R-06-71

Deep repository – engineered barrier systems

Assessment of backfill materials and methods for deposition tunnels

David Gunnarsson, Lena Morén, Patrik Sellin
Svensk Kärnbränslehantering AB

Paula Keto, Saanio & Riekkola Oy

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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This report is a result of a joint project between Posiva Oy, Finland and SKB.
This report will also be printed as Posiva Working Report 2006-64.

Executive summary

Objectives and delimitations

The main objectives of this report are to: 1) present density criteria considering deposition tunnels for the investigated backfill materials, 2) evaluate what densities can be achieved with the suggested backfill methods, 3) compare the density criteria to achievable densities, 4) based on this comparison evaluate the safety margin for the combinations of backfill materials and methods and, 5) make recommendations for further investigations and development work.

The aim of the report is not to make detailed descriptions of the different backfilling concepts.

Requirements and constraints

The design premises are divided into *requirements* and *constraints*. The requirements express the desired backfill functions and characteristics and the constraints are features, events and processes that have an impact on the design and constrain the possible solutions. The main function of the backfill in deposition tunnels is to sustain the multiple barrier principle by maintaining the safety functions of the individual barriers. To maintain this function the backfill in deposition tunnels shall:

- restrict advective transport,
- restrict upwards swelling/expansion of the buffer,
- not in other ways significantly impair the safety functions of the barriers,
- be long-term durable and its functions be preserved in the environment expected in the repository.

The capability of the backfill to maintain these safety functions is within performance assessments evaluated through the evolution of *function indicators* /SKB 2005/. A function indicator is a measurable or calculable quantity through which a safety function can be quantitatively evaluated. Given the constraints *function indicator criteria* shall be sustained throughout the long-term safety assessment period. Examples of constraints are:

- Groundwater salinity.
- Resulting water inflow and distribution (after grouting).
- Surface roughness of rock walls and floor that may be influenced by both the rock conditions and the excavation method.
- Geometry of the excavation to be backfilled.

The backfilling process must be technically feasible and its environmental impact and costs shall be as low as possible while fulfilling the safety functions mentioned above. Further the logistics should be adapted to the other repository operations and the equipment compatible with other equipment used in the repository.

In this report a *density criterion* to fulfil the *function indicator criteria* is stated for each investigated backfill material.

The function indicator criteria must not be confused with *design criteria*. Design criteria are measurable quantities through which the state of a component or sub-system at a specific occasion can be determined. They are used to determine the required characteristics at a defined occasion, e.g. the dimensions and weight of a backfill block just before installation. When determining the design criteria the constraints must be considered so that the function indicator criteria can be met throughout the assessment period.

Backfill methods

The backfilling methods considered in this report are compaction of backfill material in situ in the tunnel and placement of pre-compacted blocks and pellets.

Backfill materials

The materials investigated in the second phase of the SKB-Posiva backfilling project can be divided into three main categories:

1. Bentonite clays: two high-grade Na-bentonites from Wyoming (MX-80 and SPV200), one low-grade bentonite from Kutch (India Asha 230), and one high- and one low-grade Ca-bentonite from Milos (Deponite CA-N and Milos backfill). The high-grade bentonites are used in different bentonite-ballast mixtures.
2. Smectite-rich mixed-layer clays: one from Dnešice-Plzensko Jih (DPJ) located in the Czech Republic and one from Northern Germany (Friedland clay).
3. Mixtures of bentonite and ballast: Mixtures consisting of high-grade bentonite (30, 40 and 50 w-%) and crushed rock with different type of grain size distribution or sand.

Evaluation of the different combinations of materials and methods

The relationships between dry densities and hydraulic conductivity, swelling pressure and compressibility in saturated state for these materials were investigated. Most of the tests were performed with a groundwater salinity of 3.5%. This salinity is comparable to sea water and can be expected to be at the high end of salinities occurring during the assessment period. The purpose of the investigations was to determine the dry densities required to meet the function indicator criteria. These densities are referred to as the *density criteria*.

However throughout the assessment period a loss of material and thus density can be expected, consequently a safety margin in the installed dry density is required. At this stage of backfill development the achievable densities for alternative backfill concepts were investigated in order to estimate the safety margins for the considered backfilling methods. The resulting density criteria are presented in Table 1 together with the evaluated achievable densities and safety margins.

The general conclusion from the comparison between estimated achievable densities and the density criteria is that placing pre-compacted blocks of swelling clay or 50/50 mixture and pellets in the tunnel results in the highest safety margin.

Recommendations for further work

It is recommended that the continued work is focused on the development and testing of the block placing method using three different backfill materials, Friedland Clay, Asha 230 and mixtures of bentonite with different content of swelling minerals and crushed rock. The reason for focusing on the block placement method is that it is considered favourable since it seems feasible to achieve high average densities by block and pellet emplacement.

The materials recommended for further studies represent backfill materials with different amount of swelling minerals.

It should be stressed that these clays are examples of suitable backfill material. The development work will result in a specification for the backfill material. The specification may be expressed as relationships between density and the parameters swelling pressure, hydraulic conductivity and deformation properties. However, it is more likely that the specification will concern the type and fraction of swelling minerals and a list of contents that are not allowed or have to be under defined limits.

The continued work should be focused on understanding the effect of water inflow during backfill installation and the processes during saturation and homogenisation of the backfill. Further the technical feasibility of pre-compacted block and pellet installation should be investigated and assessed.

Table 1. The density necessary for different backfill materials to fulfil the density criteria in 3.5% salinity compared to estimated achievable densities. The density criteria to fulfil the requirement for compressibility are based on calculations by /Johannesson and Nilsson 2006/.

Material	Density criterion (kg/m^3)	Block concept		In situ concept	
		80% Filling degree, dry density		Achievable dry density from Proctor max: 85% (clays and 50/50) or 90% (30/70)	
		Density (kg/m^3)	Margin (kg/m^3)	Density (kg/m^3)	Margin (kg/m^3)
Asha 230	1,160	1,590	430		–
Milos B	1,240	1,640	400		–
DJP	1,400	1,690	290		–
Friedland	1,510	1,820	310	1,470	–40
30/70 bentonite/crushed rock (based on interpolated values)*	1,740–1,890	1,910–1,930	80–170	1,780–1,790	–60–+40
50/50 bentonite/crushed rock	1,560	1,780	220	1,540	–20

* Only results from mix 3 and 7 are used for the comparison since the density achieved to fulfil the criteria for these materials is based on interpolation and hence can be considered more reliable. Mix 1 is not used in the comparison since no blocks have been made and there is no base for estimating the achievable density. The margin expressed is for the individual 30/70 mixtures.

Contents

1 Introduction

The Swedish and Finnish repositories for spent nuclear fuel are planned to be excavated deep into crystalline bedrock. The radioactive material will be isolated from the biosphere by a multi-barrier system consisting of natural and engineered barriers, see Figure 1-1. Spent nuclear fuel is a poorly soluble ceramic material enclosed in metallic cladding assembled to fuel bundles. In a KBS-3V type repository, the spent fuel is packed into copper canisters with iron insert and placed into vertical deposition holes drilled in the floor of deposition tunnels. A buffer consisting of bentonite is placed around the canister. The function of the buffer is to restrict groundwater flow and to protect the canister. The deposition tunnels are backfilled and sealed so that the function of the barriers is not compromised and the deposition tunnels do not form water-conducting pathways in the repository. In practice this requires that the tunnel backfill shall have low permeability, low compressibility and sufficient swelling pressure to keep the contact between the backfill and the rock tight. In addition the backfill shall be long-term stable and have no harmful effects on the barriers.

This report belongs to the second phase of the joint SKB-Posiva project “Backfilling and closure of the deep repository” launched in 2003. The need for development arose from laboratory results showing that saline groundwater affect backfill characteristics /Karnland et al. 2005/. Using the installation method tested so far /Gunnarsson et al. 2004/ and a backfill material consisting of a 30/70 mixture of bentonite and ballast the backfill could maintain its functions if the groundwater salinity did not exceed 1% TDS. Since higher salinities may very well occur in the repository, SKB in cooperation with Posiva started to study the possibility to use alternative backfill materials and installation techniques. The project was divided into four major phases:

- Phase 1: desk studies to identify backfill concepts and select a few promising ones for further studies.
- Phase 2: preliminary experiments and more profound analyses to study the preferred concepts and for selection of a few main alternatives.

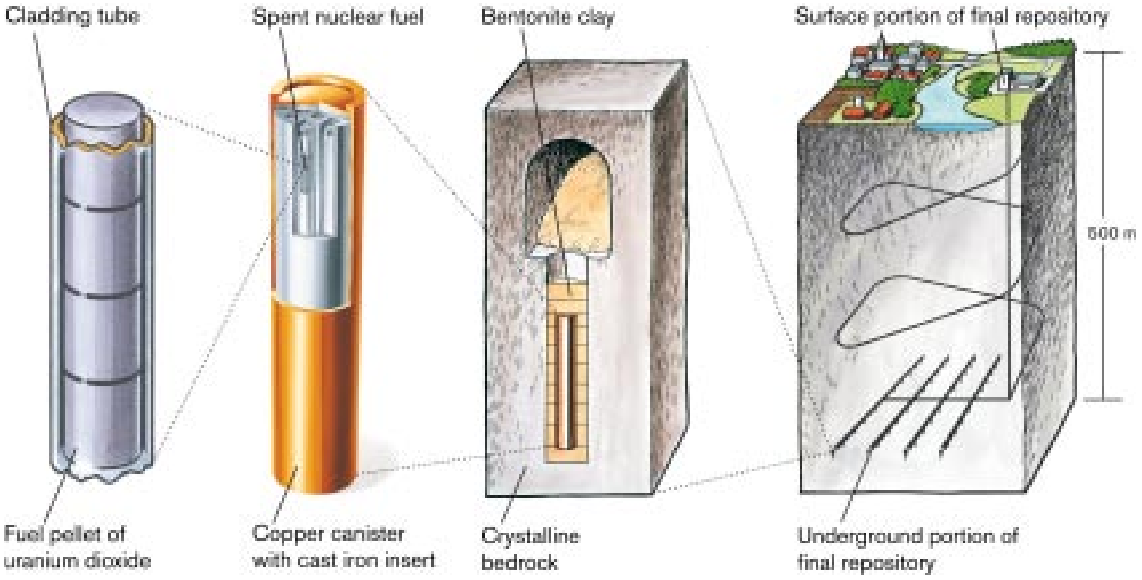


***Figure 1-1.** The KBS-3 multibarrier system.*

- Phase 3: pilot tests to assess feasibility.
- Phase 4: Large field-tests – overall verification and “dress rehearsal” of non-nuclear operation.

Six different backfill concepts were described and evaluated in phase 1 /Gunnarsson et al. 2004/. The backfill concepts chosen for further studies in phase 2 were based either on in situ compaction or on installation of pre-compacted backfilling blocks in the tunnel. The backfill materials included in the study were a variety of bentonite and smectite-rich clays and different type of mixtures of bentonite and ballast.

The main objectives of this report are to:

1. present density criteria for alternative backfill materials in deposition tunnels,
2. evaluate achievable installed dry densities for alternative combinations of backfill materials and installation methods,
3. evaluate the safety margin, defined as the difference between achievable dry densities and the density criteria for the investigated backfill concepts,
4. make recommendations for further investigations and development work

The analyses included in the report are based on work performed in the project and reported in the following reports:

- Geotechnical properties of candidate backfill materials for the deep repository /Johannesson and Nilsson 2006/.
- Piping and erosion of backfill material during installation /Sandén and Börgesson 2006/.
- Effect of material parameters on the compactibility of backfill materials /Keto et al. 2006/.

2 Design premises

2.1 General

The backfill comprise material and installation method used to seal rock cavities, tunnels and shafts in a KBS-3-repository. Different requirements may be put on the backfill in the different types of rock cavities, tunnels and shafts. The requirements and constraints accounted for in this report concerns the backfill in deposition tunnels in a KBS-3V repository. The main function of the backfill in deposition tunnels is to sustain the multiple barrier principle by maintaining the safety functions of the individual barriers.

As providing long-term safety is the main purpose of a final repository for spent nuclear fuel, the possibilities to fulfil the functional requirements related to safety and radiation protection is the primary objective of backfill design. This report is focused on investigating what densities are necessary to attain to sustain the backfill functions.

2.2 System requirements

A KBS-3 repository is a final repository for spent nuclear fuel where:

- The spent nuclear fuel is enclosed in water-tight and load bearing canisters.
- The canisters are deposited at 400–700 m depth in crystalline bedrock.
- The canisters are surrounded by a buffer preventing groundwater flow and protecting the canister.
- The rock cavities required to deposit the canisters are backfilled so that their functional characteristics are similar to those of the pristine bedrock.

In a KBS-3V repository which is a variant of a KBS-3 repository the canisters are deposited in vertical deposition holes drilled from the floor of deposition tunnels.

The design premises are divided into *requirements* and *constraints*. The constraints are features, events and processes that have an impact on the design and constrain the possible solutions.

Requirements expressing the functions and characteristics of the KBS-3 repository are referred to as *system requirements*, and requirements expressing the functions and characteristics the backfill, and other sub-systems, must have to fulfil the KBS-3 system requirements are called *sub-system requirements*. The backfill sub-system requirements are based on the following KBS-3 system requirements:

- Nuclear safety and radiation protection:
  - The safety functions shall be sustained by several barriers complementing each other.
  - The final repository shall be robust and reliable.
  - The safety functions shall be sustained as long as required considering the radiotoxicity of the spent nuclear fuel.

- Environmental impact
  - The final repository shall be efficient regarding consumption of raw material and energy.
- Flexibility and efficiency
  - The operation period shall be flexible and adopted to the nuclear power program.
  - The final repository shall be efficient regarding costs.

2.3 Backfill sub-system requirements

The backfill comprises of the material and the installation technique used to seal rock cavities, tunnels and shafts. The backfill is a part of the engineered barrier system. The role of the backfill is to maintain the multibarrier principle by sustaining the barrier safety functions.

Based on the above system requirements on a KBS-3 repository, the sub-system requirements on the backfill in deposition tunnels in the KBS-3 variant with vertical deposition KBS-3V are:

- Nuclear safety and radiation protection:
  - The backfill shall restrict advective transport in deposition tunnels so that the function of the bedrock is not impaired.
  - The backfill in deposition tunnels shall restrict the upwards swelling/expansion of the buffer so that the function of the buffer is not impaired.
  - Not in other ways significantly impair the safety functions of the barriers.
  - The backfill shall be long-term resistant and its functions shall be preserved in the environment expected in the repository.
  - The backfill shall be based on well-tried or tested technique.
  - The backfill properties shall be controlled against specified acceptance criteria.
- Environmental impact
  - The backfill shall be efficient regarding consumption of raw material and energy.
- Flexibility and efficiency
  - Backfill installation shall be possible to perform in the specified rate.
  - The backfill shall be cost efficient.

In order to design a backfill or to assess whether it fulfils the functional sub-system requirements the functions need to be expressed quantitatively or as measurable or calculable quantities or barrier conditions. For the functional sub-system requirements related to nuclear safety and radiation protection such measurable or calculable entities are referred to as *function indicators* and the quantitative value assigned to a function indicator is termed *function indicator criteria* /SKB 2005/. Function indicator criteria related to long-term safety and radiation protection are determined based on the results from the most recent long-term safety assessment of the repository.

For the backfill the following function indicator criteria regarding nuclear safety and radiation protection have been settled for the current phase of backfill design:

- To restrict advection of groundwater the hydraulic conductivity shall be less than 10^{-10} m/s.
- To prevent groundwater flow the swelling pressure shall be at least 0.1 MPa.
- To prevent loss of buffer density the compression modulus shall be at least 10 MPa.

The function indicator criteria must not be mixed with *design criteria*. Design criteria are measurable quantities through which the state of a component or sub-system at a specific occasion can be determined. They are used to determine the required characteristics at a defined occasion, e.g. the dimensions and weight of a backfill block just before installation. When determining the design criteria the constraints must be considered so that the function indicator criteria can be met throughout the assessment period.

Since the function indicator criteria have been considered to have high priority the work presented in this report is focused on investigating what densities are necessary to fulfil these criteria.

The function indicator criteria related to long-term safety and radiation protection are hence the basis for the backfill design. The criteria used for determining necessary density in this report, simply referred to as "criteria" in the report, are based on the function indicator criteria but have been slightly modified:

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

In this report the density necessary to fulfil all three criteria for a specific material is referred to as the *density criterion*.

The requirement on swelling pressure was increased to 200 kPa from the 100 kPa stated as function indicator criteria. The main reason for this was that it is easier to measure 200 kPa in the test set-up.

The function indicator for the compression properties of the backfill stated in SR-Can /SKB 2005/ is that the compression modulus should be at least 10 MPa. In this report a method of calculating the change in buffer density as an effect of backfill deformation is applied. The requirement used in this report is that the buffer must stay above the density limit 1,950 kg/m^3 at the top of the canister. This is defined as the lower density limit for the buffer defined in the SR-Can.

The function indicators are valid after the backfill has homogenised and been fully saturated and are valid for the entire tunnel volume.

Regarding flexibility and efficiency requirements the following has been settled:

In the Swedish system the backfilling rate shall be at least 6 m in 24 hours. In the Finnish system the effective backfilling rate is approximately 5 m/day. The current cross-section of the Swedish disposal tunnels is 25 m^3 /SKB 2006a–c/ while the cross-section of the Finnish disposal tunnels is 14 m^3. Therefore the installation capacity needs to be twice as fast for the Swedish system compared to the Finnish one.

At this stage of backfill design a backfill that can fulfil the above stated function indicator criteria and backfilling rate is developed.

For the non-functional sub-system requirements quantifiable measures for investigation of requirement fulfilment can not be formulated. If alternative solutions fulfilling the functional requirements are at hand, the possibilities to fulfil the non-functional requirements are investigated for each alternative. The alternative or alternatives that best corresponds to the full set of sub-system requirements is/are chosen for further development/implementation.

2.4 Constraints

The site-specific constraints involve:

- Total water inflow and distribution to the tunnels.
- Salt content of the inflowing water.
- Evolution of salt content of groundwater over time.
- Surface roughness of rock walls and floor that may be influenced by both the rock conditions and the excavation method.

Constraints from repository design are:

- Technical feasibility.
- Geometry of the excavation to be backfilled.
- The logistics should be adapted to the rest of the repository operation and the equipment should be compatible with other repository equipment.

More constraints will probably be added as the design evolves but these will be worked out as an optimisation of the repository system where the backfill operation is a part.

2.5 Design requirements

The backfill criteria will be used when defining the design requirements. These will be specific for the different combinations of site specific constraints, backfill materials and methods.

Examples of design requirements for the block placement method:

- Gaps between blocks, horizontal and vertical.
- Density and water ratio of blocks.
- Geometry of the volume filled with pellets.
- Bulk density and water ratio of the pellets after installation.
- Backfill rate for blocks and pellets.
- Variation in density over the cross-section (after saturation).

Examples of design requirements for the in situ compaction method:

- Variation in density over the cross-section.
- Backfilling rate.

This report is not directed at these design requirements. Except for the criteria used in this report there are a number of processes during backfilling, saturation and homogenisation that may be dimensioning for the design requirements. They may also be dimensioning for the requirements that the backfilling operation sets on the allowable water inflow to the tunnels.

3 Design method

3.1 General

The design of the backfill, and other sub-systems, is carried out in several steps or phases. As providing long-term safety is the main purpose of a final repository for spent nuclear fuel, the possibilities to fulfil the functional requirements related to safety and radiation protection are first investigated. Alternative concepts with potential to fulfil the safety and radiation protection requirements are designed. The alternatives considered to be best from a safety and radiation protection point of view are selected for further development. For alternatives considered to be technically feasible – i.e. to a large extent based on available and robust technique – the environmental impact, industrial welfare during preparation and installation, costs and efficiency are investigated. This stepwise development and successive comparison of alternatives is carried out to meet the requirement on optimization and to use best available technique to avoid harmful effects on man and environment.

3.2 Method applied in the current phase of development

The design method of the backfill in deposition tunnels applied in this phase of development can be summarised as follows:

1. Determine the dry density that is necessary to fulfil the criteria for the different investigated backfill materials.
2. Investigate alternative backfill installation methods.
3. Estimate the achievable installed dry densities for alternative combinations of materials and installation methods.
4. Determine the safety margin as the difference between maximum achievable dry densities and the dry density necessary to fulfil the criteria.

As it is likely that some backfill material, and thus density, will be lost during saturation and in the future during the assessment period, it is desirable that the dry density of the installed backfill is higher than the density criteria.

4 Backfill materials

4.1 Investigated materials

The materials investigated in the second phase of the SKB-Posiva backfilling project can be divided into three main categories: bentonite clays, smectite-rich mixed-layer clays and mixtures consisting of bentonite and ballast (see Sections 4.1.1, 4.1.2 and 4.1.3). The evaluated required densities for these materials in order to fulfil the performance requirements are presented in Section 4.2. These densities are based on the investigations performed and reported by /Johannesson and Nilsson 2006/.

4.1.1 Bentonite clays

The bentonite clays investigated in /Johannesson and Nilsson 2006/ were:

- High-grade commercial bentonite products (MX-80, SPV200 and IBECO Deponit CA-N) tested mixed together with ballast material.
- Low-grade non-commercial bentonites (Asha 230 and Milos backfill) tested without adding any ballast material to them.

MX-80 is an old trade name for a Na-bentonite produced in Wyoming (USA) by the American Colloid Company (Volclay). SPV200 is a product name for the same type Wyoming Na-bentonite. The only essential difference between the MX-80 and the SPV200 is the granule size distribution. The Wyoming bentonites formed during the Cretaceous period in hydrothermal alteration of volcanic ash /Elzea and Murray 1990/. Based on the semi-quantitative evaluation by /Carlson 2004/, the montmorillonite content of MX-80 bentonite is 80–85%. The accessory minerals present in MX-80 are quartz, cristoballite, feldspars and calcite /Carlson 2004/. The clay may also contain traces of gypsum, pyrite, illite and amphibole /Carlson 2004/. The dominant exchangeable cation in MX-80 bentonites is Na^+ /Carlson 2004/. The other exchangeable cations present are Ca^{2+}, K^+ and Mg^{2+} /Carlson 2004/. The cation exchange capacity (CEC) of MX-80 is between 80–110 meq/100 g depending on the test method /Carlson 2004/.

The Milos bentonites formed during the Tertiary period in hydrothermal alteration of volcanic rocks /Chirstidis and Scott 1996/. The montmorillonite content of high-grade Milos Ca-bentonites is 75–80% /Carlson 2004/. The other minerals present are calcite (5–15%), quartz (< 5%), plagioclase and pyrite. The dominant exchangeable cation in the non-activated version of this clay is Ca^{2+}, but also other cations (Na^+, Mg^{2+} and K^+) are present in smaller proportions /Carlson 2004/. The CEC determined with $BaCl_2$ method by /Carlson 2004/ was 74.5%. The IBECO Deponit CA-N is non-activated high-grade Ca-bentonite.

Two low-grade bentonite clays were sampled from commercial bentonite deposits occurring on the isle of Milos (Greece) and at the Kutch district in India. The assumption was that these bentonite clays would contain a little lower amount of smectite-group minerals than the high-grade bentonites quarried from the same deposits. These clays are available in large quantities and they should be relatively inexpensive compared to high-grade bentonites. Based on preliminary data by Clay Technology AB, the amount of swelling minerals in the Miloan clay (Milos backfill) is 50–60% and in the Indian clay (Asha 230) 60–65% /Johannesson and Nilsson 2006/. The Milos backfill is non-activated Ca-bentonite and the Asha 230 is natural Na-bentonite.

Simple physical quality check tests including determination of liquid limit and free swelling value were made both for the high and low-grade bentonite clays /Johannesson and Nilsson 2006/. In general, the liquid limit correlates with the plasticity (and content of smectite-group minerals) of clays /Terzaghi et al. 1996/. However, it should be noted that sodium bentonites usually give somewhat higher liquid limit values than calcium bentonites. The liquid limits determined for the different bentonite clays with fall-cone method by /Johannesson and Nilsson 2006/ were:

- > 500% and for the high-grade Wyoming Na-bentonites (MX-80, SPV200).
- 180% for the low-grade Indian Na-bentonite (Asha 230).
- 150–157% for the both bentonite samples from Milos (this result implies that the mineralogical differences between the low- and high-grade Miloan bentonites may be relatively small).

The corresponding normalized free swelling values for the samples were 17–21 ml (MX-80 and SPV200), 5.3 ml (IBECO Deponit CA-N), 5 ml (Milos backfill) and 8.4 ml (Asha 230). The normalized free swelling value does not necessarily have very good correlation with other physical properties of bentonites, but it can give an idea on the quality of the clays.

4.1.2 Smectite-rich clays

The smectite-rich mixed layer clays (DPJ and Friedland) were tested as raw-materials for pre-compacted blocks and no ballast was added to them. The main differences between smectite-rich clays and bentonite clays are usually in the origin (e.g. weathering of sediments), smectite-content and abundance of mixed layers consisting of illite/smectite or mica/smectite.

The clay named as DPJ was sampled from a place called Dnešice located at the Czech Republic. Based on semi-quantitative evaluation of bulk samples /Carlson 2004, Prikryl et al. 2006/, the smectite content of the clay varies from 20% to 66%. The smectite mineral is either montmorillonite or beidellite, and layers of illite are present between the smectite layers /Prikryl et al. 2006/. The other minerals present in the bulk samples are kaolinite (0–50%), illite, quartz and goethite /Carlson 2004, Prikryl et al. 2006/. The CEC of the clay determined with $BaCl_2$ and NH_4-acetate methods was 40–47% /Carlson 2004/. The exchangeable cations present are Ca^{2+} and Mg^{2+} /Carlson 2004/. The liquid limit of DPJ-clay tested in WP1 was 109% and the normalized free swelling was 4.8 ml /Johannesson and Nilsson 2006/.

The swelling component of the Friedland clay is mixed-layer mica/montmorillonite and the content is approximately 45% /Pusch 1998/. The other minerals present are quartz, mica, chlorite, feldspars and kaolinite /Pusch 1998, Carlson 2004/. The dominant exchangeable cation is Na^+ and the CEC of the clay varies from 35–45 meq/100 g depending on the test method /Carlson 2004/. The liquid limit of Friedland clay tested by /Johannesson and Nilsson 2006/ was 109% and the normalized free swelling was 7.7 ml.

4.1.3 Mixture of bentonite and ballast

Crushed rock with different type of grain size distributions was produced from Olkiluoto mica gneiss in order to study the effect of certain material properties on compactibility of the bentonite-ballast mixtures /Keto et al. 2006/. The same crushed rock was used in the study by /Johannesson and Nilsson 2006/. Also sand with uniform grain size distribution was used in both of these studies. The ballast names used in this report are:

- **Ballast A**: sand (0.1–1.2 mm).

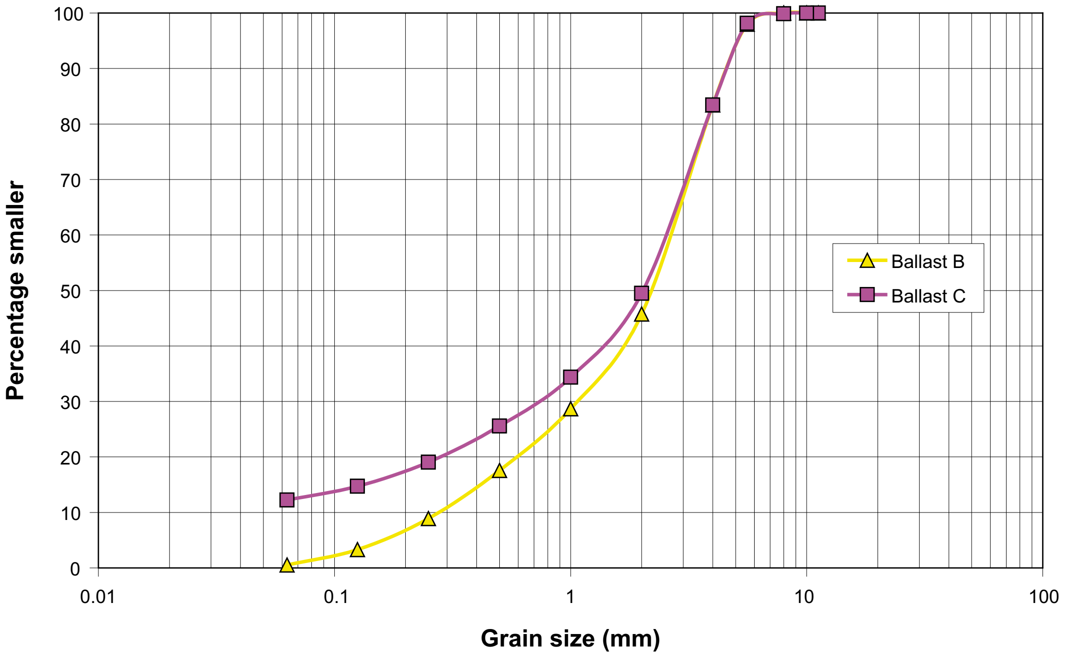


***Figure 4-1.** Grain size distribution of crushed ballast materials B and C (OL2b and OL2a in WP2).*

- **Ballast B**: crushed rock (0–5 mm), fine fraction 0%, see Figure 4-1 for grain size distribution.
- **Ballast C**: crushed rock (0–5 mm), fine fraction approximately 12%, see Figure 4-1 for grain size distribution.

A set of different type of mixtures were prepared in the studies reported in /Keto et al. 2006/ and in /Johannesson and Nilsson 2006/ with the aim to vary the:

- Bentonite content (30, 40 or 50%).
- Bentonite type (Na- or Ca-bentonite).
- Grain shape: sand versus crushed rock.
- Grain size distribution of the ballast material: comparison of ballasts A, B and C.

The effect of these parameters on the required densities is discussed in the following Section (4-2).

4.2 Required densities for the backfill materials in salinity of 3.5%

The different backfill materials studied in /Johannesson and Nilsson 2006/ can be divided into three main groups with respect to content of swelling minerals:

1) Bentonites (Asha and Milos backfill).
2) Smectite-rich clays (DPJ and Friedland clay) and mixture consisting of bentonite and ballast with proportions of 50:50.
3) Mixtures of bentonite and ballast (30/70 and 40/60).

The hydraulic conductivity and swelling pressure results for different backfill materials tested in 3.5% salinity by /Johannesson and Nilsson 2006/ are presented in Figures 4-2, 4-3, 4-4 and 4-5. In general, the hydraulic conductivity and the swelling pressure of bentonites and smectite-rich clays (Figure 4-2) depend on the smectite-content of the material and the results are in accordance with the division into the three groups presented above. For example, the results for Friedland-clay are relatively close to the results for mixture 5 with bentonite-ballast ratio of 50:50.

In general, the differences between the results for the 30/70 mixtures and for the 40/60-mixture are relatively small (see Figures 4-3 and 4-5). There is scatter between the swelling pressure and hydraulic conductivity results for different 30/70 bentonite/ballast mixtures. The effect of ballast materials is shown in the results for the 30/70 mixtures 3, 6 and 7 (with the same bentonite, but different ballast material). Better results are gained for mixtures with ballast C (crushed rock with 12% of fines) and A (sand) than with ballast B (crushed rock with no fine fraction). Preferably more data should be available to verify and explain the effect of ballast material on the properties of the mixture. The effect of bentonite type is shown in the results for the 30/70 mixtures 1, 2 and 3 with the same ballast material but different bentonite (MX-80, SPV or Deponit CAN). Except for the hydraulic conductivity results for mix 1, it seems that the results are a little better for mixtures with sodium bentonite than for the mixture 3 with Ca-bentonite. However, when comparing the results for other Ca-bentonite mixtures (6 and 7), the effect is not as clear (the effect of the ballast type may compensate the effect of the bentonite type). Mixtures 1 and 7 create very high swelling pressure (> 1 MPa) for high densities.

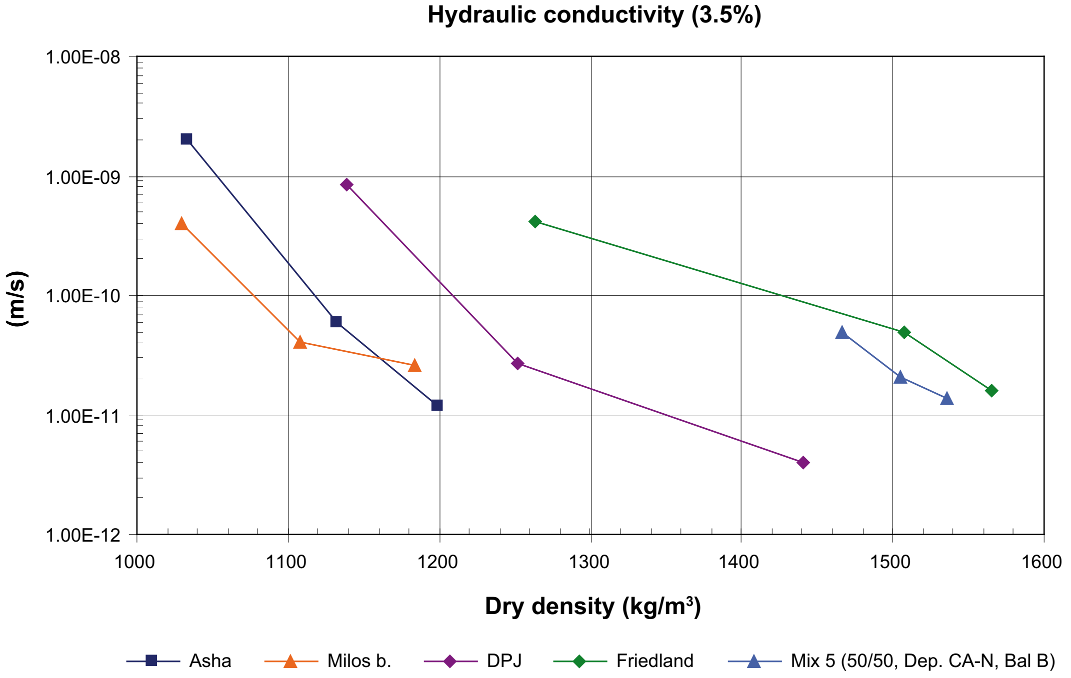


Figure 4-2. Hydraulic conductivity of low-grade bentonites (Asha and Milos), smectite-rich clays (DPJ and Friedland) and mix 5 consisting of ballast and bentonite (50:50). Data obtained from /Johannesson and Nilsson 2005/.

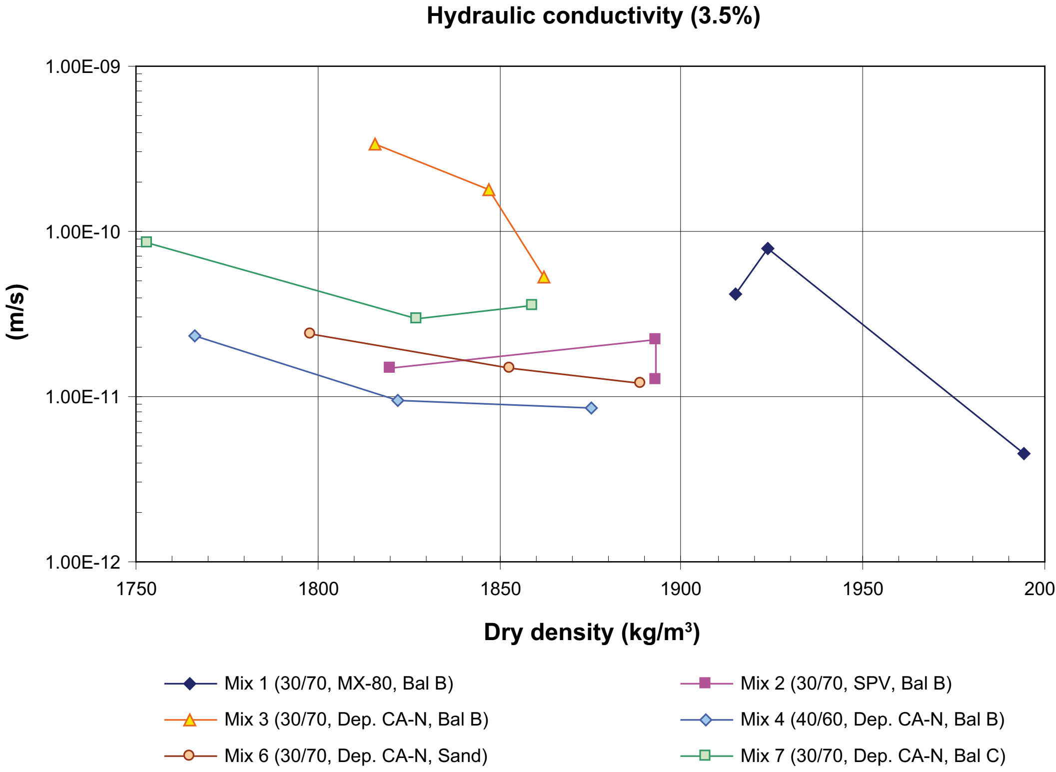


Figure 4-3. *Hydraulic conductivity of 30/70 and 40/60 mixtures /Johannesson and Nilsson 2005/.*

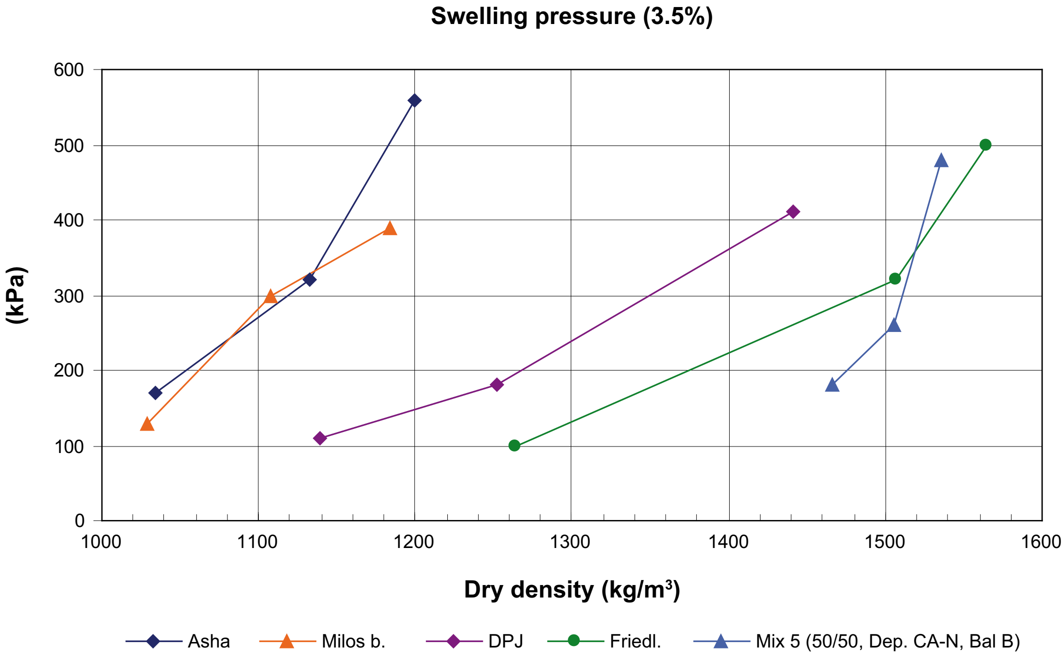


Figure 4-4. *Swelling pressure results for low-grade bentonites (Asha and Milos), smectite-rich clays (DPJ and Friedland) and mix 5 consisting of ballast and bentonite (50:50). Data obtained from /Johannesson and Nilsson 2005/.*

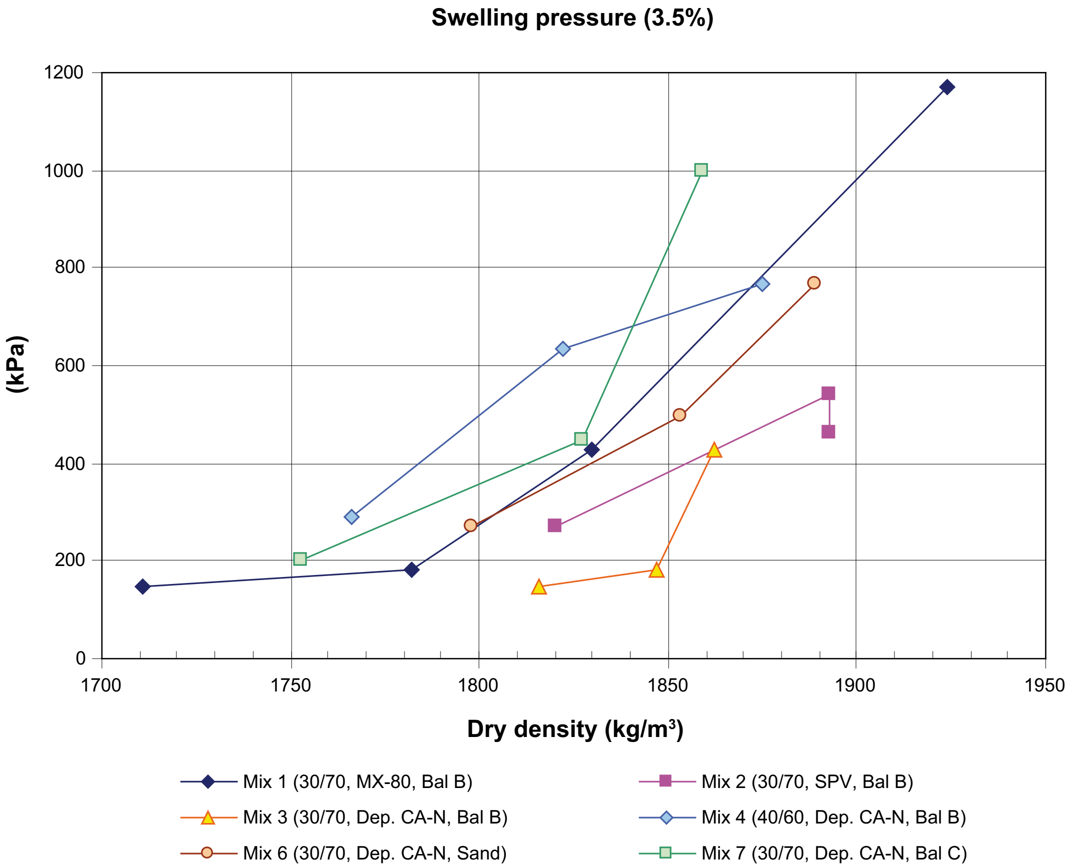


Figure 4-5. *Swelling pressure results for 30/70 and 40/60 mixtures /Johannesson and Nilsson 2005/.*

The compressibility results for different backfill materials are presented in Figures 4-6 and 4-7. The compression properties of bentonites and smectite-rich clays seem to depend mainly on the smectite content of the clay. The compression properties of the mixtures seem to depend on the bentonite ballast ratio of the mixtures. These conclusions are valid when these materials are in saturated state, since the compressibility tests were performed for saturated samples. The grain size distribution of the ballast material has no significant effect on the compressibility of the studied 30/70 mixtures.

Since the amount of swelling minerals has significant effect on the compressibility of saturated backfill materials, the compressibility of these materials in unsaturated state may be higher. This could present a problem in a worst-case scenario, where the buffer would reach saturation prior to the backfill material. Therefore, the deformation properties of these materials in unsaturated state need to be studied further in phase III.

The required dry densities in 3.5% salinity evaluated by /Johannesson and Nilsson 2006/ are presented in Table 4-1. See Chapter 2 for the criteria that were used as basis for determining the required dry densities.

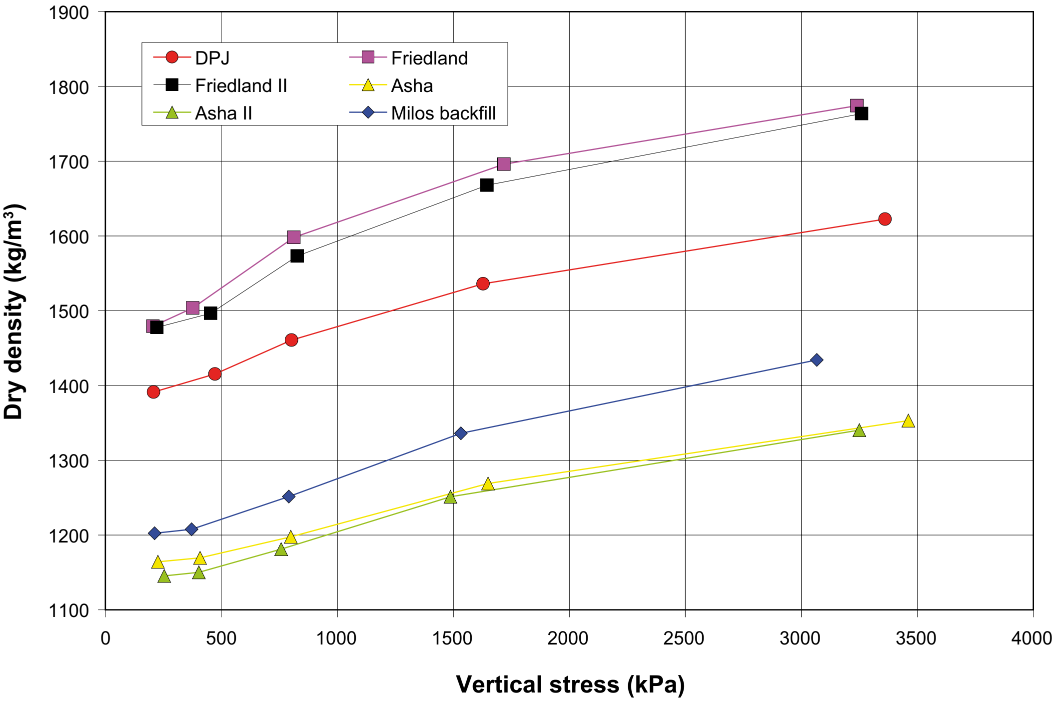


Figure 4-6. *Oedometer results plotted as a function of dry density for low-grade bentonites (Asha and Milos backfill) and smectite-rich clays (DPJ and Friedland clay) /Johannesson and Nilsson 2005/. The compressibility of these materials (in saturated state) depends on the amount of swelling minerals.*

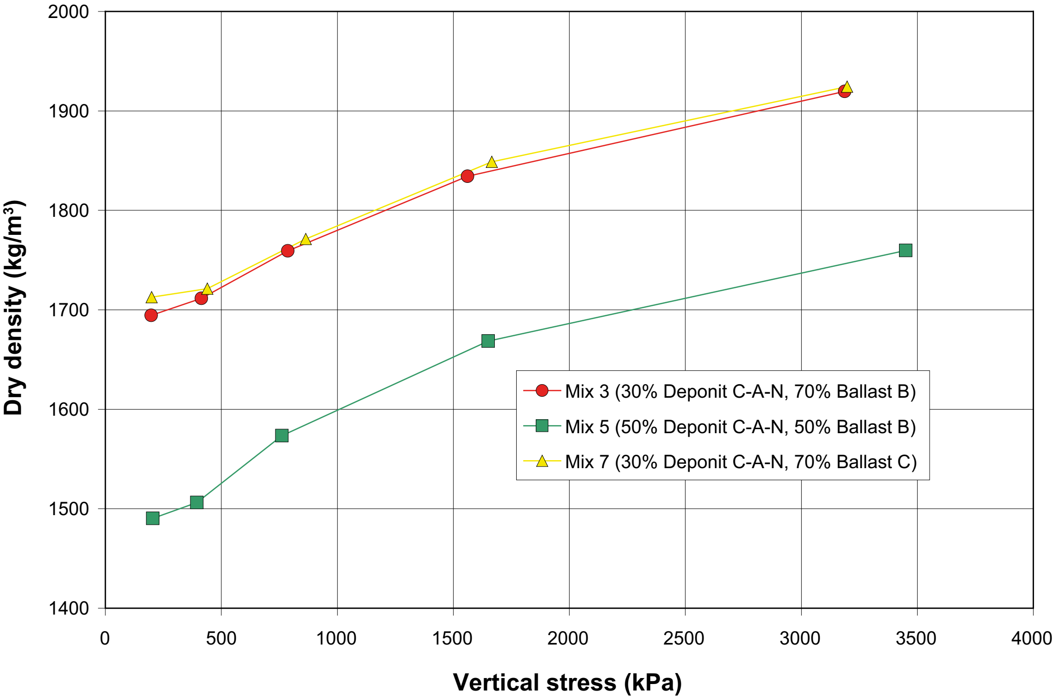


Figure 4-7. *Oedometer results plotted as function of dry density for three types of bentonite ballast mixtures (30/70 and 50/50) /Johannesson and Nilsson 2005/. The compressibility of bentonite-ballast mixtures (in saturated state) depends on the bentonite ballast ratio of the mixture.*

Comparison of the results presented in Table 4-1 and the previous tests results on mixture of ballast and bentonite (30/70) and on Friedland clay was done in /Johannesson and Nilsson 2006/. In general, the previous swelling pressure and hydraulic conductivity test results are in relatively good accordance with the new results and the differences can be explained with the differences in the material properties (e.g. the maximum grain size) and in the test method (size of the test cell and salinity of the percolating water) /Johannesson and Nilsson 2006/.

Parallel hydraulic conductivity tests were performed for the similar type of 30/70 mixtures in /Keto et al. 2006/. In these tests, the maximum grain size of the ballast material was 10 mm (instead of 5 mm), the tests were performed in a large test cell with a flexible wall permeameter, and the samples were compacted to 95% from the maximum Proctor dry density (> 1,900 kg/m^3). The hydraulic conductivity of all 30/70 samples tested remained below 1E–10 m/s /Keto et al. 2006/. The results are in accordance with the results in /Johannesson and Nilsson 2006/.

Based on the data in Table 4-1, compressibility is the material property determining the required dry density for the pure clays (bentonite clays and smectite-rich clays) and for the 50/50 mixture. For the other mixtures (30/70 and 40/60) the determining property is either the hydraulic conductivity or the swelling pressure. In general, the required dry density is lower for the clays than for the bentonite ballast mixtures. The difference between the required dry density for the 40/60 mixture and the 30/70 mixtures is relatively small. The difference between the 50/50 mixture and the 30/70 mixtures is more distinct.

In practice, the dry density for each backfill material should be somewhat higher than its target density presented in Table 4-1 in order to increase robustness of the system. How high the safety margin should be, needs to be evaluated in the next research phase. It should be noted that when compacting mixtures in the tunnel, the achievable density decreases with increasing bentonite content. The achievable dry density over the cross-section of the tunnel with both in situ and pre-compacted blocks is evaluated in Chapter 5.

Table 4-1. The required dry densities for different backfill materials in order to fulfil the performance requirements for 3.5% TDS based on phase II laboratory studies by /Johannesson and Nilsson 2006/.

Material-types	**Required dry densities (kg/m^3) based on:**		
Bentonite clays	**Hydraulic conductivity**	**Swelling pressure**	**Deformation properties**
Asha 230	1,120	1,050	**1,160**
Milos backfill	1,090	1,060	**1,240**
Smectite-rich clays:			
Friedland	1,400	1,350	**1,510**
DJP	1,220	1,240	**1,400**
Mixtures of bentonite and ballast:			
30/70-mixtures	1,700–1,890*	1,730–1,800	1,690
40/60 mixture	~ 1,670	~ 1,740	–
50/50 mixture	1,280	1,450	**1,560**

*Based on interpolated results for mixtures 1, 3 and 7.

4.3 Uncertainties

4.3.1 Long-time degradation

Mineral alteration

The advantageous physical properties of the backfill, e.g. swelling pressure and low hydraulic conductivity, are determined by the interaction between water and the montmorillonite mineral in the material. Other minerals with the same principal structure but different layer charge occur in nature. If the layer charge is near zero (pyrophyllite), there is virtually no interaction with water, which results in radically different properties than for montmorillonite. Minerals with higher layer charge and thereby more balancing cations may lead to greater interaction with water. However, the cations can be bound to the mineral surfaces if the layer charge is sufficiently high, and the interaction with water ceases.

Transformation from montmorillonite to illite is well documented in several different geological formations, and has been reproduced under laboratory conditions. However, illite is not a well defined material, and may be seen as a transition material from montmorillonite to mica minerals. All intermediate stages from swelling to non-swelling material may be found (mixed layer smectite-illite) and several models have been suggested in order to describe the reaction. The conversion always involves a charge increase, mainly due to a decrease in silica content and an uptake of charge compensating potassium ions.

The overall kinetics of the smectite-to-illite reaction can be described by:

$$-dS/dt = A \times [K^+] \times S^2 \times \exp(-E_a/RT),$$

where S is the smectite fraction in the illite/smectite material, A is frequency factor, E_a is activation energy, R is the universal gas constant, and T is temperature /Huang et al. 1993/. After integration of the above equation, the smectite content at a certain time can be calculated if the temperature and potassium concentration in the pore water are known. According to the model, practically no clay conversion is possible in a KBS-3-type repository at these conditions as shown in Figure 4-8.

Based on this it is clear that no alteration of the smectite to illite in the backfill will occur, even at timescales of 1 M years.

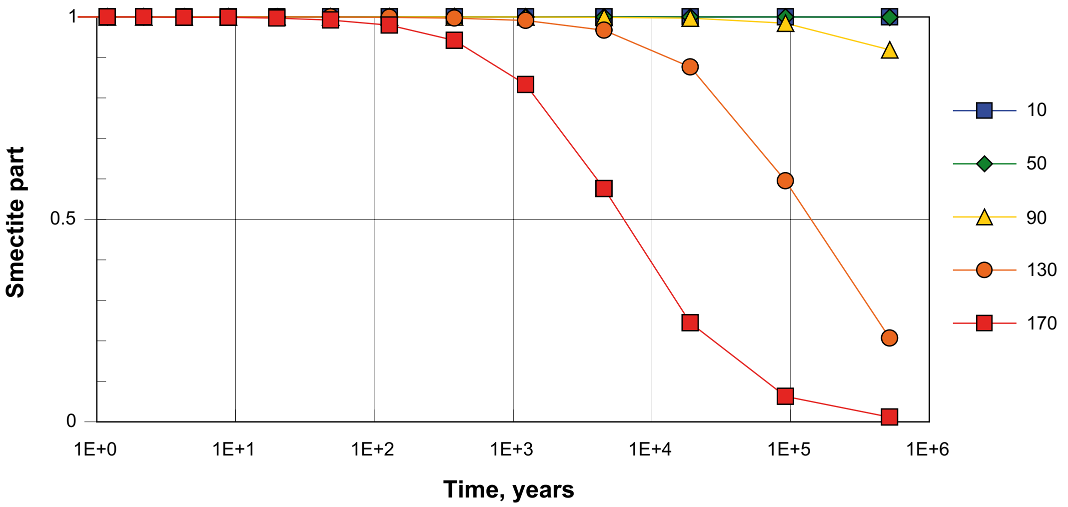


Figure 4-8. *Remaining smectite part for different temperatures in a hydrothermal system with $[K^+]$ = 0.002 mole/litre (80 ppm) according to the Huang et al. (YEAR) kinetic model and laboratory determined constants (E_a = 27.4 kcal/mole and $A = 8.5 \times 10^{-4}$) /Karnland et al. 1995/.*

Chemical erosion

Two possible types of erosion have been identified for the bentonite materials. The first is mechanical erosion where a shear stress from the flowing water in a fracture can remove clay particles from the buffer. The second is chemical erosion where the clay particles are dispersed into the groundwater.

From a mechanical point of view the shear stress exerted by the flowing groundwater is much less than the typical Bingham yield stress (1.0 Pa) of the gel front. It can thus be concluded that the bentonite buffer is physically stable with respect to the tearing off by the shear force exerted by the flowing groundwater on the gel front /Liu and Neretnieks 2006/.

When the montmorillonite in the bentonite buffer is in contact with water, a clay gel may form. If the ionic strength of the water is lower than the critical coagulation concentration (CCC) of the montmorillonite, the gel may disperse into a colloid sol in the water. The relatively abundant divalent cations, especially Ca^{2+}, are of great importance since the CCC is inversely proportional to the square of the valence number. For pure Na-montmorillonite, the clay will disperse readily in waters having concentrations lower than the CCC.

In SR-Can the loss of buffer is calculated with a model developed in /Liu and Neretnieks 2006/. According to the model, losses occur when the concentrations of cations in the groundwater falls below the CCC. In practice, the concentration of Ca^{2+} ions will determine if this is the case. The model further predicts that the loss rate depends linearly on the difference CCC-$[Ca^{2+}]$ and on the equivalent flow rate Qeq.

The same type of modelling as described above could be done for the backfill as well. A DFN model can produce equivalent flow rates and fracture spacing for the tunnel. The results from this together with data on the backfill geometry and composition make it possible to calculate rates of erosion. This has not been done yet. Erosion of backfill is considered to be a smaller problem compared to erosion of the buffer, since the volume of the backfill is much larger. A small loss of material would not have a large impact on the overall backfill properties.

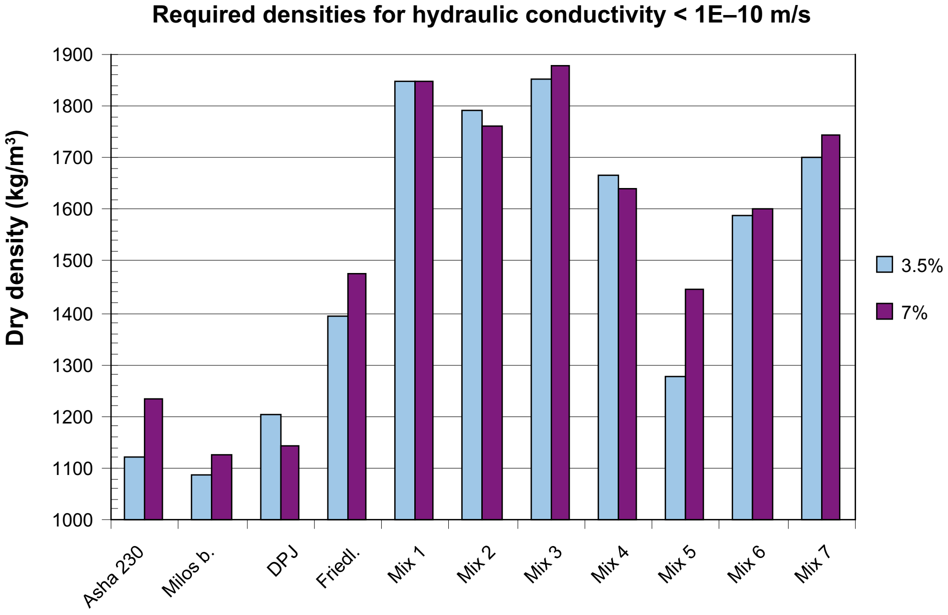
4.3.2 Uncertainties of laboratory results

It is considered that the methods used for determining the density criteria in the study by /Johannesson and Nilsson 2006/ give good indications on the relationship between dry density and hydraulic conductivity, swelling pressure and compression properties. However, it is not possible to estimate the accuracy of the density criteria, since the amount of samples studied was limited and more tests should be performed to be able to do the estimation.

The scatter observed in the hydraulic conductivity results for the 30/70-mixture may be due to insufficient homogeneity due to poor mixing technique /Johannesson and Nilsson 2006/. Therefore, the effect of mixing technique should be further investigated. Significantly higher hydraulic conductivity was measured for mixture 1 compared to the other mixtures. In addition to heterogeneity of the sample, the reason for this could have been in boundary flow between the sample and the cell and/or piping. The risk of piping or boundary flow and how this is affecting the hydraulic conductivity should also be further investigated. The sizes of the samples tested by /Johannesson and Nilsson 2006/ were relatively small (Ø 50 mm, h 20 mm). However, the results gained with this method were to be comparable with the results gained with another method in a larger test cell (100 mm) /Keto et al. 2006/.

4.3.3 Sensitivity to changes in salinity and density

The hydraulic conductivities and swelling pressures were also measured in salinity of 7% /Johannesson and Nilsson 2006/. Based on the evaluated density criteria considering hydraulic conductivity both in 3.5% and 7% (Figure 4-9), the increase in salinity has the highest effect on Mix 5 (mixture of ballast and bentonite, 50/50), on low-grade bentonite Asha 230 and on Friedland-clay. The reason for the significant effect on Mix 5 cannot be explained with the available data. The effect on the latter two ones may be due to enhanced



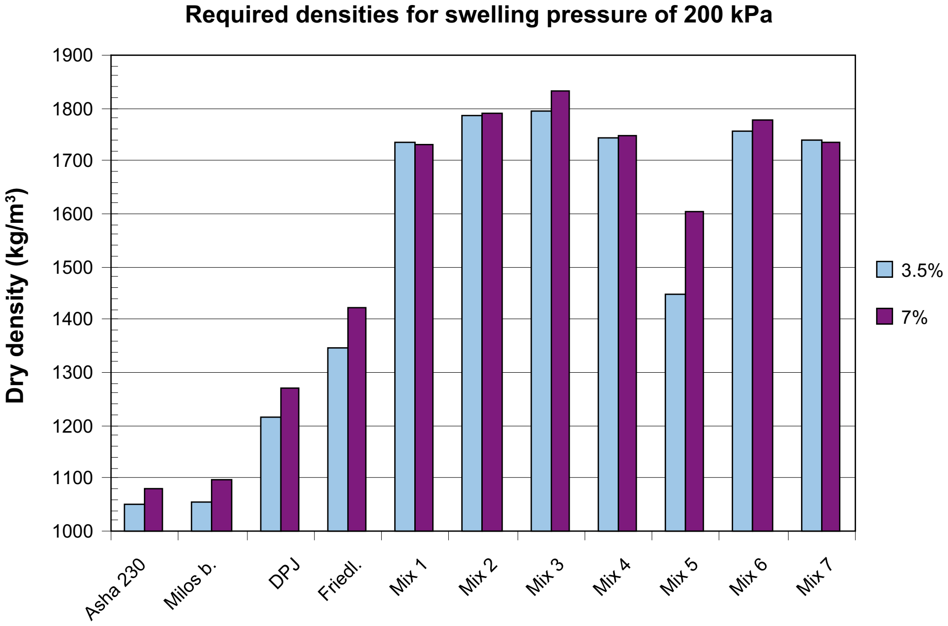


Figure 4-9. *The effect of increase in groundwater salinity to the evaluated density criteria concerning hydraulic conductivity < 1E–10 m/s and swelling pressure > 200 kPa /Johannesson and Nilsson 2005/.*

ion exchange, since both of these clays assumingly have sodium as the dominant exchangeable cation and the water used in the test contained both Ca^{2+} and Na^{+} ions in proportion of 50:50. For all the other backfill materials the effect of increasing salinity on the density criteria (concerning hydraulic conductivity) is relatively small and in some cases even reverse. However, when observing the hydraulic conductivity results plotted as a function of dry density (see Figures 4-10), it can be seen that the increase in salinity has a distinctive effect on all of the backfill materials, although in some cases the effect on the density criteria may be insignificant.

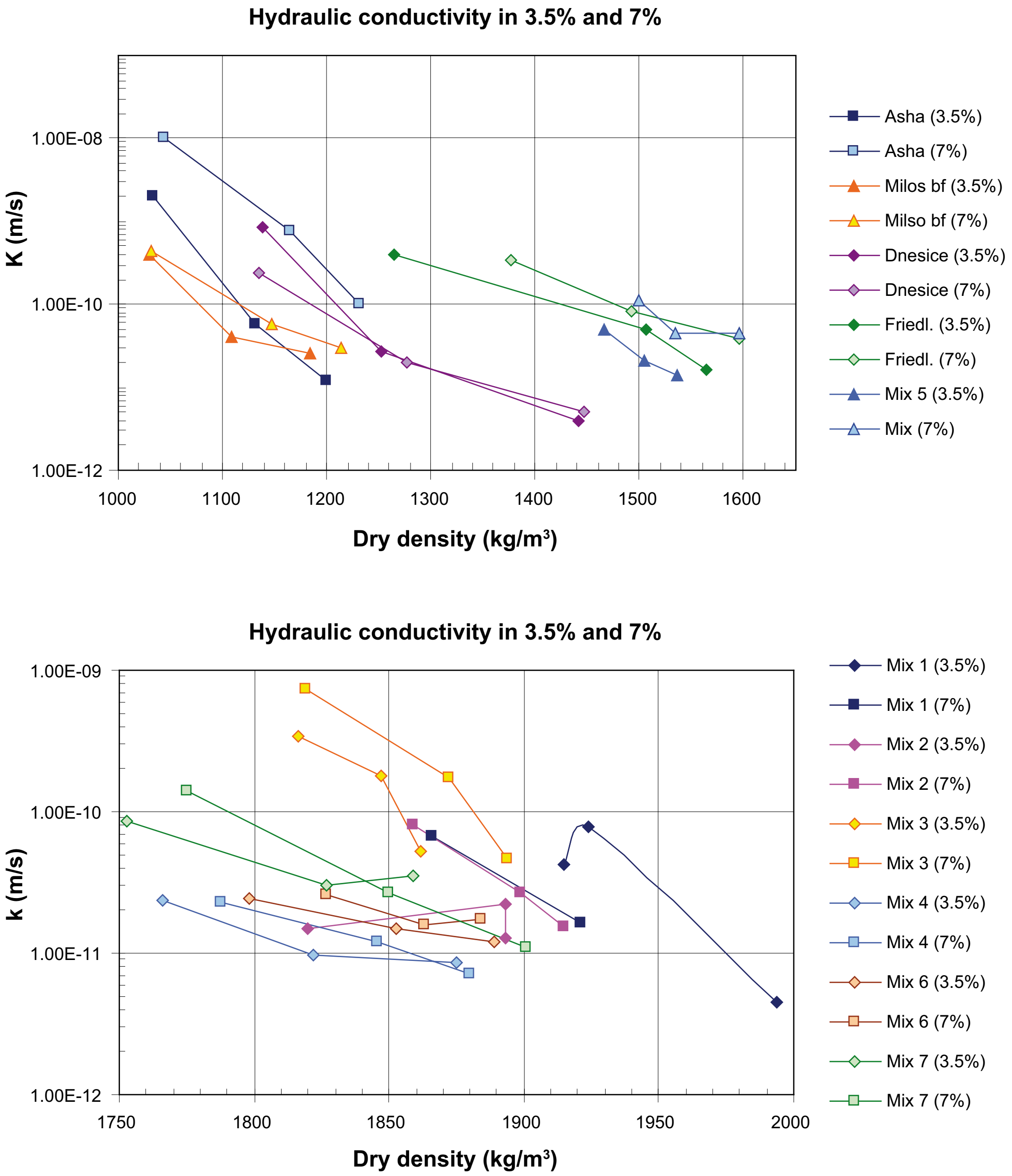
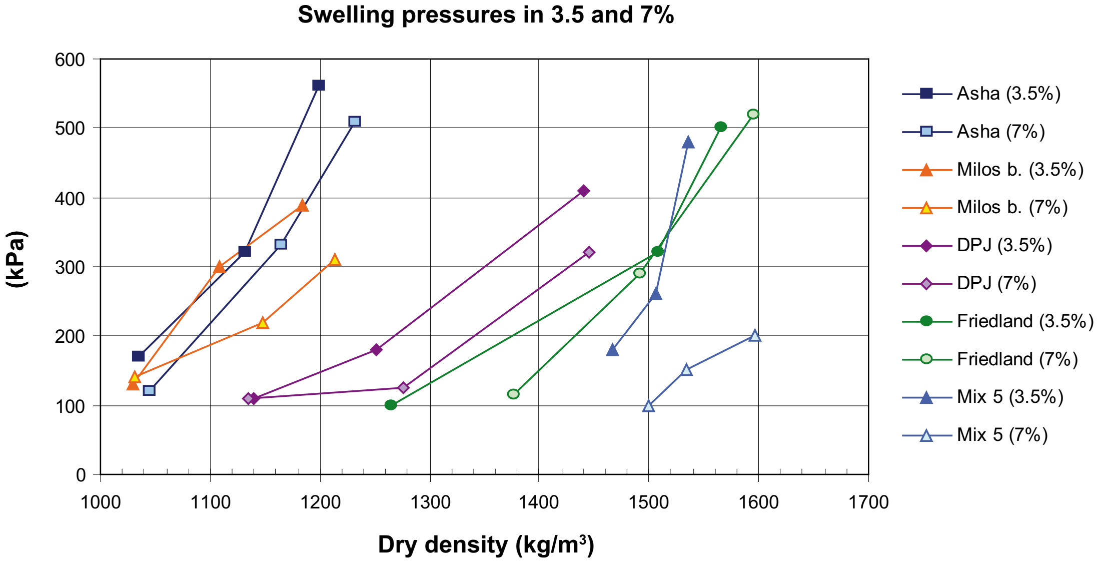


***Figure 4-10.** The hydraulic conductivity results in salinity of 3.5% and 7%. Data obtained from /Johannesson and Nilsson 2005/.*

Based on Figure 4-9, the increase in salinity has the biggest effect on the estimated required dry densities (concerning swelling pressure) of Mix 5 and of the smectite-rich clays from Czech (DPJ) and Germany (Friedland clay). For all the other materials, the corresponding effect is relatively small or insignificant. Once again when comparing the swelling pressure results plotted on a graph, the effect of increasing salinity can be observed for all of the samples.



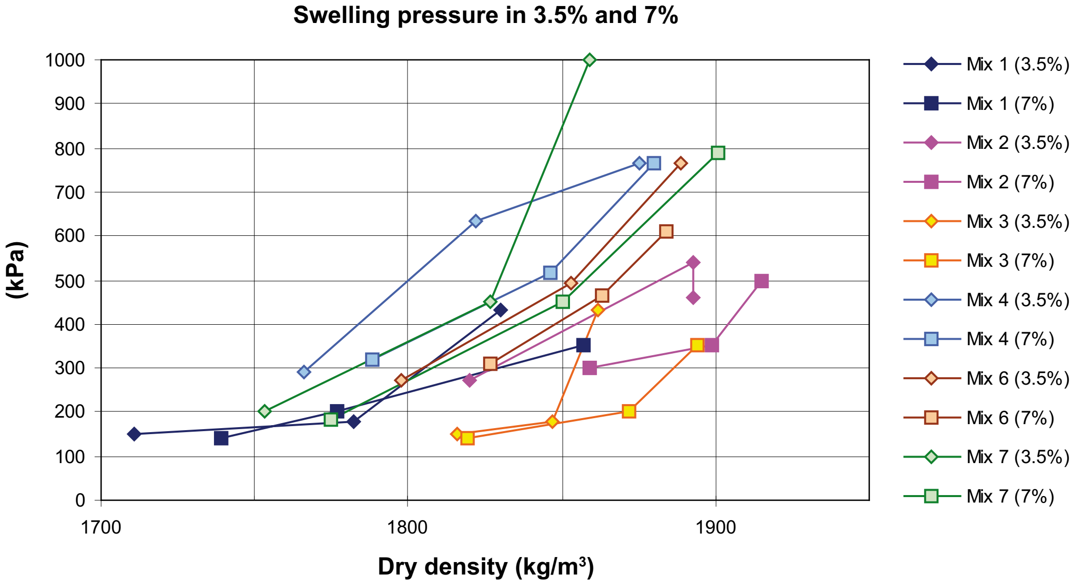


Figure 4-11. *The swelling pressure results in 3.5% and 7% salinity. Data obtained from /Johannesson and Nilsson 2005/.*

The effect of increasing salinity on the deformation properties was not studied in phase II. However, it is probable that if the swelling pressure of the material is affected by the increased salinity, the effect is also seen in the deformation properties. This may be the case especially with the 50/50 mixture.

Comparing the sensitivity of the materials to change in density is not very simple due to limited amount of laboratory tests and the scatter in the results and due to apparent non-linear dependence of dry density and hydraulic conductivity/swelling pressure results for some of the samples (see Figures 4-12 and 4-13). In principle, the steeper the inclination of the curve is, the more sensitive the material properties are to decrease in density. Based on Figure 4-12, mixture 1 may be somewhat more sensitive in this respect than the other materials. In general, the swelling pressure of the mixtures seems to be a little more sensitive to drop in density than the swelling pressure of bentonites and smectite-rich clays (Figure 4-13). No other conclusions on this issue can be made. Preferably more data should be available to verify the trends.

Based on Figures 4-10 and 4-11, the sensitivity of hydraulic conductivity/swelling pressure to the drop in density does not seem to depend very much on the salinity of the water, since the differences between the inclination and shape of the curves in 3% compared to 7% are insignificant.

There are no significant differences between the shape and inclinations of the compressibility curves for different backfill materials (see Figures 4-6 and 4-7). Therefore, it is not possible to separate materials based on their sensitivity to decrease in density with respect to compressibility.

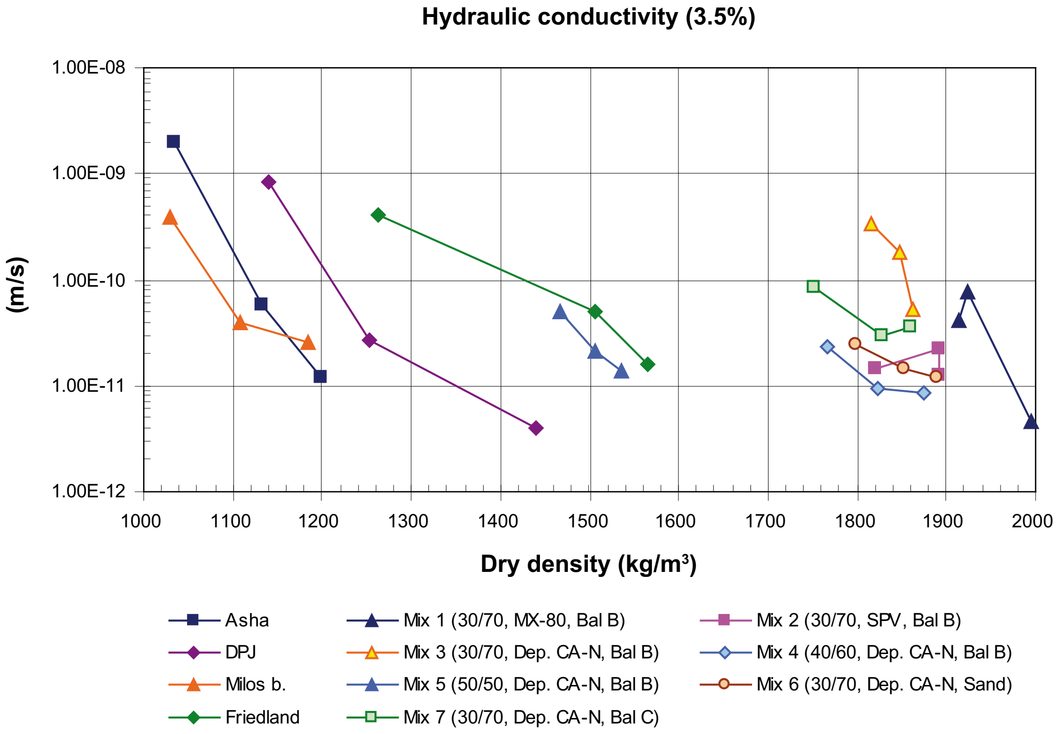


***Figure 4-12.** The steeper the inclination of curve is the more sensitive the hydraulic conductivity of the material is to drop in dry density. Data obtained from /Johannesson and Nilsson 2005/.*

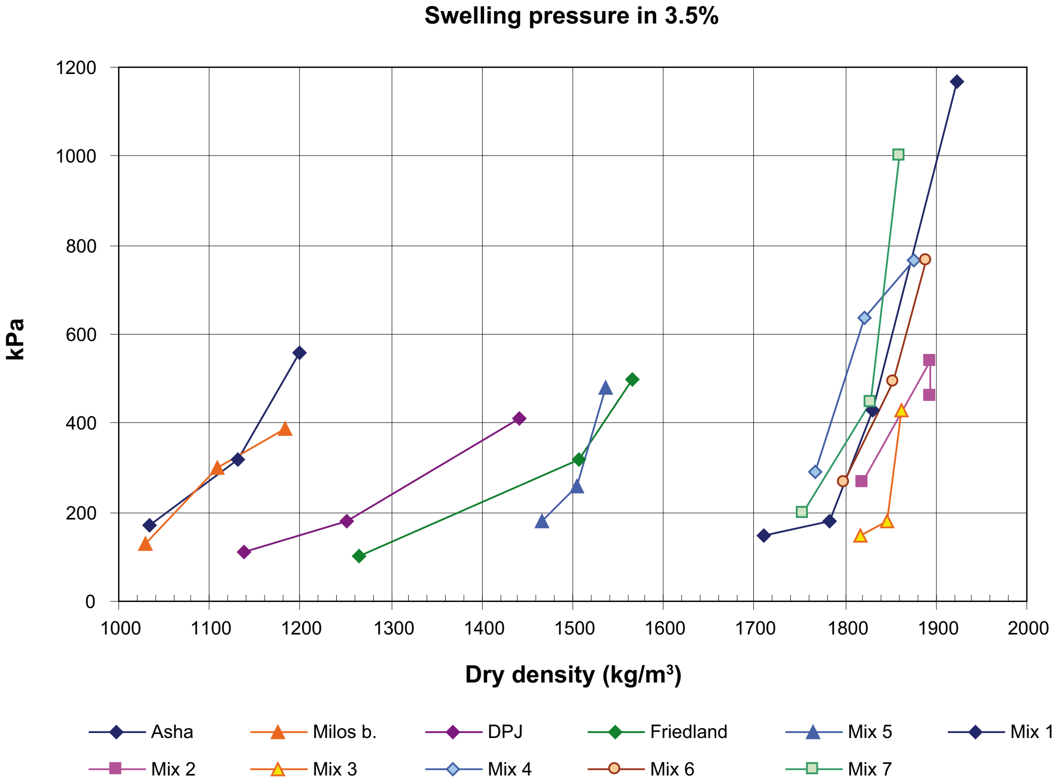


Figure 4-13. *The steeper the curve is the more sensitive the swelling pressure of the material is to drop in dry density. Data obtained from /Johannesson and Nilsson 2005.*

4.3.4 Discussion

The uncertainties concerning the density criteria for different backfill materials are:

- Compressibility of the backfill materials in unsaturated state and in higher salinity than 3.5%.
- Uncertainties in the laboratory results /Johannesson and Nilsson 2006/ used for evaluating the required densities: separation of mix 1 during the oedometer test, limited amount of tests per material and the effect of the size of the test cell. However, the results seem to be in accordance with the results gained with another method and with a large test cell /e.g. Keto et al. 2006/.
- The effect of ballast material in different 30/70 mixtures. The 30/70 mixtures with ballast B (crushed rock with no fine fraction) had poorer hydraulic conductivity and swelling pressure results than mixtures with ballast A (sand with uniform grain size distribution) or with ballast C (crushed rock with 12% of fines). Is there a difference in the homogeneity of these mixes or is the result only a coincidence? The amount of fine fraction in the ballast material could explain the difference in the hydraulic conductivity when comparing the results for mixtures 3 and 7 (with ballast B and ballast C), but not the difference between mixtures 3 and 6 (with ballast B and A). The differences in the compactibility of these mixtures were relatively small /Keto et al. 2006/, although the maximum dry density of the mixture with sand as a ballast material was a little lower than for the mixtures with crushed rock as a ballast material. In order to study the effect of the ballast material on the hydraulic conductivity and swelling pressure of the bentonite ballast mixtures further, tests should be performed for different mixtures in the same dry density.

- Why is the 50:50 mixture so much more sensitive for the increase in salinity from 3.5% to 7% than the other bentonite ballast mixtures? Based on the effective clay dry density presented for the mixtures in /Johannesson and Nilsson 2006/, the situation should be vice versa.
- Long-term stability of different material properties.

5 Backfilling methods

5.1 Backfilling with pre-compacted blocks

5.1.1 Description of the method

In this backfilling method the backfill materials are compacted into blocks and pellets prior to their installation into the disposal tunnel. The blocks are piled in the tunnel and the volumes remaining between the blocks and rock walls are filled with pellets.

Pressing of blocks and pellets

In case the chosen backfill material consists of clay, the material is delivered with a water ratio and granule size distribution suitable for block pressing. Alternatively the water ratio is adjusted in the production facility at the site. In case the material consist of mixture of bentonite and ballast, the mixing of the components need to be performed prior to the block pressing.

The manufacturing of blocks has been tested both in laboratory and in industrial scale. In the laboratory-scale tests, two different compaction pressures (25 and 50 MPa) and multiple water ratios were used in order to determine the optimum water content and maximum dry density for the blocks /Johannesson and Nilsson 2006/. The results achieved for the candidate backfill materials are presented in Figures 5-1 and 5-2.

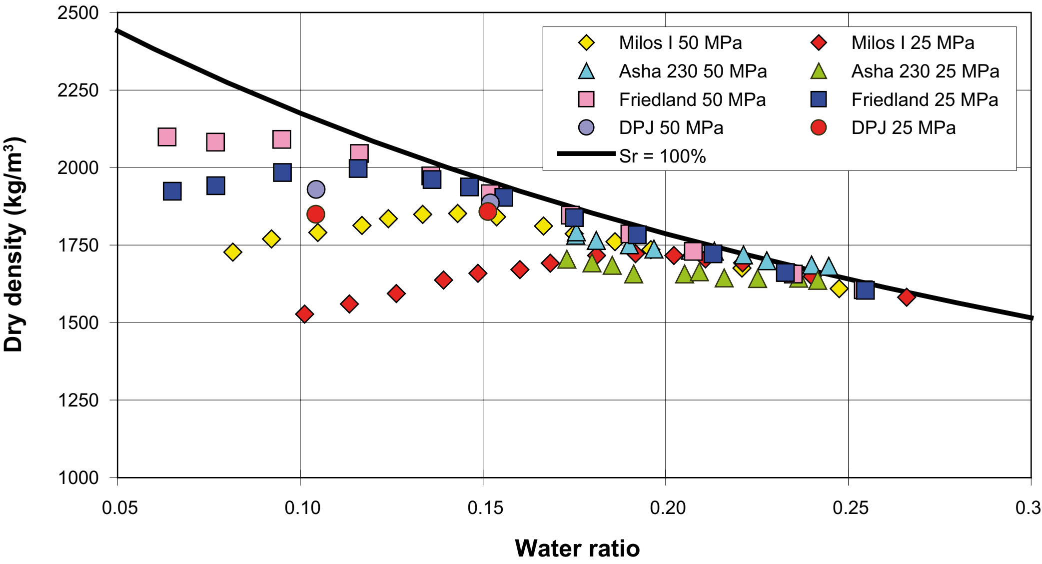


Figure 5-1. *Dry density plotted as function of water ratio for three clays compacted at two different compaction pressures (50 and 25 MPa). Plot from /Johannesson and Nilsson 2005/.*

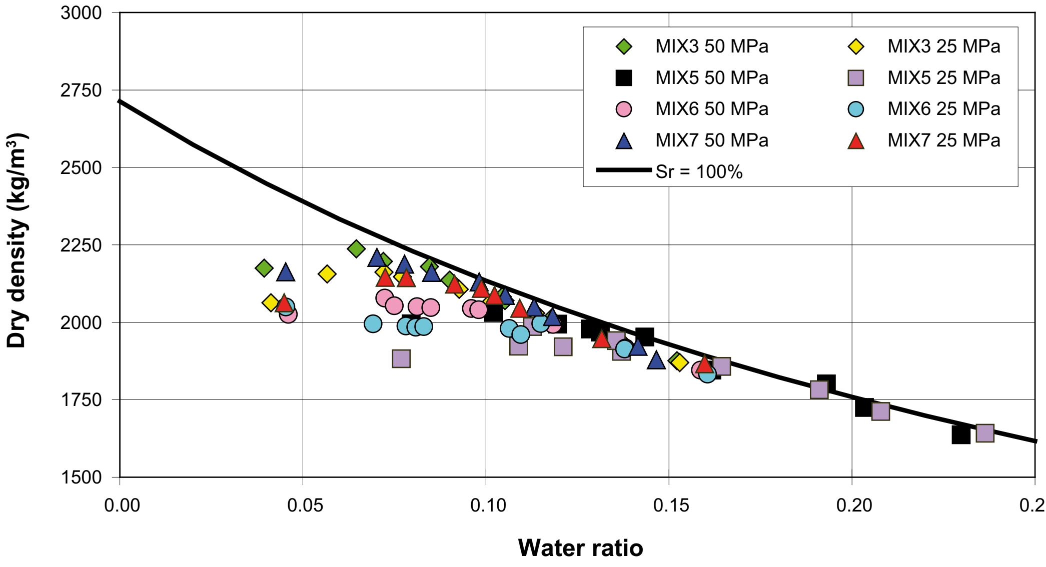


***Figure 5-2.** Dry density plotted as function of water ratio for four mixtures compacted with two compaction pressures (50 and 25 MPa). Plot from /Johannesson and Nilsson 2005/.*

The block pressing in industrial-scale was tested at LAEIS GmbH's block pressing test facility in Germany. The tests were performed with Friedland clay and with a 30/70-mixture consisting of Ca-bentonite from Milos (Deponite CA-N) and ballast B. The blocks were compacted with 25–50 MPa and the resulting density is shown in Table 5-1. The variation in block height is due to variation in block mass, water ratio and applied press force. In a production facility the block height will vary much less.

The main conclusion from the industrial-scale tests was that it is possible to produce high quality blocks with high enough production rate with about the same density as was achieved in the laboratory with the tested materials. It is also estimated that blocks with a maximum size of 800 x 600 x 500 mm (0.24 m^3) can be produced with pressure of 30 MPa. The estimated production capacity with the commercially available equipment is 1 stroke per minute. In total about 25 blocks were produced.

Table 5-1. Block dimensions, water ratio and dry density in the block pressing tests performed in LAEIS test facility.

Material	Dimensions (mm) Length	Width	Height	Water ratio (%)	Dry density (ton/m^3)
30/70	300.25 +/–0.25	300.25 +/–0.25	140–160	7.57–9.53	2.16–2.27
Friedland	300.3 +/–0.5	300.3 +/–0.5	163–170	10.8–12.1	2.01–2.10

Figure 5-3. *Photo of some of the test blocks produced.*

Logistics and placement

In the Swedish case it is assumed that 80% of the tunnel cross-section is filled with blocks and 18% with pellets. The block size used in the Finnish disposal tunnels may be smaller enabling filling the cross-section of the tunnel with blocks up to approximately 90%. The backfill rate required in the Swedish case is 6 m in 24 hours for a tunnel with a cross-section of 25 m^2. For the Finnish system the required effective rate is 5 m/day for a tunnel with cross-section of 14 m^3. The description on logistics and emplacement presented below is based on the Swedish plans and disposal tunnel dimension. However, the principles of installation are the same for the both cases.

Levelling of the floor needs to be done prior to installation of the blocks. The two main alternatives are levelling the floor with mixture of bentonite and ballast or with steel beams placed on the floor of the tunnel.

The design of the placement equipment is based on block sets with the dimensions 120×80×52 cm (L×W×H). This would correspond to two blocks with the size of 80×60×50, which is the estimated maximum block size from the block pressing tests. These two blocks would be handled as one unit. Since the tunnel dimensions have not been fixed yet, the block dimensions will be adapted to fit the final tunnel dimensions.

The blocks would be manufactured in a block pressing plant at the repository site from where they would be transported to the deposition level either with a skip or with a truck via the ramp.

At the deposition level the blocks would be reloaded to special remote-controlled transport vehicles in an underground reloading hall. The transport vehicles would then run all the way to the backfilling front via transport and disposal tunnels. In Figure 5-4 a principle design of the vehicle is shown next to the equipment for placing the blocks.

Both the block placement equipment and the transport unit are equipped with conveyor belts so that blocks can continuously be brought forward. The transport unit moves into the tunnel and conveys the block unit to the placing unit and then moves out of the tunnel to be reloaded. The placement machine places the block in the placement tool (Figure 5-5) and moves it to the desired location (Figure 5-6) where the blocks are placed. Figure 5-7 shows the function of the placement tool.

Figure 5-4. *Block placement equipment (left) and transport unit (right) at the backfilling front.*

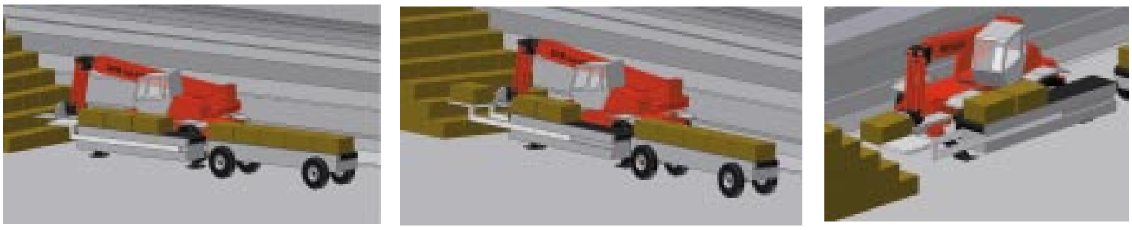


Figure 5-5. *Loading of blocks to the placement tool.*

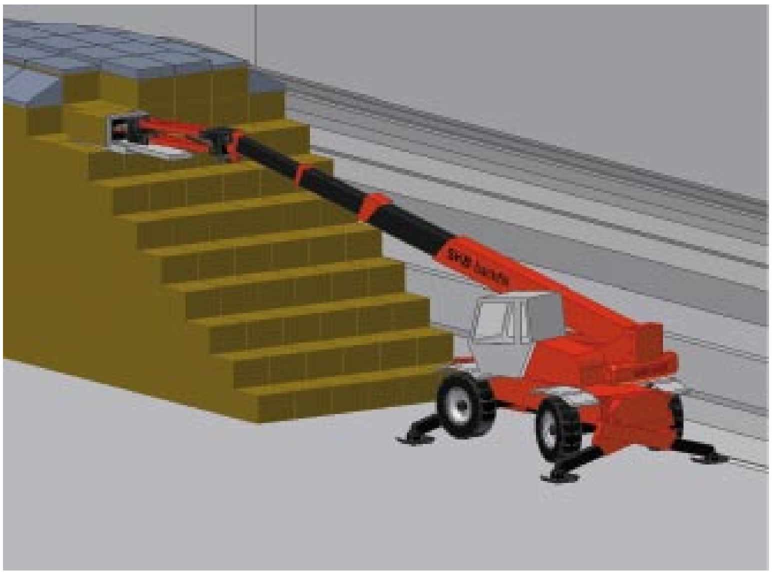


Figure 5-6. *Moving the blocks to the desired location.*

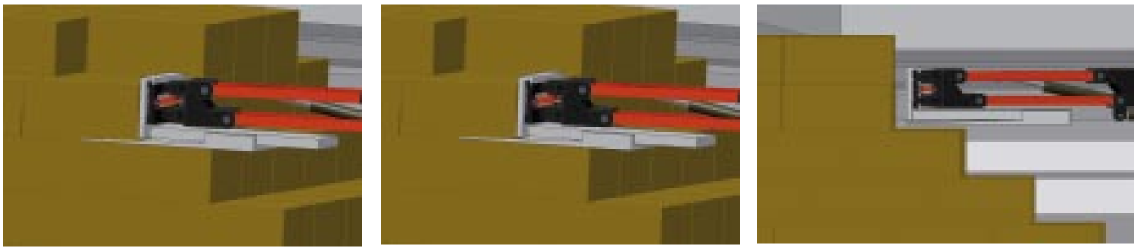


Figure 5-7. *Placing the blocks.*

The vehicles may be propelled by caterpillar tracks or by rubber wheels.

If a fraction higher than 80% of the tunnel cross-section needs to be filled with blocks, smaller blocks are required. If smaller block units can be used, the block-filled fraction of the tunnel will increase. However, this could slow down the backfilling rate, since the larger the size of the pallet is, the higher is the backfilling rate. These factors will be investigated in further planning phases in order to optimize the sizes of the blocks and block units.

An inventory of techniques for placing pellets has been made. Since no commercial product was found, a few applicable techniques were investigated. These included pneumatic transport and feed screws. The technique of slinging, using the centrifugal force to throw pellets was chosen and a test equipment was manufactured, see Figure 5-8.

The objective for building and testing the pellet thrower was to investigate if it is possible to throw pellets 2 m horizontally without losing more than 5 cm elevation. The equipment consists of a rotating disc with shovels within a metal sheet box. Within the box there is an inlet for pellets and an outlet where the pellets are thrown out. The disk is powered by an electrical motor. The revolutions per minute can be controlled with a frequency control unit.

The main conclusion from the test of the equipment was that the technique seems to be feasible for the purpose.

Figure 5-8. *Test equipment for placing pellets "pellet thrower".*

5.1.2 Filling degree

The backfilling with blocks and pellets has not been tested in large scale or in field tests so far, but if the floor is flat and smooth and the tunnel is dry the backfilling should be a fairly straight-forward process

For the conceptual design of the backfilling equipment it has been assumed that either 80% (in the Swedish case) or 90% (in the Finnish case) of the tunnel cross-section is filled with blocks. In this chapter three examples of filling degree, where 70%, 80% and 90% of the cross-section is filled with blocks, are used for comparison. For all three examples 2% of the tunnel cross-section is void and the remaining volume is filled with pellets.

5.1.3 Block and pellet density

The estimation of block density is based on the laboratory-scale block pressing tests reported by /Johannesson and Nilsson 2006/, see Figures 5-1 and 5-2. In these tests blocks were pressed with a pressure of 25 and 50 MPa. The density used in the estimation is 97% of the maximum achieved density in the test. The estimated densities are given in Table 5-2.

The bulk pellet dry density used in the estimation is 1,100 kg/m^3. The justification for using this density is that it has been achieved under field conditions, for example when filling the gap between buffer blocks and deposition holes in the prototype repository as reported by /Börgesson et al. 2002/. When testing the influence of roller compression force and water ratio on pellet density, a dry density of 1,200 kg/m^3 was achieved when mixing 50% pellets with 50% crushed pellets and pouring the mixture into a jar without compaction /Gunnarsson and Börgesson 2004/.

Table 5-2. Estimated densities for blocks and pellets.

Backfill Material	Maximum density (25 MPa) (kg/m³)	97% of maximum density (25 MPa) (kg/m³)	Maximum density (50MPa) (kg/m³)	97% of maximum density (50 MPa) (kg/m³)
Asha 230	1,695	1,644	1,794	1,740
Milos B	1,727	1,675	1,853	1,797
DJP	1,858	1,802	1,929	1,871
Friedland	2,000	1,940	2,090	2,027
Mix 3 (30/70 Milos bal B)	2,162	2,097	2,236	2,169
Mix 6 (30/70 Milos sand)	2,006	1,946	2,067	2,005
Mix 7 (30/70 Milos BalC)	2,150	2,086	2,210	2,144
Mix 5 (50/50 Milos bal B)	1,995	1,935	2,040	1,979

Higher densities can be achieved if the bentonite is dried prior to compaction, mixed to an optimised pellet or granule size distribution and compacted. This has been tested in the Bacchus project reported by /Volckaert and Bernier, 1996/ and in the Reseal project by /Volckaert et al. 2000/. The disadvantage of this is that drying of the pellets is relatively costly. Due to separation achieving an optimised grain size distribution is very difficult when placing pellets in the space between the blocks and the tunnel walls. Compaction of the pellet fill is also difficult due to the geometry. It is possible that pellets can be applied with higher density than 1,100 kg/m³ for the considered circumstances but this remains to be shown.

5.1.4 Estimation of achievable densities

The estimated achievable densities based on the densities and volumes presented in Section 5.1.2 and 5.1.3 are given in Table 5-3.

The design bases for the conceptual design of the backfilling equipment were that at least 80% of the tunnel volume should be filled with blocks and the remaining volume, except for 2% void, would be filled with pellets. In the preliminary estimations for the logistics in the tunnel it seems probable that this filling degree can be achieved. A higher filling degree can also be achieved if smaller blocks are used.

Table 5-3. Resulting densities assuming that the backfilling degree is 70%, 80% or 90% of the total volume of the tunnel and the blocks are prepared with pressure of 25 MPa or 50 MPa. It is assumed that 2% of the total cross-section is void and the rest is filled with pellets with bulk dry density of 1,100 kg/m³.

Backfill material	Dry density for 25 MPa (g/cm³)			Dry density for 50 MPa (g/cm³)		
	70%	80%	90%	70%	80%	90%
Asha 230	1,460	1,510	1,570	1,530	1,590	1,650
Milos backfill	1,480	1,540	1,600	1,570	1,640	1,710
DJP	1,570	1,640	1,710	1,620	1,690	1,780
Friedland	1,670	1,750	1,830	1,730	1,820	1,920
Mix 3 (30/70, Deponit CA-N, crushed rock, no fine fraction)	1,780	1,880	1,980	1,830	1,930	2,050
Mix 6 (30/70, Deponit CA-N, sand)	1,670	1,750	1,840	1,710	1,800	1,900
Mix 7 (30/70, Deponit CA-N, crushed rock with fine fraction of 10%	1,770	1,870	1,960	1,810	1,910	2,025
Mix 5 (50/50, Deponit CA-N, crushed rock, no fine fraction)	1,660	1,750	1,830	1,690	1,780	1,880
Average 30/70-mixture with crushed rock	1,770	1,870	1,970	1,820	1,920	2,040

The backfilling technique remains to be demonstrated in further work. Especially the influence of water flowing into the tunnels needs to be investigated.

5.1.5 Uncertainties

One very important uncertainty is the water inflow to the tunnel during installation, which may lead to premature swelling of the blocks. This together with piping and erosion may result in lower final density in the tunnel than expected. In extreme cases the water inflow could even result in practical problems with the installation. This uncertainty has not been quantified yet.

How much water inflow that can be handled is also related to how the blocks are placed on the tunnel floor. In a relatively dry tunnel a mixture of crushed rock/bentonite can be compacted to form a smooth and stable surface for the block stapling but this material may be sensitive to flowing water. Another solution would be to staple the blocks on steel beams placed on the floor of the tunnel. The beams would be placed perpendicular to the tunnel direction and be held up from the floor with spacers. Yet another solution would be to excavate the floor so that it is flat enough to place the blocks directly on the floor. To be able to correctly assess the feasibility of all three solutions require more development and investigations.

Another important issue to be studied further is whether the resulting dry density (after saturation) is high enough in all parts of the backfilled tunnel. This is important in order to be able to verify that no permanent water conducting pathways are left in the backfill, especially to the zone near the roof and walls. In addition, the whole saturation process and interaction between the backfill and the buffer in different saturation states needs to be investigated in order to study the processes and risks before the system has reached full saturation. To be able to investigate the homogenisation and saturation processes, laboratory tests, field tests and modelling are required in further research phases. This work will be governed by the results from long term safety assessments.

There are also other uncertainties associated with manufacturing of blocks and pellets and the installation in the tunnel that are:

- Variation in raw material.
- Variation in the density of blocks and of individual pellets.
- Gaps between the blocks placed in the tunnel.
- Homogeneity and thereby density of the pellet filling.

Since it is probable that piping channels are created to the backfill, especially in the pellet filled section, the sealing of these channels after the system has reached full saturation needs to be described and studied further in next research phases.

5.2 Backfilling with backfill material compacted in the tunnel

5.2.1 Description of the method

The main stages of the in situ compaction method tested previously at Äspö are presented in Figure 5-9. The method is based on compacting backfill material to inclined layers with a plate compactor. Two different types of plate compactors were designed and tested, one

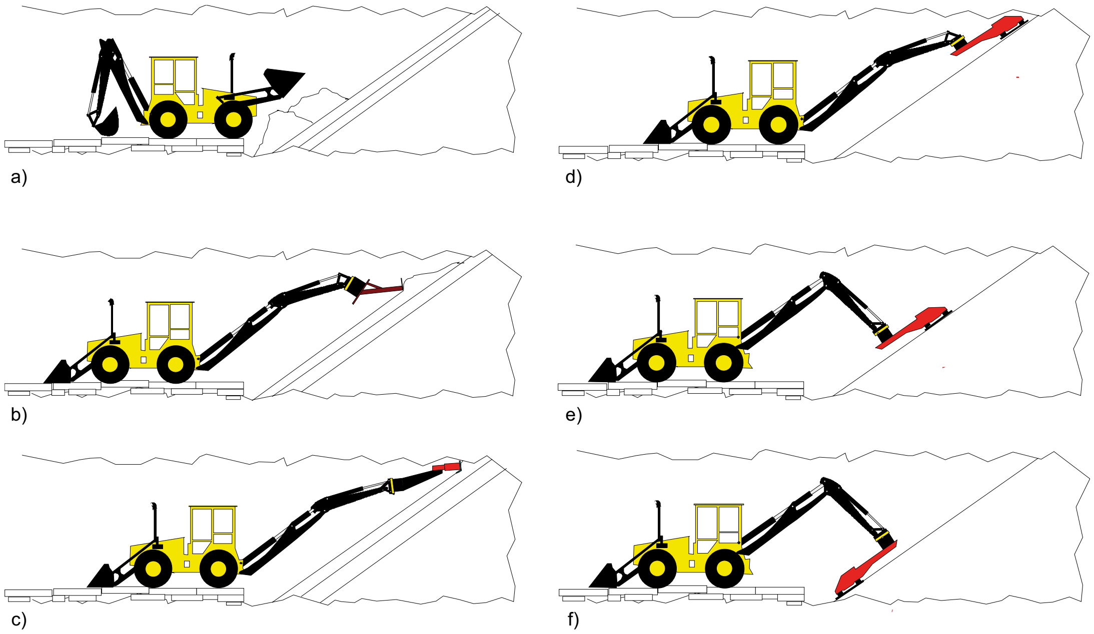


Figure 5-9. *Compaction of inclined layers of backfill material in a tunnel. The letters a–f indicate the different steps of the backfilling: a) – b) moving the material into the tunnel by pushing it in place, c) compacting the material at the roof and d) – f) compacting the rest of the layer /Gunnarsson and Börgesson 2002, Gunnarsson et al. 2004/.*

for the main volume of the backfill and one for the roof section. The layer thickness and the inclination of the layers were 20 cm and 35° for the mixture of bentonite and ballast and 30 cm and 25° for the Friedland-clay /Pusch and Gunnarsson 2001, Gunnarsson et al. 2004/. Development of the in situ compaction technique and the method is ongoing, but no new practical tests were conducted during the second phase of this project. The dry densities gained in previous tests are discussed in Chapter 5.2.2.

Alternative methods and equipments have been discussed in order to obtain sufficient density and backfilling rate with the in situ technique. However, the applicability of the alternative methods remains to be studied in further research phases.

5.2.2 Densities achieved in previous field tests

Summary of the Äspö field tests and the dry densities achieved in the tests are presented in Table 5-4. In general, the dry densities achieved for the central part of the backfill was considerably higher than the ones gained for the zones near the rock surfaces (see Figure 5-10). The water ratios of the mixtures were adjusted to optimum (10–13% for the 30/70 mixtures) according to Proctor compaction tests. The water ratio of Friedland-clay was intended to be adjusted to the optimum (10–12%), but in practise the material delivered was first too dry leading to dusting during compaction. The moisture in the material delivered for the second attempt was unevenly distributed.

Estimations on achievable dry densities are presented in Section 6.2 (see Tables 6-2 and 6-3).

Table 5-4. Summary on the field tests performed at Äspö HRL.

	Field test of tunnel backfilling	**Backfill and plug test**	**Pre-tests for the prototype repos.**	**Prototype repository**	**Field test with Friedland clay**
Material	Mixture of bentonite and ballast	Mixture of bentonite and ballast	Mixture of bentonite and ballast	Mixture of bentonite and ballast	Friedland clay (smectite-rich mixed-layer clay)
Bentonite content	0/10/20/30 w-%	0/30 w-%	30 w-%	30 w-%	Amount of swelling minerals ~ 45%
Bentonite	MX-80 Na-bentonite	MX-80 Na-bentonite	Milos, high-grade Na-activated Ca-bentonite	Milos, high-grade Na-activated Ca-bentonite	–
Ballast material	TBM-muck	Crushed rock with added fine fractions	Crushed TBM-muck	Crushed TBM-muck	–
Maximum grain size	20 mm	20 mm	5 mm	20–50 mm	Clay fraction app. 60% and silt fraction app. 40%
Layer thickness and inclination	20 cm/35°	20 cm/35°	20 cm/35°	20 cm/35°	30 cm/25°
Equipments used	Vibrating roller (4.5 t) and vibrating plate (0.7 t)	Vibrating plates (0.9 t and 0.4 t)	Vibrating plates (0.9 t and 0.4 t)	Vibrating plates (0.9 t and 0.4 t)	Vibrating plates (0.9 t and 0.4 t)
Technical data on the compactors used	Roller: frequency 32 Hz, amplitude 4.4 mm, static load 12.8–15.2 kg/cm^2, centrif. force 54 kN Plate: 84 kN, amplitude 2.5 mm	Slope compactor: vibrating. weight 0.414 t, freq. 43 Hz, ampl. 2.7 mm Roof comp: 0.24 t, 43 Hz, 3 mm	Slope compactor: vibrating. weight 0.414 t, freq. 43 Hz, ampl. 2.7 mm, Roof comp: 0.24 t, 43 Hz, 3 mm	Slope compactor: vibrating. weight 0.414 t, freq. 43 Hz, ampl. 2.7 mm, Roof comp: 0.24 t, 43 Hz, 3 mm	Slope compactor: vibrating. weight 0.414 t, freq. 43 Hz, ampl. 2.7 mm, Roof comp: 0.24 t, 43 Hz, 3 mm
Resulting dry density (kg/m^3)	1,300–1,770	1,650–1,700	–	1,500–1,750	1,400–1,475
Note	High water inflow		Handling of the muck was difficult		Problems with dusting
Reference	/Gunnarsson et al. 1996, Gunnarsson et al. 2004	/Gunnarsson et al. 2001a, Gunnarsson et al. 2004/	/Gunnarsson et al. 2001b, Gunnarsson et al. 2004/	/Gunnarsson 2002, Gunnarsson et al. 2004/	/Pusch and Gunnarsson 2001, Gunnarsson et al. 2004/

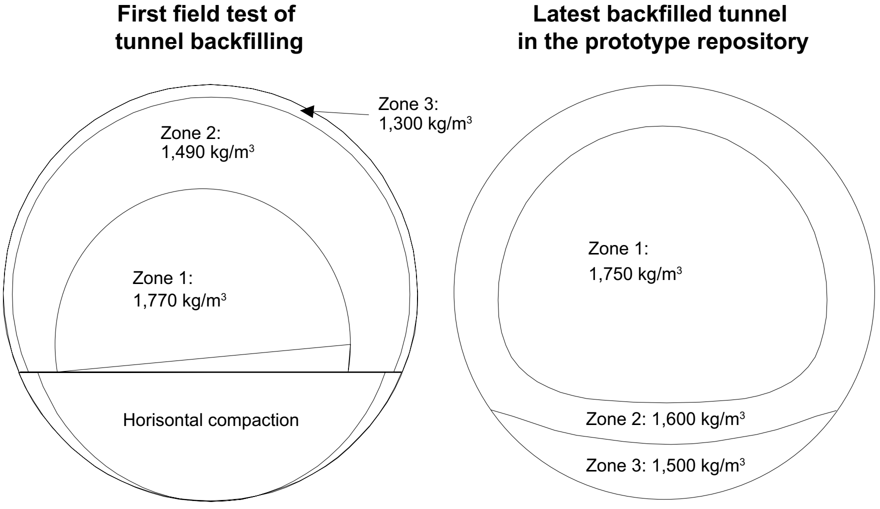


Figure 5-10. *The dry densities achieved in the field tests at Äspö were the lowest near the rock surfaces. The low density in the floor of the Prototype repository tunnel can be explained by the test instrumentation.*

6 Evaluation of the different combination of backfill materials and methods

6.1 Block concept

The comparison of calculated average dry densities and the density criteria for each candidate backfill material is presented in Table 6-1. The safety margin, calculated as the calculated density subtracted by the density necessary to fulfil the criteria, is also given in the table.

Six different mixtures with 30% bentonite and 70% crushed rock were prepared for the tests of geotechnical properties. Block pressing tests were made for three of the 30/70 mixtures and these are hence used for calculating average density based on filling degree. These mixtures are also used for comparing achievable density to the criteria.

The general conclusion from the comparison in Table 6-1 is that all the tested natural clays fulfil the density criteria with a high safety margin when comparing to the average densities estimated for block emplacement even if only 70% of the tunnel cross-section is filled with blocks. As expected the safety margin is higher for the bentonites (Asha 230 and Milos backfill) than for the mixed-layer swelling clays (DJP and Friedland clay).

For the 30% bentonite/crushed rock mixtures the margin is smaller than for the other backfill materials, and basically non-existent for the case with 70% filling degree. Depending on the mixture, the safety margin for 80% filling degree varies from 40–170 kg/m^3. For 90% filling degree the corresponding safety margin range is 140–285 kg/m^3.

Table 6-1. The density criteria compared to calculated average dry density at different filling degrees. The densities are based on blocks compacted with a pressure of 50 MPa.

Material	Density criteria (kg/m^3)	70% Filling degree Density (kg/m^3)	 Margin (kg/m^3)	80% Filling degree Density (kg/m^3)	 Margin (kg/m^3)	90% Filling degree Density (kg/m^3)	 Margin (kg/m^3)
Asha 230	1,160	1,530	370	1,590	430	1,650	490
Milos B	1,240	1,570	330	1,640	400	1,710	470
DJP	1,400	1,620	220	1,690	290	1,780	380
Friedland	1,510	1,730	220	1,820	310	1,920	410
Mix 3: 30/70, Deponit CA-N, crushed rock 0–5 mm with no fine fraction	1,850	1,830	–20	1,930	80	2,050	200
Mix 6: 30/70, Deponit CA-N, sand 0.5–1.2 mm	1,760	1,710	–50	1,800	40	1,900	140
Mix 7: 30/70, Deponit CA-N crushed rock 0–5 mm, fine fraction app. 12%	1,740	1,810	70	1,910	170	2,025	285
Mix 5: 50/50, Deponit CA-N, crushed rock 0–5 mm with no fine fraction	1,560	1,690	130	1,780	220	1,880	320

For the 50/50 mixture the safety margin is higher compared to the 30/70 mixtures but lower compared to the clays. The difference compared to the best 30/70-mixture (mix 7) is relatively small when the filling degree is 80 or 90%.

It should be noted that there are certain uncertainties in the density criteria presented in Tables 4-1 and 6-1 (see Section 4.3). The effect of these uncertainties on the dry density criteria will be studied further in phase III of the project. In addition, processes such as saturation and homogenisation of dry density across the whole tunnel cross-section are very important issues that will have effect on the function and long-term safety of the block backfill.

6.2 In situ concept

In general it can be considered that the dry densities achievable in field conditions are in the best case 90–95% from the maximum densities determined with the Proctor compaction test. This assumption is based on the compaction degree achieved with normal soil compaction methods. The same assumption can be applied for estimating what is the maximum possible dry density achievable with in situ compaction method optimized for backfill material. In general, the higher the amount of clay fraction in the compacted material, the more difficult it is to compact it with normal compaction methods. It is assumed in this report that the maximum dry density achievable for 30/70 mixtures is 90% from their maximum Proctor dry density. Due to even higher clay content, the corresponding assumption for 50/50 mixture and for Friedland-clay is 85%.

There is some scatter in the maximum dry densities determined for different 30/70 mixtures depending on the test material (e.g. ballast type) and the method (standard, modified Proctor or ICT). See Table 6-2 for the maximum dry densities achieved for 30/70 mixtures and Friedland clay with the standard Proctor compaction tests /Keto et al. 2006/.

Table 6-2 summarizes the dry densities achieved in the Prototype repository and the required dry densities in order to fulfill the performance requirements for 30/70 mixtures and for Friedland clay. The field density achieved for mixture of ballast and bentonite in the central part of the Prototype repository tunnel is sufficient in case the backfill material would consist of Mix 6 or Mix 7 (but not in case of Mix 3). The dry densities achieved for the roof section of the Prototype repository tunnel is however significantly lower than the required dry density for any of the mixtures. The field density achieved in Äspö for Friedland-clay is too low in order to fulfill the requirement concerning compressibility. All of the materials listed in Table 6-2 should be compacted to 88–93% of the maximum dry density (determined with standard Proctor compaction test) in order to fulfill all the performance requirements set for the backfill. The conclusion is that in theory it is possible to achieve these densities with in situ technique. However, this requires further development of compaction technique especially for the roof section of the tunnel. The required dry densities for the mixtures containing 40 or 50 weight-% of bentonite and for the Dnešice clay are presented in Table 6-3. In order to fulfill the performance requirements, the 40/60 mixture should be compacted to 92% and the 50/50 mixture to 86% of its maximum Proctor dry density.

There are certain uncertainties linked to the density criteria presented in Table 6-2 (see Section 4.3.4).

Table 6-2. Dry density data on mixture of ballast and bentonite (30/70) and Friedland clay. The results from Proctor compaction tests were gained in WP2 laboratory tests /Keto et al. 2006/ for the same materials that were studied in /Johannesson and Nilsson 2006/. The field density is the density achieved in Prototype repository field test at Äspö HRL /Gunnarsson 2002, Gunnarsson et al. 2004/. Symbols: $\rho_{1–3}$ = required dry densities in order to fulfill the performance requirements concerning: ρ_1 hydraulic conductivity, ρ_2 swelling pressure, and ρ_3 deformation properties. The density criteria are marked with bold font. The column at the right gives this density as a percentage of the maximum Proctor dry density.

Sample	Optimum water content	Max dry density (kg/m^3)	Field density	ρ_1	ρ_2	ρ_3	Required% from Proctor max
Mix 3: 30/70, Deponit CA-N, crushed rock 0–5 mm with no fine fraction	11%	1,990	1,500–1,750	1,850	1,800	1,690	93%
Mix 6: 30/70, Deponit CA-N, sand 0.5–1.2 mm	12.5%	1,910	1,500–1,750	1,590	1,760		92%
Mix 7: 30/70, Deponit CA-N, crushed rock 0–5 mm, fine fraction app. 12%	10.5%	1,980	1,500–1,750	1,700	1,740	1,690	88%
Friedland clay	15.4%	1,724	1,450	1,400	1,350	1,510	88%

Table 6-3. Dry density data on mixture of ballast and bentonite (40/60 and 50/50). For symbols see the text from Table 6-2.

Sample	Optimum water content	Max dry density (kg/m^3)	ρ_1	ρ_2	ρ_3	Required% from Proctor max
Mix 4: 40/60, Deponit CA-N, crushed rock 0–5 mm with no fine fraction	11.7%	1,884	1,670	1,740	–	92.4
Mix 5: 50/50,, Deponit CA-N, crushed rock 0–5 mm with no fine fraction	~ 15%	~ 1,815	1,280	1,450	1,560	85.9
Dnešice clay	–	–	1,220	1,240	1,400	–

Since the dry densities achieved for the roof section so far have been lower than the density criteria, further development of compaction technique is necessary.

Although in theory it is possible to reach high enough density with some of the tested backfill materials (e.g. mix 7), another question is how high the density should be at installation in order to reach high enough safety margin for the system. Since no unfilled space is left in the tunnel, as it is the case in the block concept, the safety margin does not necessarily have to be as high as for the block concept. In addition, the safety margin should be determined based on the actual material properties, i.e. should the hydraulic conductivity be 10 or 100 times higher than the required one (1E–10 m/s) to gain high enough safety margin. It should also be noted that the swelling pressure limit (200 kPa) used for determining the required dry densities, already contains a safety margin, since the performance requirement is 100 kPa.

In practice, the installation procedure is relatively sensitive to leakage waters. Technical solutions need to be developed in order to direct leakage waters out from the tunnel in case the water inflow disturbs the compaction process significantly.

7 Discussion and conclusions

Comparison of the density criteria and estimated achievable average dry densities for both block and in situ backfilling concepts are presented in Table 7-1. The density criterion was determined for 3.5% salinity by /Johannesson and Nilsson 2006/. The filling degree assumed for the block concept in Table 7-1 is 80% of the tunnel cross-section (for other cases see Table 6-1). A higher filling degree can be achieved if smaller block units are used. For the in situ concept it is assumed that the dry density achievable for 30/70 mixtures is in the best case 90% of the maximum proctor density determined in laboratory. The corresponding assumption for clays and 50/50 mixture is 85% due to the fact that it is harder to compact these clay-rich materials in the field compared to the 30/70 mixture.

The general conclusion from the comparison between estimated achievable densities and the density criteria is that placing pre-compacted blocks of swelling clay or 50/50 mixture and pellets in the tunnel results in the highest safety margin, see Table 7-1. In general, 30/70 blocks and bentonite pellets in the tunnel results in a relatively low safety margin, 80–170 kg/m^3 when the filling degree is 80% (see Tables 7-1 and 6-1). In case the filling degree is 90%, the corresponding safety margin is 200–285 kg/m^3 (see Table 6-1).

It is not probable that clays or 50/50 mixture can be compacted in situ to sufficient dry density. Based on the estimated achievable dry densities with in situ compaction (Table7-1), only an optimized 30/70-mixture (e.g. mix 7) can be compacted at site to meet the density criteria. In addition, based on the dry densities achieved in field tests so far, further development of material and compaction method is necessary to be able to reach the density criteria, especially in the roof section of the tunnel. In any case, the safety margin (concerning average dry density) will be significantly lower for in situ concept than for block concept.

Table 7-1. Comparison of density criteria and estimated achievable averaged dry densities for block and in situ backfilling concepts. The density criteria were determined in salinity of 3.5% /Johannesson and Nilsson 2006/.

Material	Density criterion (kg/m^3)	Block concept 80% Filling degree, dry density		In situ concept Achievable dry density from Proctor max: 85% (clays and 50/50) or 90% (30/70)	
		Density (kg/m^3)	Margin (kg/m^3)	Density (kg/m^3)	Margin (kg/m^3)
Asha 230	1,160	1,590	430		–
Milos B	1,240	1,640	400		–
DJP	1,400	1,690	290		–
Friedland	1,510	1,820	310	1,470	–40
30/70 bentonite/crushed rock (based on interpolated values)*	1,740–1,890	1,910–1,930	80–170	1,780–1,790	–60–+40
50/50 bentonite/crushed rock	1,560	1,780	220	1,540	–20

* Only results from mix 3 and 7 are used for the comparison since the density achieved to fulfil the criteria for these materials is based on interpolation and hence can be considered more reliable. Mix 1 is not used in the comparison since no blocks have been made and there is no base for estimating the achievable density. The margins expressed is for the individual 30/70 mixtures.

The scatter in the results from measurements of hydraulic conductivity for 30/70 has in previous tests been fairly large, e.g. /Johannesson et al. 1999/. The scatter in the results is probably due to inhomogeneity in the samples as discussed in /Börgesson et al. 2003/. If this is the case there may be even more problems achieving high enough homogeneity in the large-scale backfilling operation in a repository. Taking this into account not too much should be interpreted from the difference in results from the different types of 30/70 mixtures. A more conservative way of interpreting the results would be to consider the different types of mixtures as one material and the scatter as the variation that can be expected in this type of material.

The density criterion is valid for the situation where the backfill material is homogeneous over the entire volume of the backfilled tunnel. There are a number of processes during the backfilling operation and the saturation/homogenisation period that may be dimensioning for the density and the variation in density at installation so that the density criteria and thereby the function indicators can be fulfilled in the entire backfilled tunnel after homogenisation. These processes are influenced by site-specific factors such as water inflow and salt content of the ground water as well as the backfilling method. These processes have to be defined, understood and quantified to be able to state the design criteria for variation in density at installation.

Examples of possible dimensioning processes during installation:

- Water intrusion into gaps between blocks: decrease in density due to swelling, displacement of blocks and possibly problems with feasibility.
- Forming of water pockets during installation.
- Piping and erosion in the backfill materials due to water inflow.
- Swelling of buffer during installation, and how the backfill is affected by the swelling of the buffer for different saturation cases.
- Operational safety issues.

Examples of possible dimensioning processes during the saturation and homogenisation period:

- Homogenization of blocks and pellets.
- Healing of piping channels.
- Swelling of buffer – deformation of backfill for different saturation cases.
- Water, gas and swelling pressure build-up.
- Post-closure piping.

The study of these processes has been initialised but will need further study and analysis.

7.1 Recommendations on further work

It is recommended that the continued development is focused on the development and testing of the block placing concept with three different backfill material types, Friedland clay, Asha 230 and mixtures of bentonite and crushed rock, with varying amount of swelling minerals.

The reason for focusing on the block placement method is that it seems feasible to place clay material in the tunnels with the very high average density required.

The reason for focusing the work on the Asha 230 and the Friedland clay are that they represent two quite different clay types from the spectra available on the market. Both clays are supplied by major dealers and the probability that the quality is similar over time is hence considered to be high. The reason for continuing the work with the crushed rock/bentonite mixtures are that they have a probability of finally meeting the requirements and that it would result in much less material transport.

It should be stressed that these clays are examples of suitable backfill material. The development work will result in a specification for the backfill material. The specification may be expressed as relationships between density and the parameters swelling pressure, hydraulic conductivity and deformation properties. However, it is more likely that the specification will concern the type and fraction of swelling minerals and a list of contents that are not allowed or have to be under defined limits.

The further work for studying the material properties should include:

- Complementary laboratory tests to verify the hydraulic conductivity and swelling pressure results for the studied materials. More tests are also required in order to explain the influence of ballast material on the hydraulic conductivity and swelling pressure of bentonite-ballast mixtures.
- Compressibility of backfill materials in unsaturated state and in salinity of 7%.
- Modelling (or alternative calculations) is needed to verify the calculations concerning backfill and buffer interaction.
- The required dry densities should be re-evaluated based on the complementary data.
- For the swelling clays and the low grade bentonites hydraulic conductivity and swelling pressure should be investigated also for densities in the same order of magnitude as would be achieved if pre-compacted blocks and pellets were placed in the tunnels.

Concerning the block placement method the most important work concerns understanding the effects of water inflow during installation and initial water saturation. Laboratory tests, large-scale tests and probably modelling for understanding and quantifying the processes listed below are recommended.

- Water intrusion between blocks and subsequent block displacement.
- Piping and erosion in the pellet filling.
- Buffer and backfill interaction for different saturation scenarios.
- Homogenisation and water saturation processes.

Other work to decrease and understand uncertainties that do not have as high influence on the long term function of the backfill include:

- Block pressing tests to understand variation in density in the blocks and the block geometry.
- Tests to understand the variation in density in the pellet filling.

Considering the method of compacting material in the tunnel the following work is recommended:

- Optimisation of the compaction technique with special focus on the roof section. This includes optimisation of the compaction equipment parameters (modelling and small-scale tests), new optimised design for the roof compactor, and practical compaction tests.
- Applicability of alternative in situ compaction techniques.
- Control of leakage waters.
- Further material tests on 30/70 mixtures especially healing of piping channels.

8 References

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