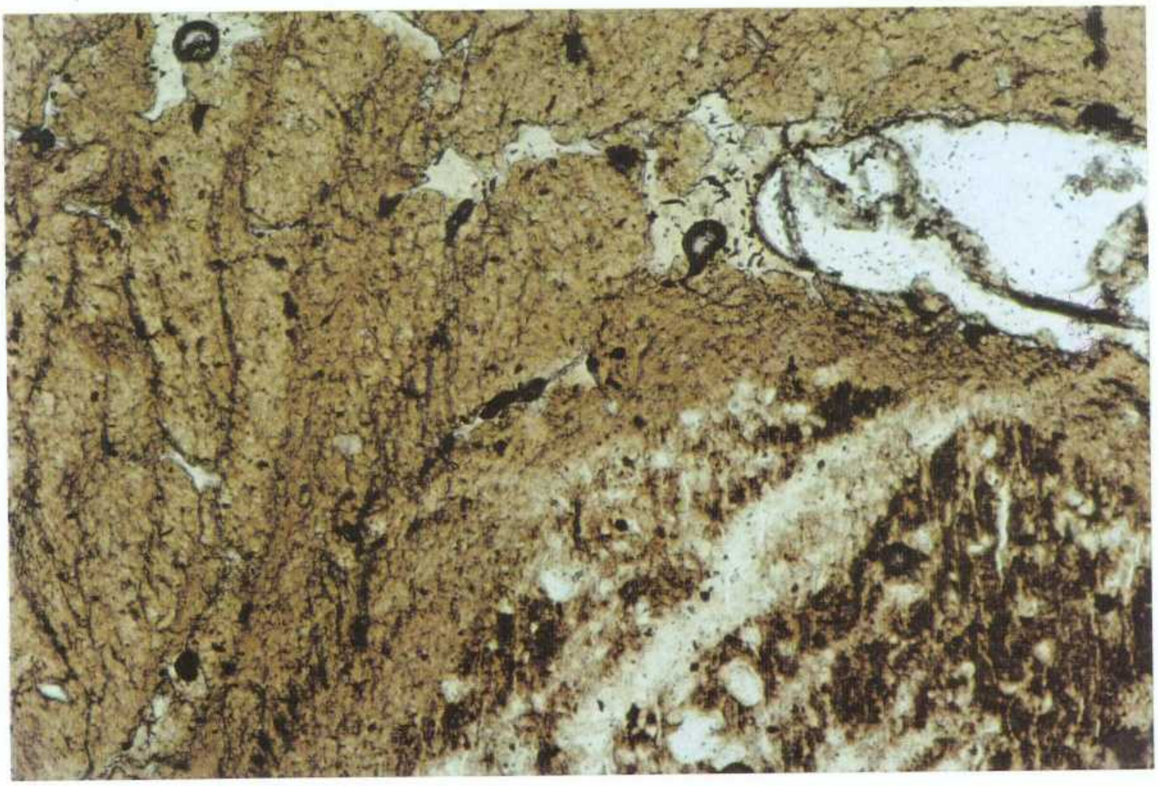


Figure 25. *Micrograph of Friedland clay prepared by compacting air-dry grains. 100 x magnification. Light micoscopy.*

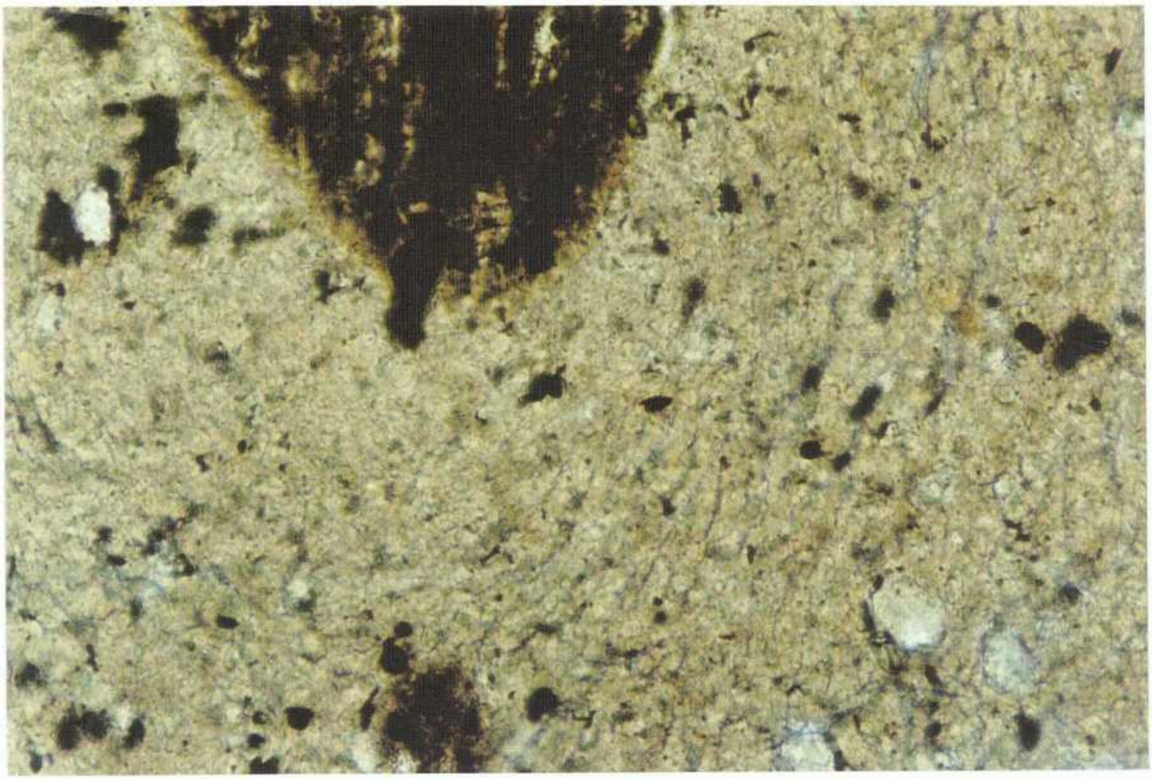


Figure 26. *Micrograph of Friedland clay prepared by compacting air-dry grains. 200 x magnification. Light micoscopy.*

Electron microscopy

The sectioning and microscopy were made by Dr Joern Kasbohm, Dept. of Geology, University of Greifswald, Germany. Figure 27 is a digitalized TEM picture, which shows the same flow structure with softer clay bands (green) separating denser fragments of the original grains as one can imagine from the light microscopy. The connectivity of the softer, more permeable bands varies but is assumed to be sufficiently high to have an impact on the bulk conductivity. It is believed that higher bulk densities than 1900 kg/m^3 at saturation, like the density that is expected to be achieved in practice (2000 kg/m^3), will reduce the connectivity and improve the homogeneity.

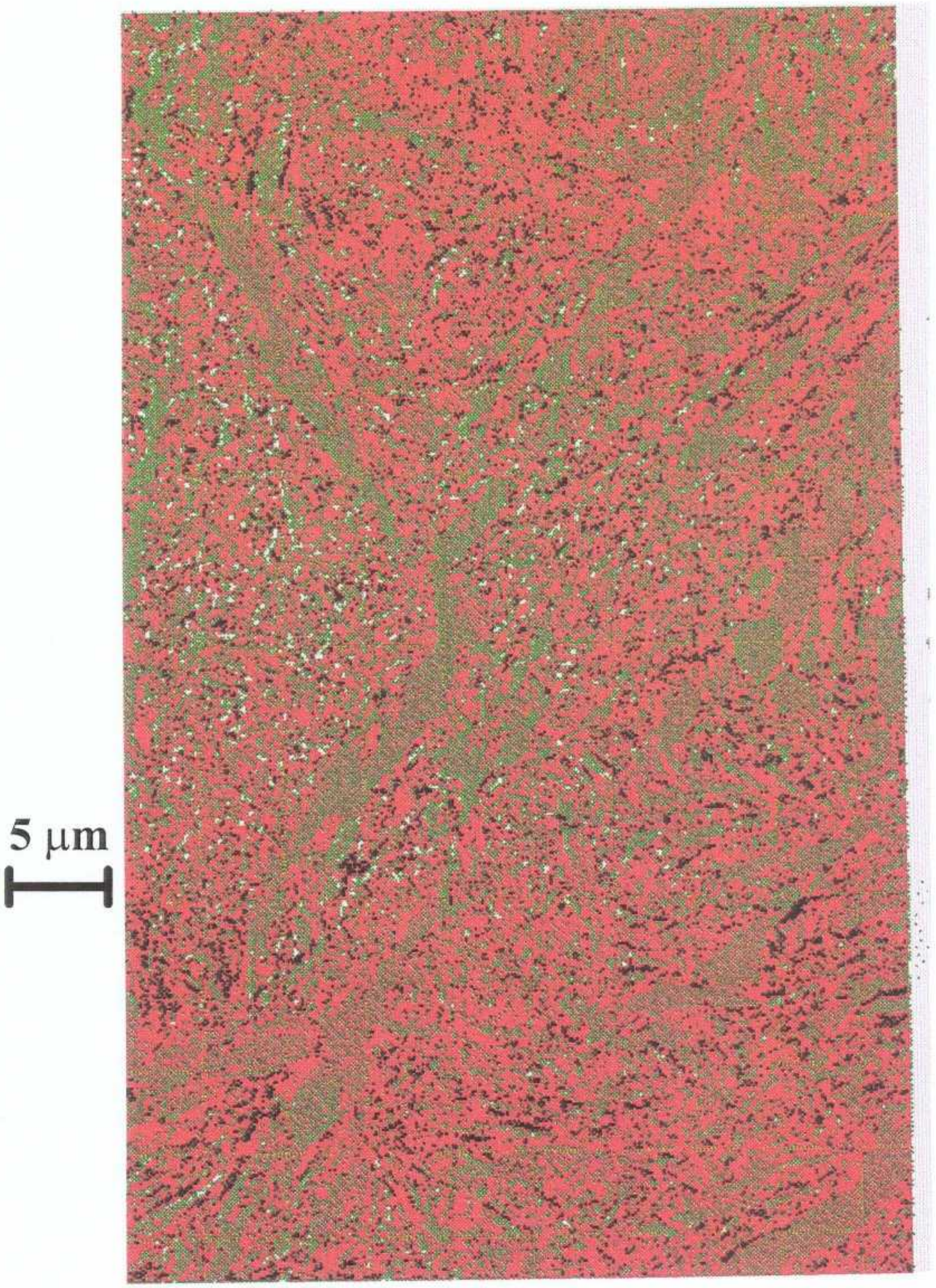


Figure 27. *Digitalized TEM micrograph of Friedland clay prepared by compacting air-dry grains. 2500 x magnification. Black objects are very dense and impermeable. Red objects are dense and practically impermeable. Green objects are permeable clay gels. White objects are open, unfilled voids.*

5.3.5 Quantitative interpretation of micrographs

Modern techniques for quantitative evaluation of microghaphs involve digitalization as examplified by Figure 27. Corresponding digital pictures obtained from light micrographs of 10/90 and 30/70 mixtures of MX-80 and TBM muck are examplified in Figure 28 for the particular purpose of showing the stronger variation in density of the clay gels in the clay-poor mixture than in the mixture with more clay, and for making the presence of very fine rock debris obvious. Such digital pictures form the basis for estimating gel densities.

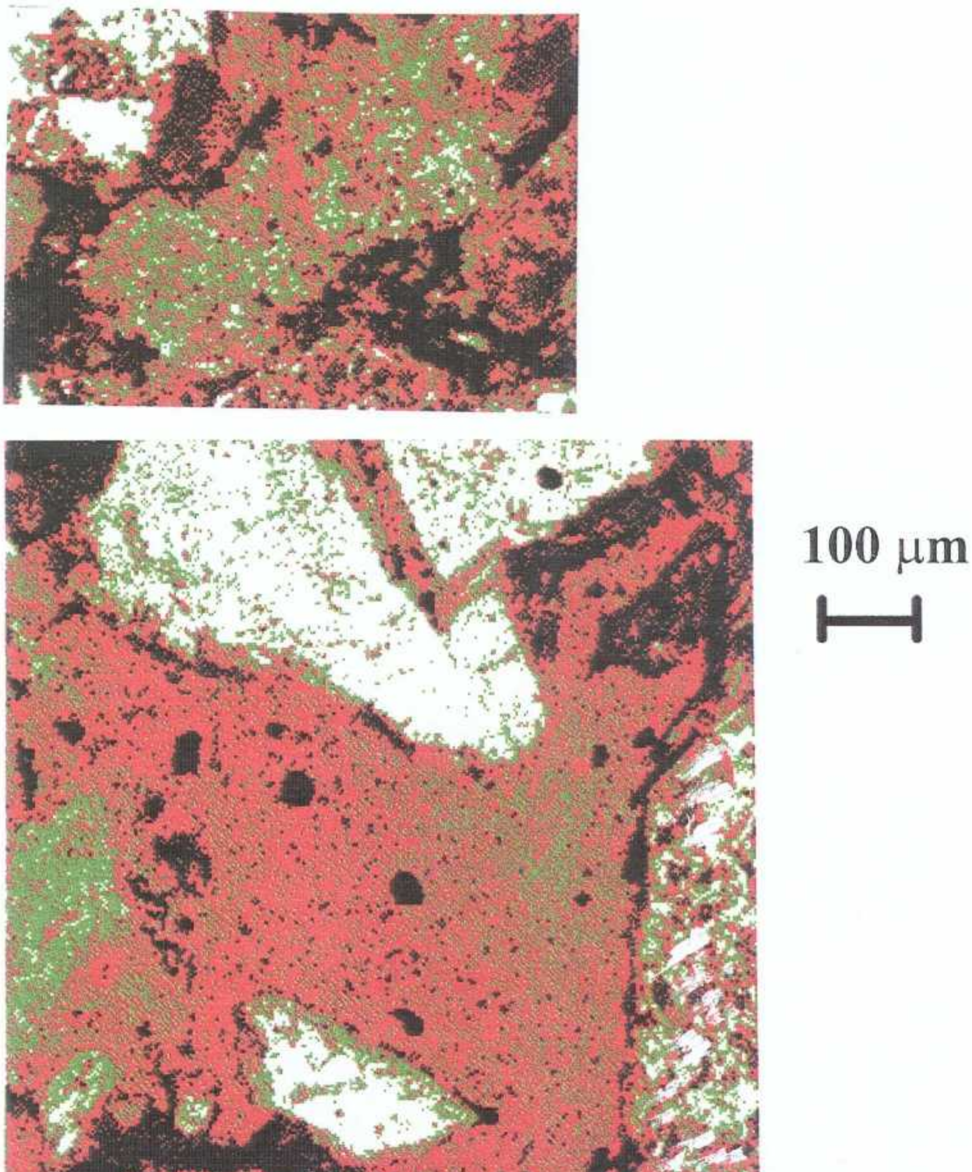


Figure 28. *Digitalized micrographs of 10/90 (upper) and 30/70 backfills. Notice the heterogeneous red/green/white/black clay gel located between the big ballast grains (white) in the 10/90 backfill and the more uniform red (dense) clay in the void between (white) ballast particles in the 30/70 backfill. The black zones are very small rock debris particles.*

6 COMPARISON OF BENTONITE/BALLAST MIXTURES AND FRIEDLAND CLAY AS TUNNEL BACKFILL

6.1 Basis of comparison

Comparison of the investigated bentonite/ballast mixtures and Friedland clay intended for backfilling of KBS3 tunnels will be made here with respect to the following properties:

1. Accessible raw materials
2. Preparation, homogeneity
3. Compactability
4. Ability to minimize upward expansion of buffer clay in deposition holes
5. Ability to support tunnel roofs
6. Ability to self-seal
7. Hydraulic conductivity
8. Chemical performance
9. Cost

6.2 Accessibility

6.2.1 Mixtures of MX-80 and crushed TBM muck

Na bentonite

The origin of the most extensively exploited Cretaceous North American deposits of sodium bentonite was volcanic glass deposited in shallow marine/brackish estuaries. It emanated from comprehensive volcanic acticity in the western Cordillera by which vast quantities of ash were formed and blown east by prevailing winds. The process resulted in a series of ash deposits on the inland sea. They gradually settled and became buried by marine or land-derived materials. With time, these deposits were deeply buried and consolidated by more recent sediments and many of these ancient ash layers altered to bentonite [14].

The bentonite beds have a character that depends on the initial ash composition and granulometry, as well as on the porewater chemistry of the deposits. There are fairly large variations in each respect. Thus, the beds in the North and West are more "ashy" with a lower smectite content because of their proximity to the volcanoes or due to inclusion of terrestrial material brought into the area at sea level fluctuations. The deposits in the central basin tend to be more homogeneous.

In the US there are large bentonite resources in the Black Hills region of South Dakota, Wyoming and Montana as well as in the Gulf region, especially in Texas and Mississippi. The thickness of the beds in the Black Hills area ranges between a few centimeters and a few meters, the best producing horizon being the "Clay Spur". The Black Hill bentonites have sodium as major adsorbed cation while the

Canadian bentonites of similar origin in Manitoba, Saskatchewan and Alberta like the Gulf bentonites often have calcium as major adsorbed cation.

MX-80 is prepared from Black Hills bentonites, the outcrops of which are often light yellow or green resulting from redox effects while the bentonite deeper down is bluish. The manufacturers of commercial bentonites ususally mix material from differently colored beds, which means that certain chemical variations occur in the product. Also, mixing is used to even out differences in smectite content. The large variation in thickness of the exploited beds is a major reason for variations in grain size and mineral content.

Experience from many years of research for SKB has indicated that MX-80 has a varying composition and that the quality expressed in terms of smectite content and contaminants like coal is somewhat less good in recent years than it once was. Considering the limited access to first class sodium-rich smectite clay in the Black Hills area some additional loss in quality is expected in future.

Ballast

Ballast from crushed TBM muck, i.e. the material used in the present study, will be available in large quantities for backfilling a forthcoming KBS3 repository. The most important safety-related property is the content of K-bearing minerals, primarily microcline feldspar, which will serve as potassium source in future conversion of the smectites in the buffer and backfill. However, since no upper limit with respect to the content of such minerals has been set, it is expected that practically all crushed TBM muck can be used as ballast in backfills. The fact that the crushed rock contains debris that prevents effective filling of the voids between ballast grains with clay may require washing of the ballast or an increase in clay content beyond the presently considered 30 %.

6.2.2. Friedland clay

In the Neubrandenburg area in northern Germany there are large quantities of smectitic clays that have been used for isolation of shallow waste piles for decades. One deposit, which is located in the Friedland area, was formed in Tertiary time by sedimentation of large quantities of clay in an estuary. The clay material emanates from eroded older sediments and represents a mass of at least 10^8 tons of homogeneous clay down to a depth of at least 100 m in an area of more than 2 square kilometers.

Figure 29 is a photo taken in April 1998 of the about 20 m deep major clay production pit in which samples were taken for checking the homogeneity of the mass. 20 samples were taken and mineral and granulometry data determined. Taking the content of particles finer than 20 μm as a measure of effective compactability and important minerals, the variation along 20 m deep vertical profiles is as shown in Table 6. It demonstrates a small variation in grain size distribution that agrees with mineral data.

Table 6. *Content of minus 20 μm particles in 20 m profile as a measure of the homogeneity.*

Depth, m	Content of minus 20 μm particles
1	89.03*
2	90.25
3	92.77
4	98.98
5	95.56
6	96.23
7	97.66
8	99.03
9	99.89
10	99.99
11	98.37
12	99.19
13	99.86
14	88.45*
15	98.25
16	91.94
17	99.73
18	96.64
19	98.04
20	98.90

* 100 % smaller than 63 μm

Figure 29. *Photograph of the clay pit at Friedland. Arrows indicate slots excavated for taking samples.*

6.3 Preparation, homogeneity

6.3.1 Bentonite/ballast mixtures

Table 3 demonstrates that there is a large variation in conductivity for each density and bentonite content. This is probably due to differences in microstructure but for the lowest bentonite content, 10 % by weight, it is probably also caused by leakage along the oedometer/soil interface. Relevant tests require an effective seal of pure MX-80 applied at the contact.

The recorded variation in conductivity is typical for samples taken from mixtures prepared in the laboratory and further variation is known to result from the handling, application and compaction of backfills on a full scale [4]. Mixing of MX-80 clay and ballast naturally leads to a variation in the content of smectite because the mixing operation does not produce uniform distribution of the components neither on a macroscopic scale nor in the microstructure. Variation in compaction energy causes a density distribution that will not be evened out with time at the low clay contents that are considered here.

Preparation of MX-80/ballast mixtures at optimum water content means that a third component, water, is added, which naturally causes even stronger variation in composition and density. Differences in water content, which have been reported to be +/- 0.9 percent units per day in an Äspö test [2], cause variations in macroscopic density by affecting the compactability and they are believed to have a significant influence on the movement and migration of clay in the ballast voids.

One reason for poor homogeneity, the addition of water, is eliminated by applying "dry mixing and compaction". The aforementioned SFR case shows that it may yield the same dry density as preparation of soil at optimum water content but this needs to be checked for mixed materials with crushed rock ballast.

The microstructural investigation shows that the homogeneity and density of the clay component is improved when the bentonite content is increased. This also makes the microstructure less sensitive to cation exchange from Na to Ca, and to an increased salinity of the porewater. Thus, percolation of an effectively compacted 30/70 MX-80/ballast backfill by strongly brackish water is not expected to yield a higher hydraulic conductivity than about 10 times the value recorded for percolation by distilled water. For backfills with 10 % MX-80 the corresponding increase may be 100 times. It is of particular importance to realize that the rock debris in crushed ballast has a significant influence on the hydraulic conductivity of backfills with a low clay content.

Based on these considerations it is proposed that backfills of mixed MX-80/crushed ballast should be prepared by "dry mixing and compaction" and that the bentonite content should be significantly higher than 10 % by weight.

6.3.2 Friedland clay

Variations in homogeneity of compacted air-dry Friedland clay powder will be small as concerns the distribution of clay minerals since the homogeneity of the raw material is high. Compaction is expected to yield density variations of the same magnitude as in compacted mixtures of air-dry MX-80/ballast with 30 % MX-80.

6.4 Compactability

6.4.1 Achievable density

Compaction with plate vibrators will be less effective than when heavy vibratory rollers are used. The equipment developed for the Äspö tests yield relatively high dry densities but significant parts of a backfill will still have a somewhat lower density than the average value. Conservative values should hence be used for comparing the performance of the different backfills. We will assume the following data:

* Dry density=2160 kg/m^3 (2360 kg/m^3 at saturation) of mixtures of **10 % MX-80 and 90 % crushed TBM muck**. With well graded glacial silt/sand/gravel ballast the average dry density is 1920 kg/m^3 (2210 kg/m^3 at saturation).

* Dry density=1700 kg/m^3 (2070 kg/m^3 at saturation) of mixtures of **30 % MX-80 and 70 % crushed TBM muck.**

* Dry density=1600 kg/m^3 (2000 kg/m^3 at saturation) of air-dry **Friedland clay**.

6.4.2 Degree of water saturation

Figure 30 shows the void ratio *e* versus water content of powders of Friedland clay and MX-80 bentonite compressed in an oedometer at 100 MPa pressure. One finds that the Friedland clay has an appreciably lower void ratio for any water content and that it therefore yields higher densities. The diagram also shows that for a water content of 8-10 % the compacted Friedland clay, in contrast to the MX-80 bentonite, becomes almost completely water saturated. This demonstrates that the Friedland clay grains move into stable positions in dense arrangements more easily than MX-80 grains, which indicates that the compactability of air-dry Friedland clay is very good and that the dry density 1600 kg/m^3 (2000 kg/m^3 at saturation) specified in section 6.4.1 is indeed conservative.

It is believed that comparison of the physical performance of MX-80/ballast mixtures and Friedland clay using the density data in section 6.4.1 is fair.

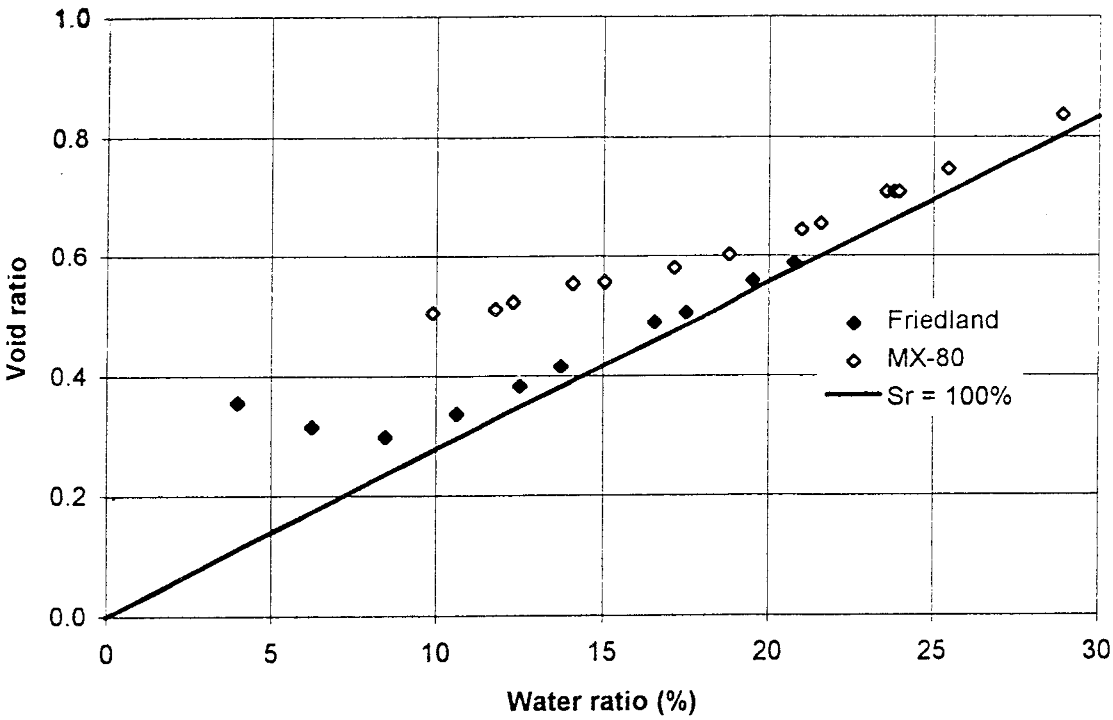


Figure 30. Void ratio versus water content of Friedland clay and MX-80 compressed at 100 MPa. The full line represents complete water saturation, which is reached at around 10 % water content for Friedland clay and at about 25 % water content for MX-80.

6.5 Effect on upward expansion of buffer in deposition holes

Compression of tunnel backfill with 10 % MX-80 is expected to be considerably smaller than for mixtures with 30 % MX-80. Friedland clay is intermediate in this respect because its density is lower and its content of expandable minerals higher.

It is concluded that Friedland clay compacted to a dry density of 1600 kg/m^3 (2000 kg/m^3 at saturation) offers greater mechanical resistance to loading and hence causes less expansion of the buffer than MX-80/ballast mixtures with up to 30 % MX-80.

6.6 Ability to support tunnel roofs

Referring to the criterion that 100 kPa swelling pressure is required one finds that mixtures of 10 % MX-80 and crushed rock, saturated with strongly brackish Ca-dominated water to the reference density 2200 kg/m^3 will not do, while mixtures with 30 % MX-80 at the reference density 2070 kg/m^3 fulfil the requirement with no margin. Friedland clay with a density of 2000 kg/m^3 after saturation with 3.5 $CaCl_2$ solution has a swelling pressure that is five to ten times higher than required.

It is concluded that the rock-supporting potential of Friedland clay is superior to that of MX-80/ballast mixtures with up to 30 % MX-80.

6.7 Self-sealing ability

The self-sealing capacity of mixtures of clay/ballast with 10 % MX-80 is negligible. A mixture with 30 % MX-80 also has a limited self-sealing potential due to the relatively low content of expandable minerals (about 21 %) and because the majority of the smectite stacks are largely expanded after complete hydration. Also, the high content of ballast particles, particularly angular grains, reduce the expandability and hence the self-sealing ability by causing high internal friction. Friedland clay should have a higher self-sealing capacity due to its higher content of expandable minerals (45 %).

Figure 31 illustrates the expandability of Friedland clay and pure MX-80 with about 75 % expandables, both saturated with distilled water to a density of 1950 kg/m^3 (1500 kg/m^3 dry density). After saturation under confined conditions, the samples were allowed to absorb more distilled water while being exposed to an effective pressure of 10 kPa in the oedometer. One finds that the Friedland clay expanded by more than 40 %, while pure MX-80 expanded by more than 180 %. Since the clay gel density in a mixture of 30 % MX-80 with a density at saturation of 1950 kg/m^3 is lower than this figure, the expected expandability of such a mixture is probably not higher than that of the Friedland clay. However, since only about 20 % of the Friedland clay consists of montmorillonite its gelforming and self-sealing capacities may still not be better than those of a mixture with 30 % MX-80.

It can be assumed that the self-sealing capacity of Friedland clay compacted to the achievable dry density 1600 kg/m^3 (2000 kg/m^3 at saturation) is comparable to that of a mixture of 30 % MX-80 and crushed rock ballast compacted to the achievable dry density 1700 kg/m^3 (2070 kg/m^3 at saturation).

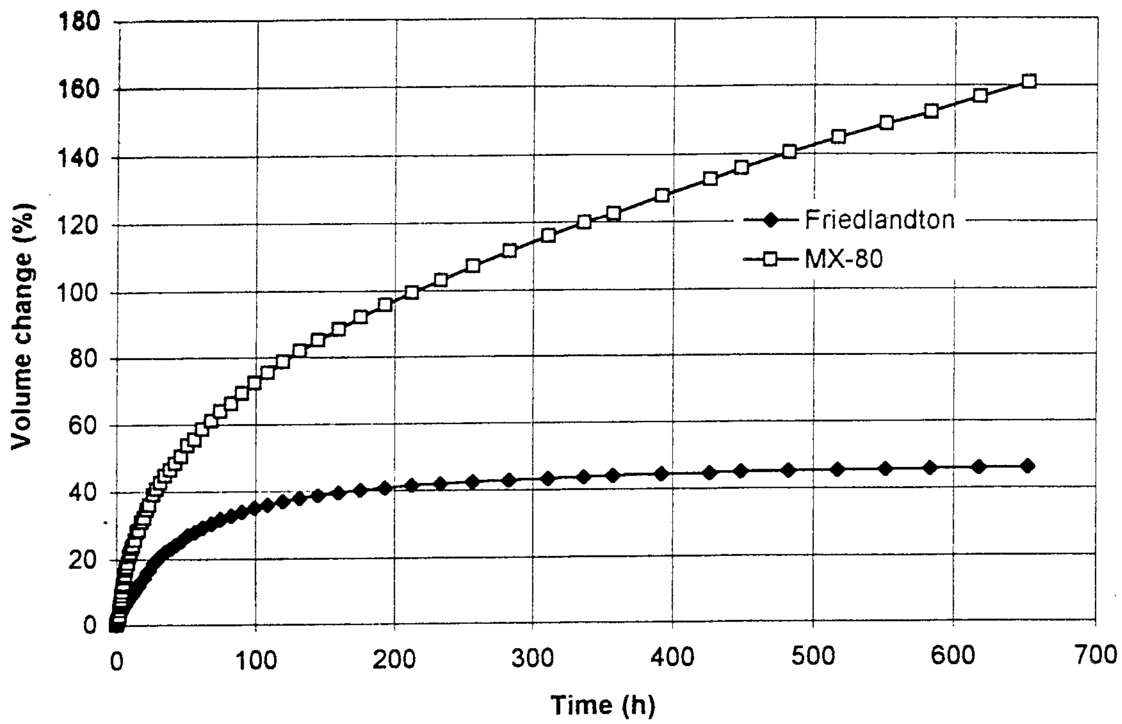


Figure 31. Expansion of saturated Friedland clay and pure MX-80.

6.8 Hydraulic conductivity

6.8.1 General

The relative amount of interlamellar (internal) water in clays with expandable minerals controls the hydraulic conductivity. The hydration potential of clay minerals is a good measure of the content of such immobile water and it is illustrated by the water content at different RH. Figure 32 shows that MX-80 has about twice the hydration potential of Friedland clay, which is in agreement with the mineral analyses. They demonstrate that the content of expandable minerals of MX-80 is about 75 % and about 45 % in Friedland clay, in which mixed-layer minerals with somewhat lower hydration potential dominate over the montmorillonite content.

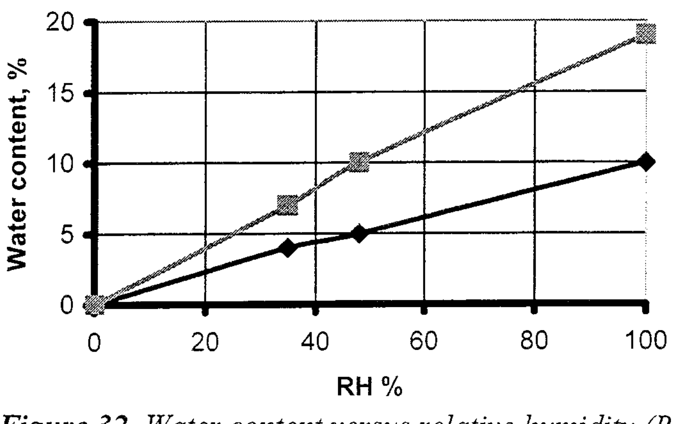


***Figure 32.** Water content versus relative humidity (RH) of the air in which air-dry powder of MX-80 and Friedland clay are stored. MX-80 is represented by the upper curve.*

6.8.2 Major differences between mixed backfills and Friedland clay

It is concluded from the laboratory studies that the evaluated hydraulic conductivity of mixtures of MX-80 and ballast varies strongly for any density, while data from the fewer Friedland clay tests indicate less variation. This is clearly related to incomplete filling of clay of the voids between the ballast grains in the mixtures and to significant variations in density of the clay component. In mixtures of MX-80 and crushed rock ballast fine debris prevents the clay from filling the void space and adhering to the solid ballast grains, which is believed to raise the bulk conductivity. At incomplete clay filling the risk of piping and erosion is also increased and it is therefore essential to obtain a high degree of clay filling of the voids between ballast grains, which is naturally more difficult for low bentonite contents.

No criterion has been set as to the required hydraulic conductivity of the backfill but taking the average hydraulic conductivity of the rock around the tunnels to be on the order of 10^{-11} m/s (excluding the excavation-disturbed zone) as in Stripa granite, backfills of 30 % MX-80 and crushed rock ballast mixtures with the achievable density 2070 kg/m^3 at saturation will not do, while Friedland clay fulfils the requirement. If the rock conductivity is 10^{-10} m/s, 30/70 mixtures saturated with strongly brackish water dominated by Ca will provide the same bulk conductivity as the rock, while Friedland clay backfill with a density of 2000 kg/m^3 at saturation will have a bulk conductivity that is 10 times lower than that of the rock. If the rock conductivity is 10^{-9} m/s, mixtures with 20 % MX-80 will do, while mixtures with 10 % MX-80 can not be accepted unless the rock conductivity is as high as about 10^{-7} m/s.

It is concluded that for any average hydraulic conductivity of the rock surrounding tunnels in the repository, backfilling with Friedland clay makes the tunnels tighter than the rock, while backfilling with mixtures of clay and ballast with up to 30 % MX-80 may turn them into major hydraulic conductors.

6.9 Chemical performance

The chemical data specified in sections 3.2.3 and 3.3.3 imply that the contents of SiO_2 and Al_2O_3 in the Friedland clay are about 10-15 % lower than that of MX-80 while the concentration of other elements are very similar. The clay components are hence comparable. Including also the ballast material in the mixed backfills the silica and aluminum concentrations will increase but also the amount of potassium, calcium and iron will be raised to higher values than those valid for Friedland clay.

As to the mineral content the differences in clay mineral content is the most obvious feature. Considering montmorillonite in the first place, Friedland clay has a slightly smaller amount than backfills with 30 % MX-80, which, theoretically, make the microstructure of the latter type of backfills more homogeneous.

However, the fact that Friedland clay also contains expandable minerals of other kinds (mixed layer minerals) the mineralogy of this clay is superior as manifested by the microstructural homogeneity as well as by the higher swelling pressure and lower hydraulic conductivity at the respective reference densities.

It is concluded that since potassium is an unwanted component and calcium contributes to replacement of initial sodium, and iron may be a source of cementation in the buffer, Friedland clay is superior to MX-80/ballast mixtures from a chemical point of view.

6.10 Cost

The total required mass for backfilling of tunnels and shafts in a KBS3 repository is on the order of 1000 000 tons. The approximate cost of MX-80 bentonite is 2500 SEK per ton per August 1998, which means that even backfills with only 10 percent bentonite cost well over 250 MSEK to which comes expenses for the major backfill component, handling and application. The total material cost for fully prepared backfill with 10 % bentonite will be at least 300 MSEK, while it rises to 800-1000 MSEK for mixtures with 30 % bentonite. Using cheaper commercial montmorillonite-rich bentonites the cost for 30 % clay mixtures may be brought down to 600-800 MSEK.

The alternative candidate material type, natural smectitic clay, represented by the Friedland clay in the present study, is clearly competitive. Thus, referring to the price offer given by the German manufacturer DURTEC in early 1998, the material cost will be 700 SEK per ton, i.e. about 700 MSEK for 1000 000 tons.

7 CONCLUSIONS

The comparison of the performance of backfills prepared by mixing MX-80 and crushed rock ballast on the one hand and Friedland clay on the other, shows that Friedland clay performs better than mixtures with 30 % MX-80, referring to the densities that should be achievable in practice. Mixtures with lower content of MX-80 will not fulfil the requirements specified in the report.

Considering cost Friedland clay prepared to yield air-dry powder grains is cheaper than mixtures of 30 % MX-80 and crushed ballast.

Both technically and economically it appears that the Friedland clay is a competitive alternative to mixtures of 30 % MX-80 and crushed ballast. However, it remains to be demonstrated on a full scale that Friedland clay ground to a suitable grain size distribution can be acceptably compacted on site.

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