R-09-52

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Abstract

Posiva and SKB initiated a joint programme BACLO (Backfilling and Closure of the Deep repository) in 2003 with the aim to develop methods and materials for backfilling of deposition tunnels. This report summarises the work done in the third and final phase of the BACLO programme. The main objective of this phase was to study how the various processes active during backfill installation and saturation as well as technical constraints affect its design basis. The work focused on the performance and technical feasibility of a block backfill concept, which calls for filling the majority of the tunnel volume with pre-compacted backfill blocks and the remaining volume with bentonite pellets.

Several backfill composition alternatives were chosen for study and they consisted of clay materials with differing amounts of swelling minerals. A large body of information was gained on the effect of different processes on the performance of these backfill options, e.g. water inflow, piping, erosion, self-healing, homogenisation and interaction between backfill and buffer in various laboratory and small-scale field tests. More practical tests included e.g. studies how the blocks and pellets could be installed to the deposition tunnel.

Based on the new information on the effect of the processes investigated and the estimated achievable block filling degree and backfill density, recommendations were made concerning material selection, backfill layout and technical issues. In addition, issues requiring further attention to verify the long-term performance of the proposed backfill concept are identified and listed.

Keywords: BACLO, Block backfill, Performance, Processes, Technical feasibility.

Sammanfattning

Posiva och SKB startade 2003 ett samarbetsprogram BACLO (Backfilling and Closure of the Deep repository) med syfte att utveckla metoder och material för återfyllning av deponeringstunnlar. Denna rapport sammanfattar arbetet som gjorts i den tredje och avslutande fasen i BACLO-programmet. Huvudsyftet i denna fas var att studera hur olika processer aktiva under installation och vattenmättning av återfyllning samt hur tekniska begränsningar påverkar underlaget för design. Arbetet fokuserade på funktion och teknisk genomförbarhet av konceptet återfyllning med block, vilket innebär att man fyller majoriteten av tunnelvolymen med förkompakterade block och resterande volym med bentonitpelletar.

Några alternativa återfyllningsmaterial valdes ut i studien, de bestod alla av lermaterial med olika innehåll av svällande mineraler. Mycket information rörande processernas påverkan på återfyllningens funktion såsom vatteninflöde, kanalbildning, erosion, självläkning, homogenisering och interaktion mellan återfyllning och buffert har erhållits genom olika laboratorieförsök och småskaliga fälttester. Praktiska tester utfördes också där man studerade hur block och pelletar kan installeras i deponeringstunnlar.

Baserat på den information man fick fram genom de undersökta processerna och den uppskattade nåbara blockfyllningsgraden och återfyllningsdensiteten gavs rekommendationer rörande material-val, återfyllningslayout samt tekniska frågor. Dessutom identifierade och listades frågor som kräver vidare uppmärksamhet för att man ska kunna verifiera den långsiktiga prestandan i det föreslagna återfyllningskonceptet.

Nyckelord: BACLO, Block återfyllning, Funktion, Processer, Teknisk genomförbarhet.

Contents

1 Introduction

In the multibarrier principle, the safety of Swedish and Finnish repositories for spent nuclear fuel relies on natural and engineered barriers /SKB 2005/. The natural barrier component consists of the surrounding bedrock and its inherent isolating properties. The engineered barriers in a KBS-3 type repository are comprised of the waste form, copper canister with cast iron insert, bentonite-based buffer and backfill, temporary and permanent plugs used for closure and sealing of the repository. This report discusses the backfill component in deposition tunnels in a KBS-3V type repository where the canister is placed in a vertical position into disposal holes drilled to the floor of deposition tunnels shown in Figure 1-1. The main requirements on the backfill are that it should limit the upward expansion of the buffer into the deposition tunnel and prevent development of hydraulic transport pathways in the deposition tunnels so that the natural water flux at the repository level is not affected. The report focuses on backfilling of deposition tunnels, because these excavations have the potential to affect the performance of the buffer, the canister and subsequently, radionuclide transport along the deposition tunnels.

In developing confidence in backfilling approaches and backfill behaviour, an extensive body of work has been carried out as part of a programme entitled "Backfilling and Closure of the Deep Repository" (Baclo). This report summarizes the work performed in third and final phase of this joint SKB-Posiva programme. The work performed in the previous phases led to a decision to focus work on the block backfill concept, as it seemed to have the greatest promise for successful implementation.

The work performed in Baclo Phase III focused on studying the potentially critical processes during saturation of the backfill and installation of the backfill. For example, in the initial estimations of final hydraulic conductivity of backfill it was assumed that the initially heterogeneous backfill would ultimately homogenize as a consequence of the water saturation and swelling of backfill materials.

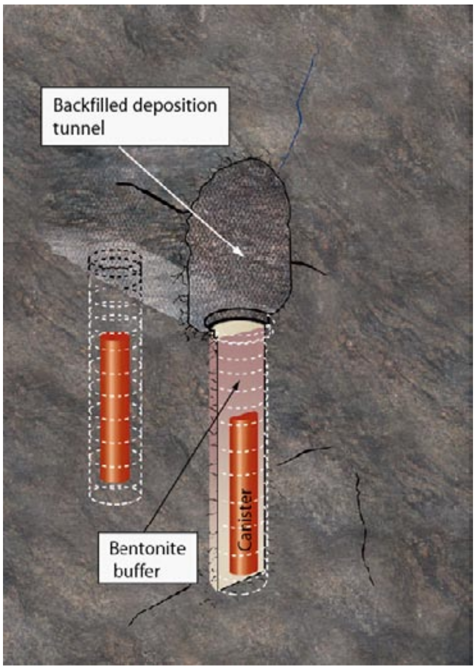


Figure 1-1. In a KBS-3V type of repository the canister is placed vertically in deposition holes. The canister, a bentonite buffer surrounding the canister and the materials used for backfilling the deposition tunnels are all components of the engineered barrier system (EBS). Figure modified after Posiva report 2006-05 /Pastina and Hellä 2006/.

However, this assumption of long-term homogenization left some open questions, mainly concerning the processes taking place during the installation and saturation period including the effect of water inflow to the tunnel (piping and erosion) and swelling (self-sealing and homogenisation with respect to dry density). Another process considered as an uncertainty was the interaction between the backfill and the buffer. In addition, it was found that the technique used for installing blocks and pellets needed to be tested and developed further before the concept could be deemed feasible.

The work identified for conduct during Phase III was divided into different subprojects including laboratory work to identify and assess specific processes of potential importance, field-tests to examine these processes at representative scales and modelling to provide a quantifiable framework for the assessment of these processes. A listing of Baclo-related reports and a summary of their contents are presented in Appendix 1. These documents provide much of the detailed background information that is summarized in this report.

The main objectives of this report are therefore to provide a brief summation of the work done in Phase III and its importance to the clay-block and pellet backfilling concept and from there to:

- provide a basis for recommending a reference design for backfilling using the block concept,
- analyze how the potentially critical processes taking place during the installation and saturation phase affect the performance of the backfill and consequently the design basis for the backfill,
- evaluate the effect of technical constraints on the performance of the backfill and the backfill design, and
- identify needs for further investigations and technical development.

In order to accomplish the above-listed reporting goals, this document has been structured as follows:

- introduction and background behind the block backfill concept,
- design premises and criteria set for backfill,
- description of the backfill materials,
- discussion on the effect of different processes on the backfill design based on investigations made during Baclo phase III,
- discussion on the effect of different technical issues on the backfill design, and
- conclusions and recommendations for the design.

2 Background

In the initial stages of repository conceptual design, the backfill design for deposition tunnels was based on a mixture of bentonite and ballast compacted in situ in the deposition tunnel /see Gunnarsson et al. 2004/. In the process of developing a robust basis for repository design and barriers performance it was determined in a number of laboratory studies /Karnland 1997, Dixon 2000, Pusch 2001/ that the performance of a backfill material, especially swelling pressure and hydraulic properties, depended not only on density but also on salinity of the percolating water, a factor that had not been completely factored into the initial design concepts. In addition, based on field tests performed in Äspö /Gunnarsson et al. 2001, Gunnarsson and Börgesson 2002/, it was found that it is difficult to compact the backfill material to densities sufficiently high as to ensure that it would be able to sustain its required swelling and hydraulic properties in cases where the groundwater salinity of the site exceeded approximately 1% TDS (TDS, total dissolved solids). This lead to a discussion within Posiva and SKB as to whether the backfill should be required to be able to function as required under higher salinities than 1% TDS. This discussion resulted in increasing the design salinity value to 3.5% TDS. For Posiva, the basis for choosing this particular value were conditions identified for a Finnish repository located in Olkiluoto, as described in /Vieno 2000/: "*Today the salinity at the depth of 500 metres varies from 15 to 25 g/l. A design basis value of 35 g/l would allow intrusion of groundwaters presently lying 100 to 200 metres below the 500 metre level. As 35 g/l is the salinity of ocean water, it would also take into account the maximum possible salinity of water infiltrating at the surface*."

The salinity issue led to the need to develop more robust backfill and backfill installation concepts and this was the reason why the Baclo program was initiated in 2003. The program was divided into different phases of which the first and second phases are reported in /Gunnarsson et al. 2004 and 2006/. The objective of Phase I desk studies was to identify backfill concepts and select the most promising ones for further investigation. Based on this study, a new concept called the "block concept" was introduced as an alternative for in situ compaction. In this concept, pre-compacted blocks are placed in the deposition tunnel with bentonite pellets. The Phase II studies included both laboratory and field-tests intended to compare in situ and block backfill concepts as well as materials alternatives (various types of swelling clays and bentonite-ballast mixtures) /Gunnarsson et al. 2006/.

Based on laboratory studies and analytical calculations presented in /Johannesson and Nilsson 2006/, a density where each material candidate was able to meet the requirements set concerning hydraulic conductivity ($< 1\times10^{-10}$ m/s), swelling pressure (> 0.2 MPa) and compressibility in salinity of 3.5% ($NaCl:CaCl_2$, 50:50) was determined. Based on this data a dry density criterion (minimum dry density where the material should be after saturation and homogenisation of the backfill) was set for each material depending on what material property demanded the highest density state. After that the average densities achievable with the two alternative concepts were estimated in order to compare which combination of materials and methods resulted in highest safety margins (consistently and substantially exceeding pre-established density criterion as can be seen in Figure 2-1). The comparison of block and in situ density assumed an 80% block filling degree for the block concept and lead to a conclusion that the focus of further development should be on block concept /Gunnarsson et al. 2006/. In addition, the materials selected for further studies represented materials with different amount of swelling minerals. The basic backfilling concept is described in Section 3 of this report.

Since the assessment made in the second phase of Baclo was based on comparing theoretical achievable average densities and the density requirements, a number of issues were identified concerning the block concept:

- suitability of backfill materials,
- effects of water inflow during installation and saturation,
- interaction between backfill and buffer,
- homogenisation and self-sealing,
- block and pellet/granule design, and
- installation methods and rates.

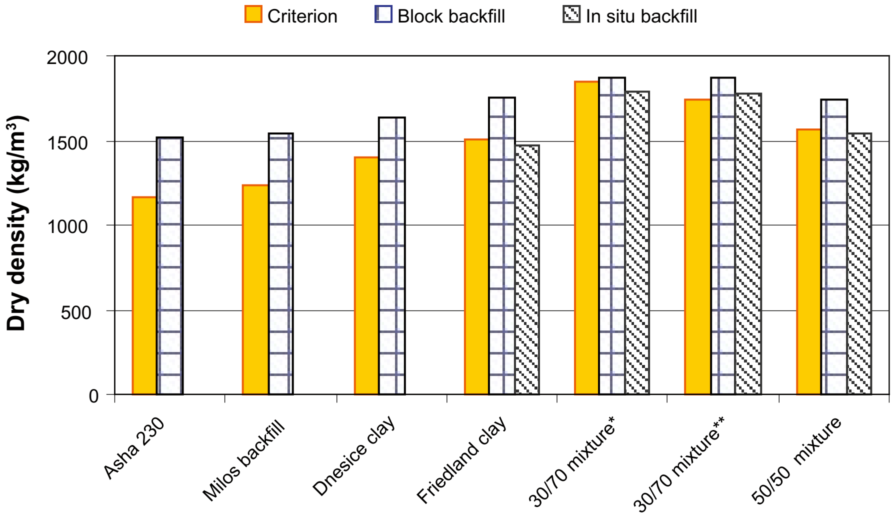


Figure 2-1. *Dry density criterion (kg/m^3) determined for different backfill materials versus the estimated achievable average dry densities (kg/m^3) achieved with 80% block placement and in situ compaction methods. (Asha 230, Milos backfill and Dnesice clay are natural swelling clays from India, Greece and Czech Republic. The 30/70 mixture contains 30% bentonite and 70% crushed rock. The difference between the two 30/70 mixtures is that the one marked * contains crushed rock (0–5 mm) with no fine fraction (< 0.063 mm) and the one marked ** has a fine fraction between of ~ 13%. The 50/50 mixture has bentonite content of 50% /Gunnarsson et al. 2006/).*

The work done in Baclo Phase III, aimed to address these questions with the help of laboratory studies, modelling, small-scale field tests in Äspö, practical installation trials and technical development work. The basic properties of the materials considered as backfilling components are provided in Section 5. The results of studies to evaluate their performance at laboratory and field scales are presented in Sections 6 and 7. The design specifications for the deposition tunnel backfill have been updated (Section 8).

3 Basic design

The basic design presented in this section was selected at the end of Baclo Phase II as the basis for further technical development and performance assessment /Gunnarsson et al. 2006/. The basic design is based on the *block concept* consisting of pre-compacted backfill blocks, pellet filling and floor material (Figure 3-1).

The degree of block filling in the basic case developed in Baclo Phase II was assumed to be 80%. The block filling degree is determined as proportion of the volume of blocks and total volume of the tunnel. In reality the block filling degree can never be constant due to normal variations in the geometry of an excavated tunnel. The investigations performed in Baclo Phase III were therefore done using three different block filling degrees: 70, 80 and 90% in order to assess the effects of deviations from the generic reference case.

The average dry density of the backfill for an 80% block-filled volume was calculated in /Gunnarsson et al. 2006/ assuming that:

- The backfill blocks are prepared using a compaction pressure of 25 MPa.
- The achievable dry density for the blocks is 97% of the maximum dry density determined with block compaction tests in /Johannesson and Nilsson 2006/.
- The volume of open space (volume not occupied by either blocks or pellets, e.g. joints between blocks) is 2% of the total volume of the tunnel.
- The bulk dry density of the pellet filling is 1,100 kg/m^3.

As an example, if the backfill blocks consist of Friedland-clay blocks with initial dry density of 1,940 kg/m^3 and the blocks fill 80% of the initial tunnel volume, the resulting average dry density would be 1,750 kg/m^3. This assumes that the pellet fill is initially 1,100 kg/m^3 in density and that full density homogenization occurs. The effect of tunnel geometry on the achievable block filling degree is discussed further in Section 7 as well as other technical matters affecting the achievable block filling degree and average dry density. The properties and composition of backfill materials considered for use are discussed in Section 5.

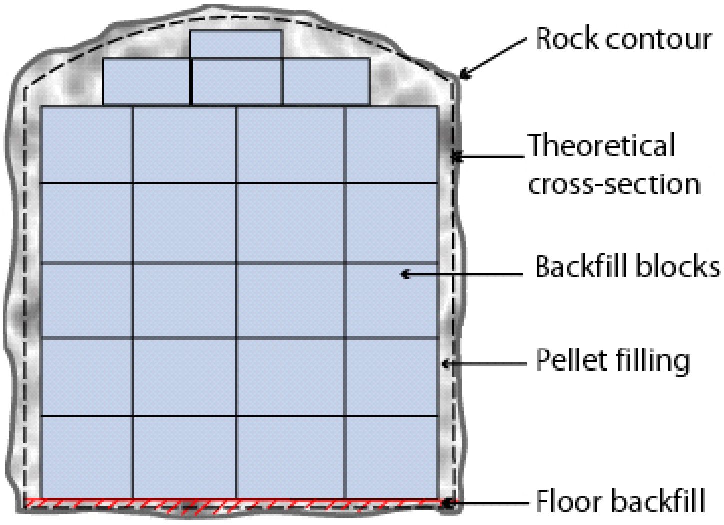


***Figure 3-1.** Schematic cross section of a backfilled tunnel. The three main components of the block backfill are 1) pre-compacted backfill blocks, 2) pellet filling and 3) material placed underneath the blocks to provide stable foundation for the block assemblage.*

4 Design premises and criteria

4.1 Introduction

This section describes the design premises and criteria set for backfilling of deposition tunnels in a KBS-3V repository with the main focus on design premises developed from the long-term performance point of view. It should be noted that all investigations performed in Baclo Phase III are based on requirements and criteria originally presented in /Gunnarsson et al. 2006/. At the time of writing this report (late 2008), SKB and Posiva are both updating their requirements for backfill. However, based on preliminary information, the content of the new performance requirements by SKB and Posiva are little changed regarding the long-term performance of the backfill. As a result, much of the focus will be on how to achieve these performance criteria and what materials will best achieve them.

The requirements set for backfilling of other tunnels and rooms within the repository differ from those set for the deposition tunnels. This is because the interaction between the backfill and the buffer and the canister create special requirements for the performance for the backfill in deposition tunnels. Based on the report by /Gunnarsson et al. 2006/, the main function of the backfill as an engineered barrier in deposition tunnels is to ensure that the multiple barrier principle is supported by maintaining the safety functions of the individual barriers (canister, buffer and surrounding bedrock).

In /Gunnarsson et al. 2006/ the requirements set for the backfill were divided into:

- system requirements for the whole KBS-3V repository aiming at providing long-term safety and radiation protection, and
- subsystem requirements, function indicator criteria, density criterion and more practical design specifications for the backfill.

In addition, it was assumed that there are number of constraints (features, events and processes), that have an impact on the design and affect backfill performance. All these requirements and constraints were used as the basis of the Baclo Phase III investigations and are discussed in Sections 4.2, 4.3, 4.4 and 4.5.

4.2 Subsystem requirements used as a basis for the backfill development

Subsystem requirements are the functional requirements that were defined for backfill based on the KBS-3 system requirements /see Gunnarsson et al. 2006/. The sub-system requirements can be divided into three groups, requirements based on 1) nuclear safety and radiation protection, 2) environmental impact and 3) flexibility and efficiency (see Table 4-1).

4.3 Criteria set based on subsystem requirements

The materials used in the backfill must be able to maintain their specified properties over the long-term despite possible changes in the repository environment and constraints (see Section 4.5). In order to achieve long-term performance and aid in the design and assessment of the performance of the backfill, the subsystem requirements were translated into quantitative values that were derived from the following *safety indicator criteria* defined in the safety assessment SR-CAN /SKB 2005/:

- to limit advective transport the hydraulic conductivity shall be less than 10^{-10} m/s,
- to prevent groundwater flow and ensure (behavioural) homogeneity the swelling pressure shall be at least 0.1 MPa, and
- to prevent loss of buffer density the compression modulus shall be at least 40 MPa. This parameter is a measure of the volume strain per unit change in pressure and provides a means of evaluating the stiffness of the material being compressed.

Table 4-1. Sub-system requirements for backfill. These functional requirements were used as a basis of backfill investigations and development in the Baclo program.

Subsystem requirements
1) 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.
The backfill shall not in other ways significantly impair the safety function of the barriers
The backfill shall be long-term resistant and its function shall be preserved in the environment expected in the repository
The backfill (manufacturing and emplacement) shall be based on well-tried or tested technique
The backfill properties shall be controlled using specified acceptance criteria.
2) Environmental impact
The manufacturing of the backfill and its emplacement shall be efficient regarding consumption of raw material and energy
3) Flexibility and efficiency
It shall be possible to perform the placement of the backfill at the specified rate
The backfill shall be cost efficient with respect to raw-materials, manufacturing and emplacement.

For practical reasons and to assess the performance of the block backfill as a system, the safety indicator criteria were modified in /Gunnarsson et al. 2006/ into following *criteria* that were used as a basis for backfill development in Baclo:

- the swelling pressure of the backfill shall be > 0.2 MPa,
- the hydraulic conductivity of the backfill shall be < 10^{-10} m/s, and
- the compression of the backfill caused by the swelling of the buffer shall not be so large that the saturated density of the buffer at the canister level decreases below 1,950 kg/m^3.

The swelling pressure is needed to provide a tight contact between the backfill and the rock, for homogenisation of the block-pellet backfill, to provide a self-sealing ability and to contribute to the mechanical stability of the deposition tunnels. The specification provided by /Gunnarsson et al. 2006/ of > 0.2 MPa was raised from the previous specification of 0.1 MPa for practical measurement purposes. At 0.1 MPa it is difficult to ensure that this pressure is present and the system is more vulnerable to slight variations in smectite content, density and groundwater salinity. At 0.2 MPa there is a higher degree of confidence that there is a substantial positive contact present at the rock-backfill contact.

The limit for hydraulic conductivity (10^{-10} m/s) comes from the assumption that under these conditions the water transport through the backfill will be a diffusion dominant process. This requirement is valid over the whole cross-section of the tunnel.

Since swelling pressure, hydraulic conductivity and compressibility of backfill all depend on the density when it is placed to the deposition tunnel, *density criteria* was determined for different material alternatives by /Johannesson and Nilsson 2006/. The density criteria for the materials considered in Baclo Phase III are presented in Section 5.

In addition to the performance requirements for the backfill there are additional factors that impact on backfill design. Specifically, the subsystem requirements concerning effectiveness and flexibility lead to development of operational criteria associated with defining adequate rate of backfilling. The backfilling rate required for the Swedish deposition tunnels is 6–8 m in 24 hours /Gunnarsson et al. 2006/, while for the Finnish deposition tunnels it is approximately 5 m per day /Keto and Rönnqvist 2006/. Any materials and emplacement options considered or developed must therefore be able to be placed at a rate that meets the production requirements established.

4.4 Design specifications

The requirements presented in previous sections will guide the identification of design specifications so that feasible solutions on material, installation design and method and quality assurance/control will provide a sufficient safety margin to long-term safety. A list of design specifications to be determined for deposition tunnel backfill consisting of pre-compacted blocks and bentonite pellets are presented in Table 4-2.

4.5 Environmental and operational constraints

There are a number of constraints under which the backfill should be able to perform. The constraints are features, events and processes that have an impact on the design and constrain the solutions that can be applied.

The site specific constraints involve:

- total water inflow into and distribution within the tunnel,
- composition of the inflowing water (salinity, pH etc),
- evolution of groundwater composition over time, and
- surface roughness of the rock walls and the floor that may be influenced both by the rock and the excavation method.

The constraints from the repository design are:

- technical feasibility,
- geometry of excavated tunnels,
- other repository operations that may limit, e.g. logistics, and
- equipment and their limitations to the backfill design.

Table 4-2. List of design specifications for backfill in deposition tunnels.

Design specification concerning installation of the backfill	
Density	– Average dry density of the backfill, required average dry density in order to fulfil the function indicators stated in SR-CAN. – Acceptable range/variations in dry density. – Bulk density of the pellet filled zone.
Geometry	– Placement of blocks into the tunnel, i.e. block layout/geometry, width of the slot between two blocks, formation of continuous horizontal and vertical slots through the backfill front, etc. – Tunnel filling degree with blocks. – Geometry of pellet filled volume.
Backfilling rate	– Installation rate of blocks. – Installation rate of pellets.
Design specifications concerning materials and manufacturing of blocks and pellets	
Blocks	– Material: required amount of swelling minerals/smecite content, smectite composition, other minerals, organics and oxidizing substances, stray materials, and granule size distribution. – Dry density and water ratio. – Dimensions, size and shape. – Required accuracy of blocks. – Compaction pressure and technique. – Use of lubricators. – Mixing technique.
Pellets	– Material: required amount of swelling minerals/smecite content, smectite composition, other minerals, stray materials. – Dry density and water ratio of individual pellets. – Granule size distribution.

5 Backfill materials

5.1 Introduction

This section will examine the backfill materials considered in Baclo Phase III. Specifically, the objectives of this section can be broken down into two main categories. Firstly, to present what is known on the mineralogy and chemistry of the material that were chosen for further studies in Baclo Phase II. This information is important in order to interpret the results from the tests described in following sections (e.g. self-sealing tests). Secondly this section will present some of the key geotechnical parameters for materials studied in order to determine at what dry density these materials are able to fulfil the requirements set for the backfill.

The materials considered for backfill were studied in Phase II of the Baclo program /Johannesson and Nilsson 2006/ and based on those investigations the following block materials with varying content of swelling minerals were chosen for further studies:

- mixture of bentonite and ballast (30:70),
- Friedland clay, and
- Asha230 bentonite.

The pellets and granules chosen for further studies were selected partly based on availability but also on pellet/granule size distribution, pellet shape and the resulting void volume. Except for one material (Friedland clay granules), the pellets/granules were assumed to have high bentonite content (high in this report meaning > 75%).

5.2 Materials studied

The different types of clay materials studied in Baclo Phase III are presented in Table 5-1 and in Figure 5-1. In order to compare the variations between different batches of same material, some earlier references are included in the table as well. The difference between bentonite pellets and granules is that the pellets are manufactured from raw bentonite by compaction and the granules consist of raw bentonite "lumps" that have been crushed to achieve a specific grain-size distribution. In the remainder of this document the term pellets is used as general term to describe any material produced by compaction. If granules of crushed, raw bentonite are used in testing, they have been identified as such in the text.

The ballast material used in the laboratory tests where bentonite-aggregate mixtures were investigated consisted of crushed rock with a maximum grain size of approximately 5–6 mm. The same ballast material was tested in Baclo Phase II and is described in /Keto et al. 2006/ (labelled as Bal O4) and in /Johannesson and Nilsson 2006/ (labelled as ballast B). The crushed rock used as ballast was produced by Interrock Oy from a mica-gneiss excavated from Olkiluoto. The grain size distribution determined by /Johannesson 2008/ is presented in Figure 5-2. The grain size distribution determined in /Keto et al. 2006/ was very similar, although the amount of fine fraction (0.0063 mm) was a little higher, approximately 3.5%. The other material parameters determined for the crushed rock described in /Keto et al. 2006/ were:

- Uniformity coefficient C_u (d_{60}/d_{10}): 11.
- Optimum water content: 11%.
- Maximum dry density (kg/m^3) determined based on Standard Proctor compaction test (EN 13286-2): 2,000 kg/m^3.
- Specific/particle density: 2,700 kg/m^3.
- Porosity (n), ratio of volume voids (V_v) and total volume of the specimen (V): 20%.

The uniformity coefficient (C_u) describes how graded/sorted the material is. When the C_u is more than 6 the material is considered poorly sorted, which can be used for assessing the hydraulic properties of the material /Fetter 1994/.

Table 5-1. Clay materials studied in Baclo III. The codes are used in this report to differentiate between materials from different batches.

Producer	Code	Tested in	References
Friedland clay			
FIM Friedland Industrial Minerals GmbH, Germany	F-clay A	Baclo Phase II laboratory investigations	/Johannesson and Nilsson 2006, Keto et al. 2006/
	F-clay B	Baclo Phase III laboratory tests and Äspö field tests (Bjuv blocks)	/Johannesson 2008, Kuula-Väisänen et al. 2008, Kuula-Väisänen 2008, Sanden et al. 2008, Dixon et al. 2008a, b, c/
	F-clay P1	Tested as pellet material in Äspö field tests	/Dixon et al. 2008a, b, c/
	F-clay X	Earlier/separate SKB/Posiva investigations with the material	/Pusch 1998, 2001, Carlson 2004, Karnland et al. 2006/
Kutch Na-bentonite (Asha 230)			
Ashapura Volclay, India	Asha 230A	Baclo Phase II laboratory investigations	/Johannesson and Nilsson 2006, Keto et al. 2006/
	Asha 230B	Baclo Phase III laboratory investigations	/Johannesson 2008, Ahonen et al. 2008, Kuula-Väisänen et al. 2008, Sanden et al. 2008/
Milos Ca-bentonite (Deponit CAN)			
Original producer Silver & Baryte Minerals, Greece. Pellets: Cebo Holland BV	Milos A	Used for 30/70 mixtures in Baclo Phase II and III laboratory tests	/Johannesson and Nilsson 2006, Keto et al. 2006, Johannesson 2008, Kuula-Väisänen et al. 2008, Kuula-Väisänen 2008, Sanden et al. 2008/
	Milos X	Earlier/separate SKB/Posiva investigations with the material	/Carlson 2004, Karnland et al. 2006/
	Milos Gr. (granules)	Milos granules used in Äspö field tests	/Dixon et al. 2008a, b, c, Ahonen et al. 2008/, This report (CT)
	Cebogel (pellets)	Cebogel pellets used in Äspö field tests and in Baclo Phase III laboratory tests	/Dixon et al. 2008a,b,c, Sanden et al. 2008, Ahonen et al. 2008, Kuula-Väisänen et al. 2008, Kuula-Väisänen 2008/
Wyoming Na-bentonite (MX-80)			
Volclay, USA	MX-80 (pellets)	Baclo Phase III lab. tests.	/Sanden et al. 2008/

5.2.1 Geological origin of raw materials

Friedland-clay is a smectite-rich clay from north-eastern Germany. The deposit is located near the town of Neubrandenburg and the clay is quarried there FIM Friedland Industrial Minerals GmbH, for use in the ceramic industry and various civil engineering applications. The clay occurrence is massive and homogeneous with estimated reserve of approximately 100 million tons /Karnland et al. 2006/. It is of Tertiary origin and formed by a series of complex processes including sedimentation, weathering, erosion and hydrothermal alteration /Pusch 2002, Karnland et al. 2006/.

The Milos clay deposits are located on the Island of Milos, Greece. Milos bentonites are produced by Silver & Baryte Minerals S.A. (S&B), which according to S&B annual report (2007) is the largest producer of bentonite in the EU and the second largest in the world. The Cebogel pellets were re-processed by Cebo Holland BV. These clay deposits were formed as a consequence of hydrothermal alteration of volcanic rocks during the Tertiary period /Christidis and Scott 1996/. The clay deposits occur in irregular bodies with thickness of 10–40 m /Karnland et al. 2006/.

The Wyoming Na-bentonites formed during the Cretaceous period as a consequence of hydrothermal alteration of rhyolitic ash layers deposited in a large basin called Mowry sea, located east of Rocky Mountains /Knechtel and Pattersson 1962, Slaughter and Earley 1965, Slaughter and Hamil 1970, Elzea and Murray 1990/. The thickness of the bentonite layers varies from a few centimetres to

***Figure 5-1.** Photographs of some Baclo test materials. A) Friedland clay blocks produced in Bjuv, B) Friedland-clay granules, C) Asha 230 B bentonite before homogenisation by mixing, D) Cebogel pellets and E) MX-80 pellets, F) Minelco granules.*

\> 3 m, the average being 0.8—1.5 m /Knechtel and Pattersson 1962/. Wyoming bentonites are produced by several companies /Dixon 1994, Dixon and Miller 1995/. AMCOL International Corporation produces the materials examined in these studies and is the leading supplier of bentonite in the world through its subsidiaries, e.g. American Colloid Company and Volclay International.

The Kutch bentonite deposits are located in the northwestern India in the Gujarat state. The deposits occur typically as "lenses" of different sizes (thickness varying from few metres up to 30 m) and are 4–5 m below the ground surface /Shah 1997, Karnland et al. 2006/. /Shah 1997/ reported the size of bentonite reserves in the area were approximately 10 million tons, plus potentially an additional 15 million tons located at greater depths. These deposits are dated as Tertiary and were formed through hydrothermal alteration volcanic ash under conditions that included marine water and semi-arid climate /Shah 1997/. The Kutch material is produced by Ashapura Volclay ltd.

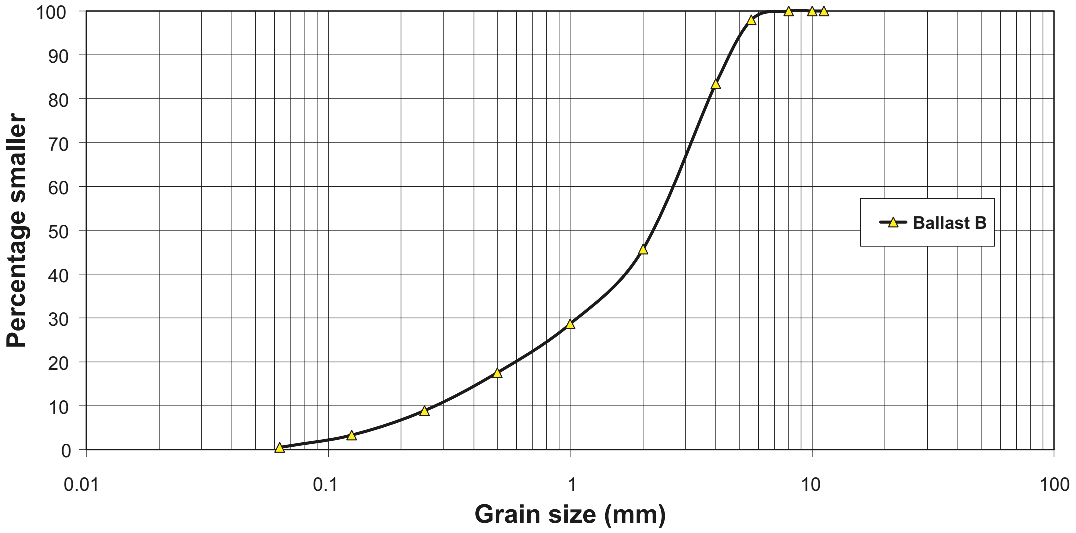


Figure 5-2. *Grain size distribution of the crushed rock used in Baclo laboratory tests /Johannesson 2008/.*

The Olkiluoto mica-gneiss was used as a granular component of the mixed clay-aggregate backfill examined in this study.

5.2.2 Mineralogy and chemistry

Friedland clay

The mineralogy of the Friedland clay has been studied by several researchers including, /Henning 1971, Pusch 1998, 2001, Carlson 2004 and Karnland et al. 2006/ (referred as F-clay X in Table 5-1). According to /Henning 1971/ the swelling component of the clay consists of randomly interlayered muscovite/montmorillonite with the montmorillonite component dominating. The mineralogical composition analyzed by /Karnland et al. 2006, Pusch 1998 and Carlson 2004/ is presented in Table 5-2.

The chemical composition of the Friedland clay determined as oxide percents with XRF (X-ray fluorescence) is SiO_2 (60%), Al_2O_3 (18%), Fe_2O_3 (7%), MgO (2%), CaO (0.4%), Na_2O (1%), K_2O (3%) and TiO_2 (1%) /Carlson 2004/. Based on /Carlson 2004/, the sulphur and carbon contents are below 1%. The exchangeable cations determined with 0.05 M Cu (II) ethylenediamine at ph 7 within the clay are Na^+ (22.2 $cmol^+/kg$), Ca^{2+} (11.0 $cmol^+/kg$), Mg^{2+} (6.9 $cmol^+/kg$) and K^+ (2.2 $cmol^+/kg$) leading to total cation exchange capacity of 42.3 $cmol^+/kg$ /Carlson 2004/.

Table 5-2. Mineralogical composition of Friedland clay.

Swelling mineral / content of swelling minerals	Accessory minerals	Reference
Mixed layer illite-smectite (montmorillonite) / range 25–34%, mean value ~ 30% determined with Siroquant analysis	Illite, quartz, kaolinite, muscovite, plagioclase, pyrite	/Karnland et al. 2006/
Mixed layer illite-smectite / average value 45%	Quartz, mica, chlorite, feldspar, carbonate	/Pusch 1998/
Mixed layer illite-smectite	Quartz, kaolinite, chlorite, plagioclase, K-feldspar, illite, pyrite	/Carlson 2004/

Milos bentonite (Cebogel pellets and Minelco granules)

The mineralogy and chemistry of Milos bentonites (referred as Milos X in Table 5-1) has previously been studied e.g. in /Carlson 2004 and Karnland et al. 2006/. The mineralogy and chemistry of Cebogel pellets and Minelco granules were investigated as a part of Posiva's Belake project concerned with development of quality control for bentonite clays (referred as Cebogel pel. and Milos gr. in Table 5-1). The results of that project are reported in /Ahonen et al. 2008/. Table 5-3 shows the estimated mineralogical composition for these materials and compares them to data presented in /Carlson 2004 and Karnland et al. 2006/. Based on these analyses the amount of montmorillonite is approximately 80% and the main accessory mineral is calcite (5–15%). The high hematite content determined for Cebogel pellets in /Ahonen et al. 2008/ is likely to be an error, because the result is not supported by the chemical composition determined for the same material (see Table 5-4).

The chemical composition of Cebogel pellets and Minelco pellets determined with XRF /Ahonen et al. 2008/ is presented in Table 5-4. For comparison, the chemical composition of Milos Ca-bentonite determined by /Carlson 2004/ with XRF and sulphur/carbon analyzer is also presented. The chemical composition of these two materials is very similar, but there are small differences in the amounts of Na_2O and CaO. The observed differences may be due that somewhat higher amount of soda ash (Na_2CO_3) may have been used for activation of Cebogel pellets and the calcite content that is higher in Minelco granules. The chemical composition also correlates fairly well with the high-grade (non-activated) Ca-bentonite from Milos materials reported on by /Carlson 2004/.

Exchangeable cations and cation exchange capacity (CEC) determined by /Ahonen et al. 2008/ for Cebogel pellets and Minelco granules is presented in Table 5-5. For comparison purposes, the data for high-grade non-activated Ca-bentonite (Deponit CA-N (MiR1)) studied by /Carlson 2004/ is also presented. The effects of soda ash activation of Cebogel pellets and Minelco granules can be seen in the results (higher Na^+ and higher CEC compared to non-activated Milos Ca-bentonite). Additionally dissolution of calcite is evident in the NH_4-acetate CEC analyses, especially in case of the Minelco granules and the high-grade Ca-bentonite.

Table 5-3. Mineralogical composition of Cebogel and Minelco materials /Carlson 2004, Karnland et al. 2006, Ahonen et al. 2008/.

Mineral	Cebogel pellets /Ahonen et al. 2008/	Minelco granules /Ahonen et al. 2008/	Milos high-grade Ca-bentonite /Carlson 2004/	Deponit CA-N (MiR1), non-activated Ca-bentonite from Milos /Karnland et al. 2006/
Montmorillonite	80	80	75–80	81.4
Quartz	<5	<5	<5	0.4
Feldspars	<5	5		0.7
Calcite	<5	10	10–15	5.5
Dolomite	<5	5		1.3
Illite				4.6
Cristoballite				0.6
Hematite	(10)			0.2
Goethite				0.4
Muscovite				1.4
Pyrite			<5	1.1
Gypsum				0.4
Lepidocrocite				0.3
Anatase				0.1
Magnetite				0.1
Rutile				0.3
Siderite				0.3
Tridymite				0.4

Table 5-4. Chemical composition (major elements in w-% determined with XRF) of Cebogel pellets and Milos granules produced from Milos bentonite (analysed by /Ahonen et al. 2008/) compared to previous analysis on non-activated Milos Ca-bentonite by /Carlson 2004/.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	S	C
Cebogel pel.	53.1	16.8	5.2	3.8	5.4	3.5	0.6		0.45	
Minelco gr.	52.0	16.8	5.1	4.0	6.7	2.7	0.8		0.34	
Milos bent.	48.7	17.3	4.8	3.0	9.3	0.7	0.3	0.8	0.47	0.59

Table 5-5. Exchangeable cations (cmol⁺/kg) and cation exchange capacity determined for Cebogel pellets and Minelco granules by /Ahonen et al. 2008/ and for non-activated Milos Ca-bentonite analysed by /Carlson 2004/.

	Exchangeable Cations				**CEC**
	cmol⁺/kg	**cmol⁺/kg**	**cmol⁺/kg**	**cmol⁺/kg**	**cmol⁺/kg**
$BaCl_2$-method	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	
Cebogel pellets	13.3	0.9	7	78.3	99.5
Minelco granules	10.9	1.0	8.8	62.2	82.9
Milos bentonite	32.6	1.7	19.9	21.3	75.47
NH_4-acetate-method	**Ca^{2+}**	**K^+**	**Mg^{2+}**	**Na^+**	
Cebogel pellets	12.2	1.4	8.0	81.3	103.0
Minelco granules	18.7	1.4	13.2	65.7	99.0
Milos bentonite	71.8	1.2	19.9	18.4	111.3

Kutch bentonites (Asha 230)

Asha 230 is the name assigned to a non-commercial clay originally sampled by Ashapura-Volclay for this project. It was assumed that this clay would have lower montmorillonite content than their usual bentonite products, making it more suitable for use in backfill. The estimated montmorillonite content of this material is 60% /Johannesson and Nilsson 2006/. However, based on XRD (X-ray diffraction) analysis ordered from the Geological Survey of Finland (2008), the Asha 230b clay has montmorillonite content of approximately 85%. This corresponds to the smectite content of high-quality Ashapura Na-bentonite analysed earlier by /Carlson 2004 and Karnland et al. 2006/. The other minerals present determined in the study by Geological Survey of Finland (2008) are: quartz (10%), hematite (<5%) and anatase (<5%). Based on the earlier analysis by /Karnland et al. 2006/ the iron oxide mineral present may be hematite and/or goethite and/or maghemite.

According to XRF results by Geological survey of Finland (2008) the chemical composition of Asha 230b is following: SiO_2 (53.7%), Al_2O_3 (17.2%), Fe_2O_3 (14.0%), TiO_2 (3.4%) Na_2O (2.7%), MgO (2.5%), CaO (0.4%), Cl (0.3%), S (0.1%), K_2O (<0.1%), MnO (<0.1%) and P_2O_5 (<<0.1%). One should note the high iron content of this clay, otherwise the chemical composition is relatively near of a typical Na-bentonite. The majority (>90%) of the iron was determined to be ferric iron (Fe^{3+}). The measurements obtained with a combustion method (LECO) and sulphur analyser (Eltra) showed that the S content was 0.07% and there was no organic or inorganic carbon present in the material.

The CEC of the Asha 230b varied between 83.3–92.6 meq/100 g determined respectively with 0.1 M $Bacl_2$ method (pH7) and 1 M NH_4-method (pH7) (Geological Survey of Finland 2008). The main cation determined using both of these methods was Na^+ (66–67%). The other cations present were Mg^{2+} (9–16%), Ca^{2+} (7–10%), Fe^{2+} (<0.01%) and Al^{3+} (<0.01%).

MX-80 (MX-80 pellets)

The mineralogy and chemical composition of Wyoming Na-bentonites and MX-80 has been discussed widely e.g. by /Elzea and Murray 1990/ and more recently by /Carlson 2004 and Karnland et al. 2006/. The montmorillonite content of MX-80 analysed by /Carlson 2004/ was 80–85%, while the CEC (meq/100 g) was 84–104 depending on the method used ($BaCl_2$ and NH_4-methods respectively). The content of major elements (determined with XRF) and sulphur and total carbon (determined using sulphur/carbon analyzer) is presented in Table 5-6. Based on the analysis of

Table 5-6. Content of major elements in MX-80 determined with XRF and content of sulphur and total carbon determined with sulphur/carbon analyzer /Carlson 2004/.

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	S	C
61.3	19.9	3.8	2.4	1.4	2.1	0.6	0.2	0.3	0.3

/Carlson 2004/, the proportion of carbonatic (non-organic) carbon is 96–97% the rest being carbon of organic origin. The nature of these carbons is important because organic carbon can increase the risk of canister corrosion, especially copper corrosion, through contributing to microbial activity, which in turn contributes to the amount of sulphide in the groundwater /Miller and Marcos 2007/.

5.2.3 Basic geotechnical properties

Friedland clay

Friedland clay blocks were used both in laboratory and in field tests performed at Äspö HRL. The raw material for the tests was the same (referred as F-clay B in Table 5-1), but the density of the test blocks differed, depended whether they had been compacted in a controlled laboratory environment or at a brick factory (in Bjuv Sweden in July 2006).

Originally, the aim was to use the optimum water content (11%) determined in /Johannesson and Nilsson 2006/ and a compaction pressure of at least 25 MPa, which had been demonstrated to result in production of a block having a maximum dry density of 2,000 kg/m^3. The original raw material had maximum granule size of less than 1 mm and a gravimetric water content of 8.4%. In order to test production of blocks, this material was moisture conditioned and mechanically compacted (via uniaxial compression). According to /Sandén et al. 2008/ the test blocks produced in Bjuv had a water content of 6.3%, a bulk density of 1,940 kg/m^3, a dry density of 1,820 kg/m^3, a degree of saturation of 33% and a void ratio (e) of 0.5. The estimated pressure used in manufacturing these blocks was only approximately 7 MPa rather than the 25 MPa needed to achieve the previously specified dry density of 2,000 kg/m^3. The resulting dimensions of the Bjuv blocks were 300×150×75 mm.

The liquid limit of the Friedland-clay used in the Bjuv blocks was 112% and the swelling index was 4.3 ml/g. Based on preliminary results by /Johannesson 2008/, blocks of this density level should yield swelling pressure of approximately 1.5 MPa and have a hydraulic conductivity of 2×10^{-12} m/s. Compared to the previous laboratory studies by /Johannesson and Nilsson 2006/ with a material from a different batch, there can be discernible variations in the results obtained using different Friedland clay batches. In these earlier studies the liquid limit of Friedland clay was 109% and the swelling index was 7.7 ml/g. The variation of swelling pressure and hydraulic conductivity of the Friedland clay as a function of dry density and water salinity is presented in the last part of this Section 5.2.3.

Asha 230 Na-bentonite

Two different batches of Asha 230 Na-bentonite were used in Baclo Phase II and Phase III investigations. In order to specifically identify the results for the two different batches of material, the one used in Baclo Phase II is named Asha 230A and the one in Phase III Asha 230B. The geotechnical index tests for Asha 230A and Asha 230B are presented in Table 5-7. The results imply that the 230B batch has a much higher smectite content compared to the 230A batch. This is supported by the swelling index results and recent mineralogical determinations performed by Geological Survey of Finland /Ahonen et al. 2008/.

Table 5-7. Geotechnical index test results for Asha 230A and Asha 230B.

	Asha 230A	Asha 230B
Liquid limit (%)	180	474
Swelling index (ml/g)	8.4	13.5
Reference	/Johannesson and Nilsson 2006/	/Johannesson 2008/

Based on the compaction tests performed by /Johannesson and Nilsson 2006/ using a compaction pressure of 25 MPa, the optimum water content is 17.3% resulting in maximum dry density of 1,700 kg/m^3. The change of swelling pressure and hydraulic conductivity of Asha 230A as a function of dry density and water salinity are presented in Figure 5-3 and Figure 5-4 respectively.

Mixture of bentonite and ballast (30:70)

The liquid limit of the Milos bentonite (IBECO Deponit CA-N, referred as Milos A in Table 5-1) used in the mixture was 157%, the initial water content was 16.3% and the swelling index (ml/g) was 5.3 ml /Johannesson and Nilsson 2006/. In order to compact blocks with a compaction pressure of 25 MPa, the mixture should have a water content between 7–8% in order to reach the pre-determined maximum dry density of 2,150–2,160 kg/m^3 /Johannesson and Nilsson 2006/. The variation of swelling pressure and hydraulic conductivity of the 30/70-mixture as a function of dry density and water salinity is presented in Figures 5-3 and 5-4 respectively.

Pellets and granules

Cebogel QSE pellets (referred as Milos pel. in Table 5-1) consist of activated Milos Ca-bentonite, pressed to form cylinder shaped pellets with diameter of 6.5 mm and length of 5–20 mm. According to manufacturers specifications, the Cebogel pellets have a dry density of 2,100 kg/m^3 and the bulk density of loosely-poured pellets will be 1,100 kg/m^3. Minelco granules (referred as Milos gr. in Table 5-1) consist of crushed and sodium-activated raw Milos Ca-bentonite, provided as granules with maximum size of 10 mm, but with a wide range of granule sizes. The maximum size of Friedland clay granules used in one test was approximately 10 mm.

The liquid limit and swelling index of Cebogel QSE pellets and Milos granules is presented in Table 5-8. The difference between the results may be due to slightly different test methods and variations in the quality of the specimen. The swelling index was determined in /Johannesson 2008/ using sample with size of 1.1. g and in /Ahonen et al. 2008/ using a sample with size of 2 g.

Swelling pressure and hydraulic conductivity

Figure 5-3 and 5-4 present the swelling pressure and hydraulic conductivity of Asha 230a and b, Friedland clay and 30/70-mixture as a function of density and salinity. The saline water was prepared mixing NaCl and $CaCl_2$ to deionized water in proportion of 50:50 (weight-%).

5.2.4 Mechanical parameters

The mechanical parameters determined for different block and pellet materials are presented in /Johannesson et al. 2008/ and in /Kuula-Väisänen et al. 2008/. The mechanical parameters used in numerical modelling for studying the compression of the backfill due to swelling of the buffer were selected from these reports and are presented in Section 6.3.3.

Table 5-8. Liquid limit (%) and swelling index (ml/g) of Cebogel QSE pellets and Minelco granules.

	Cebogel p.	Minelco gr.
Liquid limit (%) /Johannesson 2008/	576	334
Liquid limit (%) /Ahonen et al. 2008/	575	245
Swelling index (ml/g) /Johannesson 2008/	11.9	9.7
Swelling index (ml/2 g) /Ahonen et al. 2008/	28	30

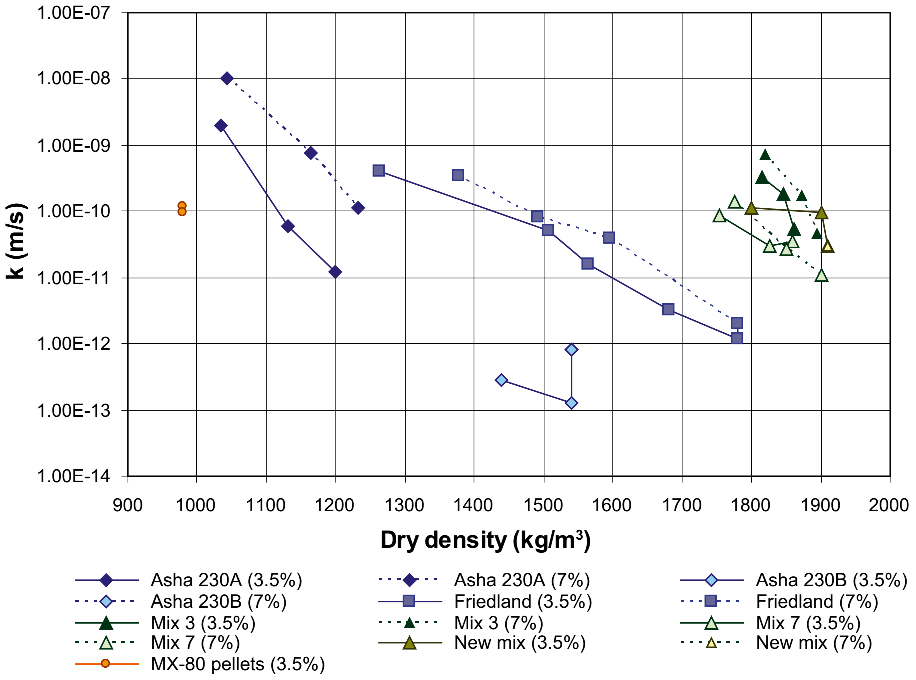


Figure 5-3. *Hydraulic conductivity as a function of dry density and salinity. Data from /Johannesson and Nilsson 2006, Sandén et al. 2008 and Johannesson 2008/. All mixtures tested have a bentonite content of 30%. Mixture 3 includes crushed rock with maximum grain size of 5 mm and no fine fraction (< 0.063 mm) as well as the new mixture. Mixture 7 includes crushed rock with maximum grain size of 5 mm and fine fraction of ~ 13%.*

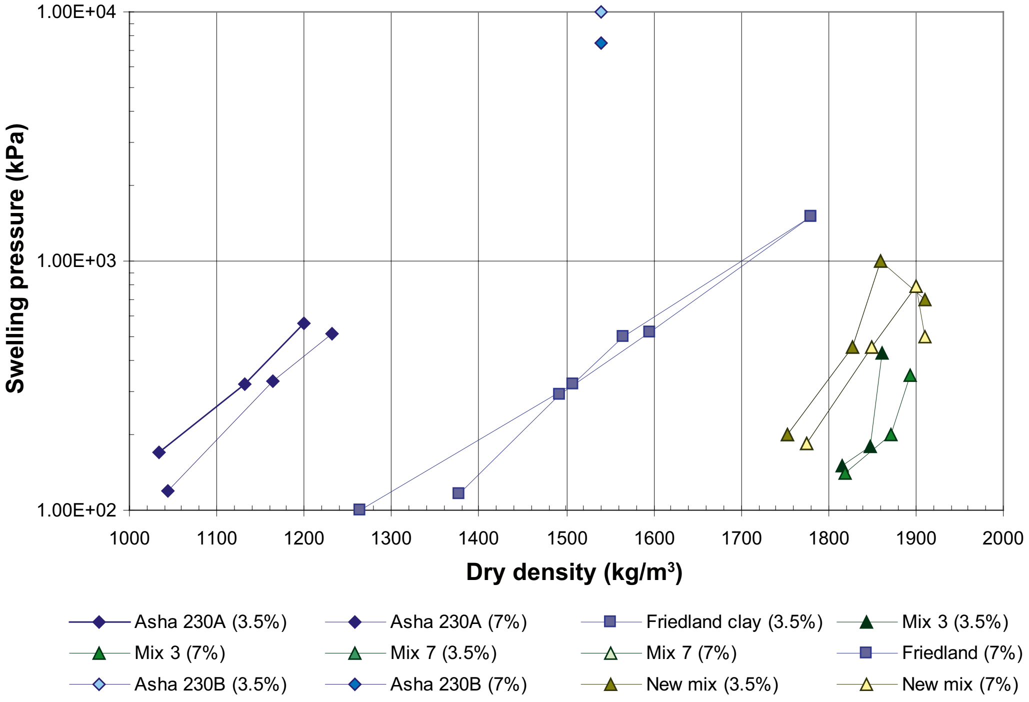


Figure 5-4. *Swelling pressure as a function of dry density and salinity. Data from /Johannesson and Nilsson 2006, Sanden et al. 2008 and Johannesson 2008/.*

5.2.5 Density criteria

The density criteria determined in /Johannesson and Nilsson 2006/ is presented in Table 5-9. The density criteria was determined in salinity of 3.5% (NaCl:$CaCl_2$, 50:50). In practice the dry density criterion means to what dry density the material should be compacted in order to meet the requirements set for a) hydraulic conductivity, b) swelling pressure and c) compressibility. For Asha 230a and Friedland clay, the determining material property is deformation, while for the mixtures it is either hydraulic conductivity or swelling pressure depending on the composition (from the data presented in Figures 5-3 and 5-4, hydraulic conductivity seems to be more critical). These densities are considered as minimum densities below which the material is not able to perform as required. Therefore, the material should be installed with sufficient safety margin. What is sufficient safety margin is a more complex matter. The safety margins are discussed further in Section 6.4.2 (average densities after saturation).

5.2.6 Summary

The materials used in the Baclo Phase III investigations are described in the preceding sections. The block materials tested were Asha 230 a/b bentonite, Friedland clay and mixture of bentonite and ballast (30:70). The pellet materials used in the Baclo phase III tests consisted of pellets (MX-80, Cebogel QSE) or granules (Minelco or Friedland clay granules).

The database on the mineralogy and chemistry of these materials is relatively limited. The results gained so far show relatively significant variations in the mineralogical composition of Asha 230 bentonite and Friedland clay. The second batch of Asha 230 (Asha 230b) used in the Baclo Phase III seems to have significantly higher montmorillonite content (~ 85%) than the material (Asha 230a) used in previous studies in Baclo Phase II (~ 60%). This conclusion is supported by the liquid limit and swelling index result for these materials. The high montmorillonite content of Asha 230b should be kept in mind when assessing the self-sealing results for the material (see Section 6-4, Homogenisation and self-sealing). Another issue to be considered with Asha 230b bentonite is its high iron content (14%) as reported by /Ahonen et al. 2008/.

The mineralogical composition of Friedland clay seems to vary considerably. This may be due to two reasons: a) differences between different material batches and b) difficulties in analysing the material due to the mixed-layer illite-smectite structure. Based on the geotechnical properties determined for these materials (e.g. hydraulic conductivity and swelling pressure), the apparent variations in the quality of this material do not seem to be as critical as for the Asha bentonite. However, if Friedland clay is still considered as a potential material for backfilling (based on its geotechnical properties and the results presented in the following sections), the natural mineralogical variations of this material will need to be assessed more thoroughly.

The materials originating from Milos (bentonite used in 30/70 mixture, Cebogel pellets and Minelco granules) seem that have more consistent mineralogical composition (the montmorillonite content varying between 75–85%) than the Friedland or Asha materials. The small differences e.g. in the liquid limit of between the various Milos-derived materials are likely attributable to differing degrees of Na-activation.

Table 5-9. The required dry densities for different backfill materials in order to fulfill the performance requirements in salinity of 3.5% based on Baclo Phase II laboratory studies by /Johannesson and Nilsson 2006/. See also Figure 2-1.

	Required dry densities (kg/m^3) based on:		
	Hydraulic conductivity	Swelling pressure	Deformation properties
Asha 230A	1,120	1,050	**1,160**
Friedland clay	1,400	1,350	**1,510**
Mix 3 (30:70)*	**1,850**	1,800	1,700
Mix 7 (30:70)**	1,700	**1,740**	1,700

* Ballast with maximum grain size of 5 mm and with no fine fraction (< 0.063 mm).

** Ballast with maximum grain size of 5 mm and with fine fraction of 13%.

A summary of the most critical mineralogical and chemical parameters (from the long-term safety point of view) for the clay materials used in Baclo Phase III is presented in Table 5-10.

The hydraulic conductivity and swelling pressure of the water-saturated candidate backfill materials depend on their density. The compressibility of a backfill material depends on mainly on the density state but also on the degree of saturation of the material (counter pressure produced by swelling of the material). Based on the studies made by /Johannesson and Nilsson 2006/, a dry density criterion was set for each material type (see Table 5-9). This information is also used in comparing the suitability of the materials proposed for use in backfilling the deposition tunnels.

Table 5-10. Summary of critical mineralogical and chemical parameters of the clays used in Baclo III investigations.

	Smectite content (%)	**CEC (cmol⁺/kg)**	**S_{tot} from XRF (%)**	**Reference(s)**
Block materials				
Friedland clay	~30	37–35	0.5	/Karnland et al. 2006, Carlson 2004/
Asha 230b*	~85	83–93	0.1	/Ahonen et al. 2008/
Milos bentonite (in 30:70 mixtures)	75–80	75–111	0.5	/Carlson 2004/
Pellets/granules				
Cebogel pellets	~80	99–103	0.5	/Ahonen et al. 2008/
Minelco granules	~80	83–99	0.3	/Ahonen et al. 2008/
MX-80	80–85	84–104	0.3	/Carlson 2004/

* Iron content up to 14%.

6 Processes considered in the backfill design

6.1 Introduction

As number of possible processes that can affect dimensioning of the block backfill concept were identified in /Gunnarsson et al. 2006/. Among these processes, those identified as being critical to backfilling and backfill behaviour were; 1) effect of water inflow during installation and early saturation of the backfill; 2) homogenization of the blocks and pellets as well as self-sealing of piping channels as a consequence of water saturation; and 3) deformation of the backfill due to swelling of the buffer.

Effects of water inflow include processes like saturation, formation of piping channels and erosion. The results from first attempts to study these processes are described in /Sandén and Börgesson 2006/ and further combined with new results gained in Baclo Phase III in /Sandén et al. 2008/ and summarized in Section 6.2. Tests aimed at studying homogenisation of the initially heterogeneous block and pellet backfill started in Baclo phase III. The previous investigations concerning deformation of the backfill due to swelling of the buffer are described in /Johannesson and Nilsson 2006/. These investigations were performed assuming that the backfill would already be in fully saturated state leaving uncertainty with respect to the system behaviour in unsaturated (backfill) state. This led to new investigations described in /Johannesson 2008/ and in Section 6.3.

The processes studied in Baclo Phase III were performed at three different scales; laboratory scale, 1/12 tunnel scale and ½ tunnel scale. These tests provided both materials properties and specific behaviour information but also allowed for assessment of the importance of test scale to the results. The objective of this section is to describe the investigations performed to study the issues related to scale (Sections 6.2, 6.3 and 6.4) and to discuss the processes and their consequences to the performance of the block backfill and the design requirements/specifications for the backfill in Section 6.5

6.2 Effects of water inflow during installation and early saturation

6.2.1 Introduction

The laboratory investigations and field tests described in this section were planned to study the effect of water inflow to the deposition tunnel during installation of the backfill and before the tunnel is sealed with a concrete plug. This is because before installation of the plug there can be a considerable water gradient through the backfill, potentially affecting the behaviour of the backfill. The main objectives investigations described in this Section (6.2) are to:

- study how water saturation propagates in the block/pellet system,
- determine under what conditions piping and erosion takes place in the block/pellet system, and
- gain input data for estimating the magnitude and consequences of erosion for the long-term behaviour of the backfill.

6.2.2 Conceptual model for early saturation and formation of piping channels

Water inflow into the deposition tunnel will take place mainly through fractures and will contribute to the wetting of the backfill. However, if the inflow is localized to fractures that carry more water than the swelling bentonite can adsorb, there will be a water pressure developed in the fracture acting on the backfill. The backfill close to the rock surface initially consists of pellets with low density and large pore space between the pellets. As a result the backfill may not be able to stop the water inflow due to the water pressure that will develop in the fracture.

There are three processes involved in the early saturation phase, namely *piping* (formation of an open channel/channels where the water can flow, possibly leading to internal erosion), *water filling* (of the empty space between the pellets), and *erosion* (of the bentonite particles in the channels where the water flows).

Piping in general will take place and the pipes remain open if the following three conditions are fulfilled:

1. The water pressure in the fracture, when the water flow is prevented, must be higher than the sum of the counteracting total pressure from the bentonite and the shear resistance of the bentonite.
2. The hydraulic conductivity of the bentonite must be so low that water flow into the bentonite surrounding the pipe is slow enough that the water pressure is raised i.e. the absorption rate of the bentonite must be slower than the inflow rate of the water.
3. There is a downstream location available for the deposition of flowing water and the removal of eroded materials.

All three of the above-listed conditions are fulfilled in the pellets filling of the backfill during the initial stages of water uptake, in the period immediately following backfill installation. The consequence of piping will be development of a preferential channel leading the flowing water out to dry or unfilled parts of the repository. Since the bentonite swells the channel should reduce in size with time, but if the erosion counteracts the swelling action and removes bentonite particles, moving them as suspended sediment to the outflow location and increasing the size of the channel. There is thus a competition between swelling bentonite and eroding bentonite. However, if the inflow rate is low and the increase in water pressure slow, the pipe may seal before water pressure equilibrium has been reached.

Water filling of the pore space between the pellets takes place as long as there are dry pellets with open voids available, if the water pipe does not hit the open surface of the backfilling front. If the water pathway does reach the open backfilling front, the filling of the void spaces will slow or cease and water will move to the free surface. When a watertight plug has been built in the end of the deposition tunnel, the internal piping may not cease until most of the pore space between the pellets in the tunnel has been water-filled.

Erosion will take place if the drag force on the clay particle due to water movement is higher than the sum of the friction and attraction forces between the particle and the clay structure.

If the water pipe reaches the backfilling front, the water in the channel will flow out from the backfill into the unfilled part of the tunnel. If this occurs, the most likely scenario is that a majority of the water entering the tunnel will continue to flow out from the backfill until the channel has been closed.

The water filling process is complicated since it is affected by piping, which in turn depends on the inflow rate and the pellets composition. The direction of the water flow is so sensitive to small variations that it can be described initially as random. However, it is also affected by small density variations and variations in pellets composition. This means that the water filling process most likely depends on the technique used to place the pellets and the existence of layers with small density variations caused by variations in filling sequence.

Since the water filling of the empty pores between the pellets has an important influence on the backfilling feasibility, a large number of tests of this process and the subsequent erosion have been performed in order to develop a probabilistic database for system evolution.

After completion of water saturation and homogenisation of the buffer and backfill and re-establishment of the hydrostatic water pressure, the water pressure and swelling pressure will interact according to the effective stress concept. The pipes or openings caused by erosion will heal over time and a homogeneous swelling pressure will be established if the density and resulting swelling pressure are high enough to overcome the internal friction. Later on, after the tunnel has been sealed, there is very little risk of piping since piping requires a strong and fast increase in water pressure gradient locally in the rock at the contact with the backfill.

6.2.3 Laboratory-scale tests focusing on effects of water inflow

Laboratory-scale tests where early saturation was studied were made in two different laboratories in Sweden and in Finland. The tests are described in detail in /Sandén and Börgesson 2006, Sandén et al. 2008 and Kuula-Väisänen et al. 2008/. Common for all these tests was that a constant water flow with specified water inflow rate (l/min) or pressure and salinity were applied to an initially unsaturated specimen. The water inflow rates were varied from 0.001 l/min to 1 l/min and the salinity of the water was either 0% (tap water), 1% or 3.5% (NaCl:CaCl2, 50:50). The duration of the tests varied from less than an hour to 53 days. The test types are presented in Figures 6-1, 6-2, 6-3 and summarized in Tables 6-1 and 6-2. The observations made during the tests were propagation of the saturation front, formation of piping channels, swelling, erosion and in some cases hydraulic conductivity. It should be noted that none of these tests were based to any specific test standard, as none exist for evaluation of these parameters.

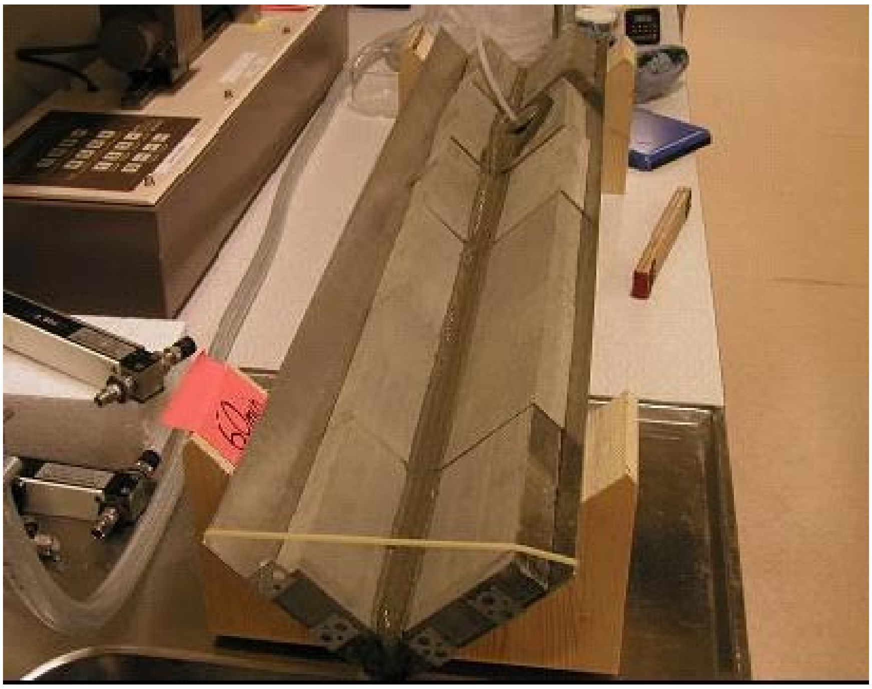


Figure 6-1. *Example of the block saturation/erosion tests performed for pre-compacted Friedland-clay blocks by /Sandén et al. 2008/. In these tests a one meter long steel profile with inclination of 1° was filled with backfill blocks. A constant water flow was applied at one end and the amount of eroded material was measured in the other end.*

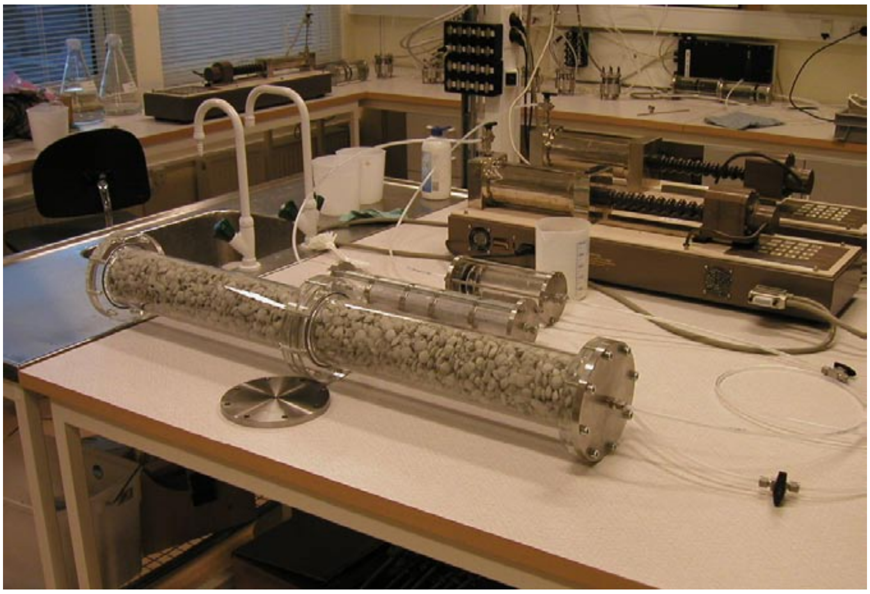


Figure 6-2. *Example of plexiglas tube tests performed by /Sandén et al. 2008/. The plexiglas tube had an inner diameter of 100 mm and a length of 1 m. The water flow was applied on the right-hand side of the tube and the amount of water outflow and erosion was measured from the other end.*

Figure 6-3. *Example of large slot tests performed by /Sandén et al. 2008/ for different types of pellet materials. The test setup is simulating the pellet filled section between the backfill blocks and the rock. The artificial slot had dimensions of 2×1×0.1 m.*

Figure 6-4. *Example of the saturation tests performed by /Kuula-Väisänen et al. 2008/. The test setup consisted of a plexiglas tube with inner diameter of 0.1 m. Water was fed to the system from above until the the test cell was filled with water. After that the water pressure head was increased from 0.5 m up to 40 m (corresponding to pressure of max 0.393 MPa and ~ 4 bar). The specimens were allowed to swell in the free space above the blocks. The specimens consisted of blocks (with initial height of 50 mm) and a combination of blocks and pellets.*

Table 6-1. List of laboratory-scale tests performed in Sweden in order to study the effect of water inflow on backfill materials.

Test	Material/materials	Inflow rate/ rates (l/min)	Salinity (%)	Duration (hours)	Measured parameters/ observations made
Erosion of pre-compacted blocks /Sandén et al. 2008/	Friedland clay blocks prepared in Germany (ρ_{dry} 2,075 kg/m^3)	0.01	tap water, 1%, 3.5%	8	Saturation and erosion (g/l). Special interest: effect of time on erosion.
		0.1	1%	8	
		1	tap water, 1%	8	
	Friedland clay blocks prepared in Bjuv, Sweden (ρ_{dry} 1,820 kg/m^3)	0.01	1%	55	
		0.1	1%	24	
Plexiglas tube tests /Sandén et al. 2008/	Mixture of MX-80 pellets (55 w-%) and bentonite powder (45 w-%)	0.01, 0.1	1%, 3.5%	50	Saturation, formation of piping channels, erosion (g/l) and pressure build up. Special interest: effect of fine fraction on erosion rate.
	MX-80 pellets without powder	0.01, 0.1	1%, 3.5%	50	
	Minelco granules	0.01, 0.1	1%	50	Saturation, formation of piping channels, erosion (g/l) and pressure build up. Special interest: effect of pellet type.
	Friedland clay granules	0.01, 0.1	1%	50	
	Cebogel QSE pellets	0.01, 0.1	1%	50	
Earlier plexi-glas tube tests /Sandén and Börgesson 2006/	MX-80 pellets	0.001, 0.01, 0.1, 1	tap water, 1%, 3.5%	3–150	Saturation, formation of piping channels, erosion (g/l) and pressure buildup.
	30/70	0.001, 0.01, 0.1	1%	0.25–8	Saturation, formation of piping channels, erosion (g/l) and pressure buildup.
Large-slot tests /Sandén et al. 2008/	MX-80 pellets	0.01, 0.1, 1	1%	8, 24, 70	Propagation of the saturation, formation of piping channels and erosion (g/l).
	Cebogel QSE pellets	0.01, 0.1, 1	1%	24, 70	

The results from these laboratory scale tests are discussed in detail in the following Sections 6.2.4 (Saturation and formation of piping channels observed in laboratory tests) and 6.2.5 (Erosion observed in laboratory scale tests).

6.2.4 Saturation and formation of piping channels observed in the laboratory tests

Based on the test performed in a plexiglas tube, artificial plexiglas slot and in plexiglas permeameters (see Section 6.2.3 for description of these tests), pure clay materials behave differently from the 30/70 mixture. Formation of piping channels were not observed for the 30/70 mixture, not even when the water pressure was increased to the allowed maximum for the equipment, 1.2–1.4 MPa /Sandén and Börgesson 2006/. In addition, it was observed both by /Sandén and Börgesson 2006/ and /Kuula-Väisänen et al. 2008/ that water moved as a continuous front through the specimen (see Figure 6-5). Another observation made in the tube-test performed in /Sandén and Börgesson 2006/ was the high pressure generated in the test setup (up to > 1.4–1.5 MPa), led in many cases to gross movement of the 30/70 specimen as a coherent plug in the downstream direction and in one case breakage of the test tube occurred. The specimen had initial dry density of 1,600 kg/m^3. The explanation for this behaviour may be the relatively low hydraulic conductivity combined with high internal friction of the material and lateral confinement of the test setup.

The pure clay materials examined (pellets, blocks) tended to behave differently from the 30/70 mixture in these laboratory-scale tests. In most cases, the water eventually formed a preferential flow path through the specimen that stayed open as long as there was a water gradient through the specimen (see Figure 6-6). It should be noted that the flow paths usually formed at the contact between the specimen and the wall of the plexiglas test cell/tube (assumingly in the areas of lowest water flow resistance).

Figure 6-5. *Example of the propagation of a saturation front in a 30/70 mixture (inflow 0.01 l/min, salinity 1%).*

Figure 6-6. *Formation of preferential flow paths in MX-80 pellets /see Sandén et al. 2008/ and in combination structure consisting of Friedland clay blocks and MX-80 pellets /see Kuula-Väisänen et al. 2008/.*

The time when the formation of the preferential flow path (piping) occurred and how much water was absorbed by the specimen before this time depended on the material type (e.g. granule size distribution) as well as the inflow rate. Differences in the water uptake and wetting patterns at low water inflow rates (≤ 0.1 l/min) are evident e.g. when comparing the wetting patterns for MX-80 pellets and Cebogel pellets (see Figure 6-7). At higher water inflow rate (1 l/min) the time for first water outbreak was the same for both MX-80 and Cebogel pellets (20 minutes), but at the end of those tests the Cebogel pellets had taken up more water than MX-80 pellets and the MX-80 pellets had formed a clear outflow channel (see Figure 6-8).

Another general observation made in the slot tests by /Sandén et al. 2008/ was that the friction angle of the air-dry pellet material was approximately 45° after installation and it did not change during the tests, i.e. the subsequent partial saturation of the pellet fill did not seem to affect the angle of the pellet slope.

Figure 6-7. Differences in the wetting patterns of MX-80 pellets (on the left) and Cebogel pellets (on the right), 48 hours after the inflow (0.01 l/min) started. The Cebogel pellets show more uniform wetting compared to MX-80 pellets. It should be also noted that with low inflow rates the wetting also takes place upwards and radially, and not only downwards as the result of gravimetric effects.

Figure 6-8. Formation of preferential water pathway through MX-80 pellets when the inflow was 1 l/min, /see Sandén et al. 2008/. Note also the more gravimetrically-influenced flow pattern compared to that observed at lower inflow rates (≤ 0.1 l/min).

6.2.5 Erosion observed in laboratory-scale test

Erosion of Friedland clay blocks

The test blocks used in block erosion tests reported by /Sandén and Börgesson 2006, Sandén et al. 2008/ were made with the Type 1 and 3 blocks as shown in Table 6-2. The Type 1 blocks were manufactured in Germany already for previous phase of the Baclo programme /see Gunnarsson et al. 2006/. The Type 3 blocks were produced in Höganäs Bjuv AB brick factory located in southwestern Sweden for use in the Äspö field tests. The Type 2 blocks were not used in the laboratory tests since these blocks were produced only to check the compaction and block dimension parameters for the actual block production activity. The reason for the low density of Type 3 blocks (referred to as "Bjuv blocks" in much of the text discussing erosion studies) was that the compaction pressure applied was only 7 MPa (due to initially undetected technical difficulties), instead of the intended 25 MPa. In addition, the water content of the material was significantly lower than in the previous block compaction tests, a factor that also affected the density attained and the durability of the blocks.

Table 6-2. Friedland clay blocks produced with a full-scale production equipments for Baclo. The Type 1 tests blocks were used in the erosion tests described in /Sandén and Börgesson 2006/ and the Type 3 in erosion tests reported in /Sandén et al. 2008/.

Sample	w0 %	Bulk density kg/m³	Degree of saturation %	Void ratio e	Dry density kg/m³
Type 1. Friedland block, test series phase 2	10.8	2,300	88.51	0.339	2,075
Type 2. Friedland block, test Bjuv april 2006	8.6	2,180	62.20	0.385	2,010
Type 3. Friedland block, production july 2006	6.3	1,940	33.26	0.526	1,820

Despite the problems encountered in production of the Type 3 blocks they were cohesive, relatively durable and so were used in both the laboratory erosion tests described below as well as in the field tests described in Sections 6.2.6 and 6.2.7. The lower achieved density meant that erosion test results using these blocks would be conservative in nature. Additionally in the field-scale tests (~ 1/12- and ½-scale), such lower durability blocks provided a conservative set of results regarding backfill durability. Results of initial field trials (Section 6.2.5) determined that the block materials played a secondary role in initial water uptake and movement in a backfill system. As a result, the lower-density of the Type 3 blocks would not result in non-conservative results or alter the basic behaviour observed in these tests.

The results from the erosion tests performed using Friedland clay blocks by /Sandén et al. 2008 and Sandén and Börgesson 2006/ are presented in Figure 6-9 and 6-10.

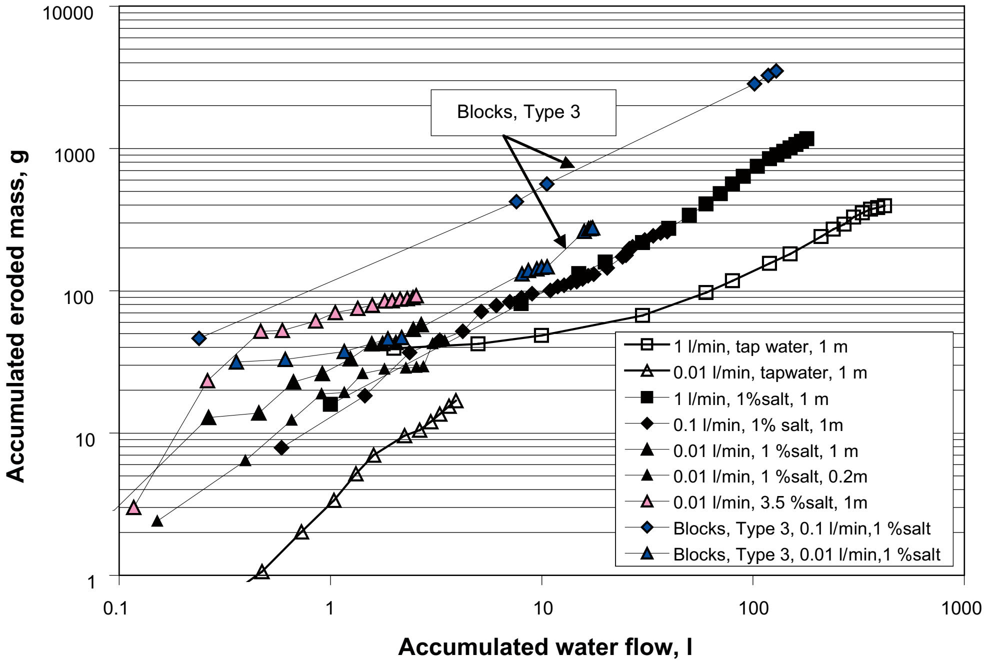


Figure 6-9. Accumulated eroded mass (g) versus the total water in flow (l) for type 1 and 3 Friedland clay blocks gained in the "steel groove" tests performed by /Sandén et al. 2008 and Sandén and Börgesson 2006/.

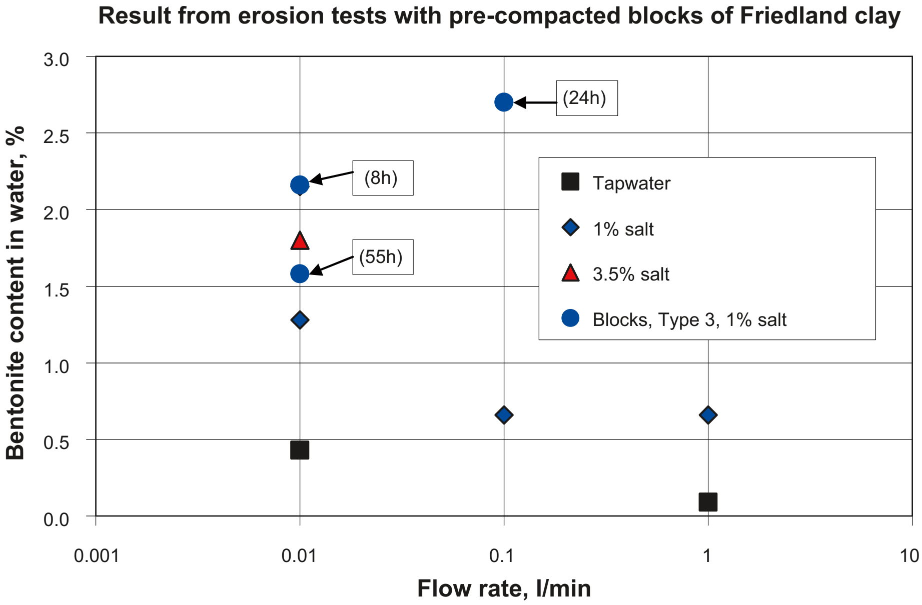


***Figure 6-10.** Effect of inflow rate (l/min) on the average clay content (%) in the discharged water measured in the "steel-groove" tests for type 1 and 3 Friedland clay blocks /see Sandén et al. 2008/. The largest clay content in the discharged water (~ 2.5%, ~ 25 g/l) was measured for the Bjuv blocks (blue dots, test series 2).*

The conclusions that can be drawn from the erosion tests provided by /Sandén et al. 2008 and Sandén and Börgesson 2006/ are as follows:

- The salt content of the water seems to affect the average amount of eroded clay particles in the discharged water. For tap water the average quantity of clay particles in the discharge water was 1–4 g/l (0.1–0.4%) when testing with inflow rates of 0.01 and 1 l/min. For 1% and 3.5% saline water, the corresponding value was 6–25 g/l (0.6–2.5%) for all tested inflow rates (0.01, 0.1 and 1 l/min).
- The water inflow rate (0.01, 0.1 and 1 l/min) did not have any clear influence the average amount of eroded particles per litre in the measured from discharged water (see Figure 6-10).
- The density of the blocks seems to influence the sediment per litre of discharged water, since the highest average amount of eroded clay particles (25 g/l) in the discharged water) occurred in the low-density Bjuv blocks. For the higher-density blocks (Type 1 and 3), the average amount of eroded clay particles (g/l) measured in the discharged water was between 1–14 g/l for the Type 1 blocks (ρ_{dry} 2,075 kg/m^3) and 8–25 g/l for the Type 3 Bjuv blocks (ρ_{dry} 1,820 kg/m^3).
- There is a small tendency for the erosion rate to decrease with time based on tests with durations of 8, 24 and 55 hours.
- The length of the test setup (0.2 or 1 m) did not seem to have any significant effect on the amount of erosion in these tests.

The scatter of the erosion results for Friedland clay blocks presented in /Sandén et al. 2008 and Sandén and Börgesson 2006/ can be explained by the variations in the salinity and differences in the initial dry density of the test blocks. It should also be kept in mind that the number of replicated tests (with exactly the same parameters) was rather small.

The saturation and erosion tests reported in /Kuula-Väisänen et al. 2008/ were performed using Friedland clay block assemblies consisting of 4 block pieces with initial dry density of approximately 2,000 kg/m^3. The tests were done in a rigid-wall permeameters made of plexiglas. It should be noted that the test setup allowed the specimen to swell, thus the density of the specimens decreased during the test. At the beginning of the tests, the cell was filled with water at an inflow rate 0.001 l/min, after which the water pressure was increased up to 40 m (~ 0.4 MPa). The amount of eroded clay was measured as function of time and water outflow. For Friedland clay the measured amount of clay particles was 0.02 g/min when the water outflow was 0.0097 l/min (at water pressure of 40 m) leading to erosion of approximately 2 g/l. In the block-pellet combination test, no erosion was observed for the Friedland clay. In a little larger-scale test performed with a block assemblage consisting of Bjuv 4–6 pieces of blocks, the erosion during the first day was 4 g/l, after which there was no erosion (at water pressure of 10 m) /see Kuula-Väisänen et al. 2008/. Since the tests were not specially designed for testing erosion, the test results should be interpreted to as tentative of nature.

Erosion of Asha and 30/70-blocks

Few erosion tests were performed with Asha 230b or 30/70 blocks. According to saturation and erosion tests performed by /Kuula-Väisänen et al. 2008/ for a block assemblage consisting of 30/70 mixture, no erosion was observed at a water pressure of 40 m. The tube-test performed in /Sandén and Börgesson 2006/ for 30/70 mixture in dry density of 1,600 kg/m^3 and 1,800 kg/m^3 showed that in most of the cases the erosion could not be measured at all, perhaps as the result of the test setup and/or due to the material properties. The only case where discernible erosion took place (specimen B:221-2, dry density 1,600 kg/m^3, water inflow of 0.001 l/min, 1% salinity) the total erosion was 18 g in three days (3 g/l based on the total water *inflow* over four days).

For Asha 230 blocks the amount of eroded clay particles in the discharged water was 79 g/l (calculated from erosion of 1 g/min and outflow of 0.0126 l/min) at a water pressure of 40 m /Kuula-Väisänen et al. 2008/.

Erosion of pellets

The erosion of different type of pellets/granules were measured by /Sandén and Börgesson 2006 and Sandén et al. 2008/ with two different test setups “tube-test” and “slot-test” described in Section 6.2.3. Some examples of the results gained from tube-tests are presented in Figures 6-11 and 6-12.

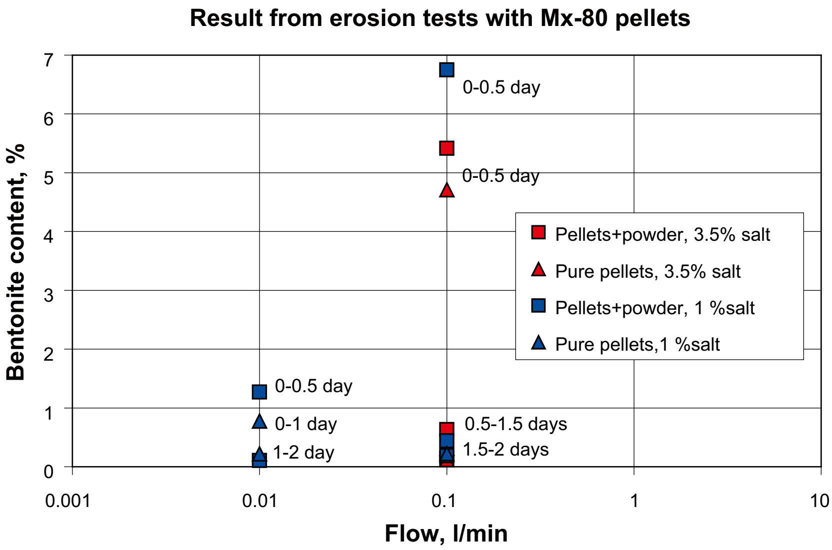


***Figure 6-11.** Bentonite content (%) measured from samples taken from the discharge water at different times for pure MX-80 pellets and MX-80 pellets mixed with powder and plotted against inflow rates. Although the powder is eroded initially, the erosion decreased with time for both materials. After one day the bentonite content in the discharge water was ~ 1–3 g/l (0.1–0.3%) in all tested cases. See /Sandén and Börgesson 2006, Sandén et al. 2008/.*

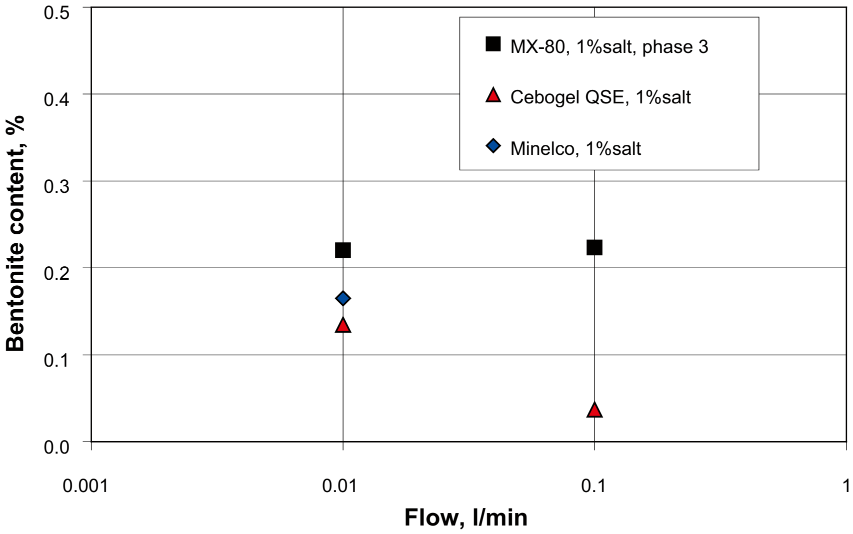


Figure 6-12. *Content of eroded particles in percent measured after 24 hours in samples taken from the discharged solution for different pellet materials and plotted against inflow rates /Sandén and Börgesson 2006, Sandén et al. 2008/.*

The general conclusions from the "tube-tests" performed by /Sandén and Börgesson 2006, Sandén et al. 2008/ are as follows:

- For the MX-80 pellets mixed with some extra powder (55 w-% pellets, rest being powder), the erosion was higher in the beginning than when pure MX-80 pellets were tested (see Figure 6-11). This difference is likely to be due to flushing of the loose fine fraction originally between the systems. After 5–10 hours the differences in the erosion rate began to decrease and after 24 hours there was no difference between the specimens, indicating that addition of small quantities of dry bentonite powder is not going to substantially alter initial water movement in the pellet-fill.
- There is a tendency for the erosion to decrease with time (see Figure 6-11). After 24 hours, the average clay content in the discharged water was 1–3 g/l for all tests performed with MX-80 pellets.
- Salinity increased the erosion initially, but erosion decreased over time.
- In some cases, where the pressure inside the test setup built up to 1 MPa, it was not possible to measure any erosion. It may be that this type of method, where the specimen is placed to such a confined conditions, is not necessarily optimal for measuring erosion of materials with high swelling capacity. This is because swelling leads to sealing and decrease in erosion. It is possible however that this behaviour might also happen in a deposition tunnel.
- Pellets and granules behave differently when inflowing water contacts them. High water pressure buildup (resistance to water inflow into clay) was observed for tests with Minelco and Friedland granules and the tests were terminated in advance to avoid damaging the test equipment. This process was probably also the reason why erosion could not be measured at all for three of the tests performed with these materials. Since the Cebogel pellets and Minelco granules have almost the same raw material (Activated Ca-bentonite from Milos), the difference in the behaviour must be due to the difference in the open space between the pellets/granules (macro porosity). Due to range in the size of the granules, the particle packing is more effective for Minelco granules than for single-size pellets. Therefore, the water inflow led to rapid swelling of the material and pressure build up in the confined test conditions.
- The erosion rate per litre of exiting water measured after 24 hours for alternative pellets materials (Cebogel QSE pellets and Minelco granules) was very similar to the results gained for MX-80 pellets. The erosion rates measured for all of the materials was below 3 g/l (< 0.3%).

Erosion was also measured at a slightly larger scale in the laboratory. These larger scale “slot-tests” described in Section 6.2.3 also provided a measure of material removal rate. The main differences between the tube-tests and the slot-test are in the scale, geometry and confinement of the test setup. In the slot tests, the erosion was measured for two different pellet materials, MX-80 and Cebogel pellets. The amount of erosion was higher for MX-80 pellets than for Cebogel QSE pellets (see Figure 6-13). This may be due to higher fine fraction in the MX-80 pellets, but the higher water content and dry density of the Cebogel pellets may also affect the behaviour /Sandén and Börgesson 2006, Sandén et al. 2008/.

When comparing the results from the two different scale tests, (tube-tests and slot test), performed by /Sandén and Börgesson 2006, Sandén et al. 2008/ it can be concluded that the test scale and/or setup affected the results. For example, the accumulated mass of eroded particles was significantly higher for MX-80 pellets tested with the slot test (< 1,500 g) than when tested with the tube test (~ 500 g), although the other parameters were the same (inflow 0.1 l/min, 1% salinity, 24 hours). For Cebogel pellets the difference between the two test types was insignificant. However, the number of tests performed using Cebogel pellets was smaller than for MX-80 pellets.

Based on the erosion of MX-80 pellets and Minelco granules observed in tests by /Kuula-Väisänen et al. 2008/, both materials are prone to erosion at relatively low inflow rates (0.01 to 0.1 l/min). The amount of eroded particles measured approximately 24 hours after start of the in the outflow water was higher for MX-80 pellets (up to 18 g/l) than for Minelco granule (0.8 g/l). These tests were done with saline water of 3.5% salinity (NaCl:$CaCl_2$, 50:50 in weight-%).

6.2.6 1/12-Scale tests at Äspö

Using the information gained by bench-scale tests intended to develop a basic understanding of water uptake and movement through backfill materials described in Section 6.2.3 through Section 6.2.5, a first up-scaling of the tests was undertaken. These field-scale tests examined the manner in which water enters and is distributed within a volume of backfill installed in ageometry similar to that proposed for tunnels and rooms. They also contained both block and pellet materials in proportions equivalent to what might be present in an actual KBS-3V emplacement tunnel. The first series of up-scaled tests (cross-sectional area of ~ 1.57 m^2) were installed in 2-m diameter mockups

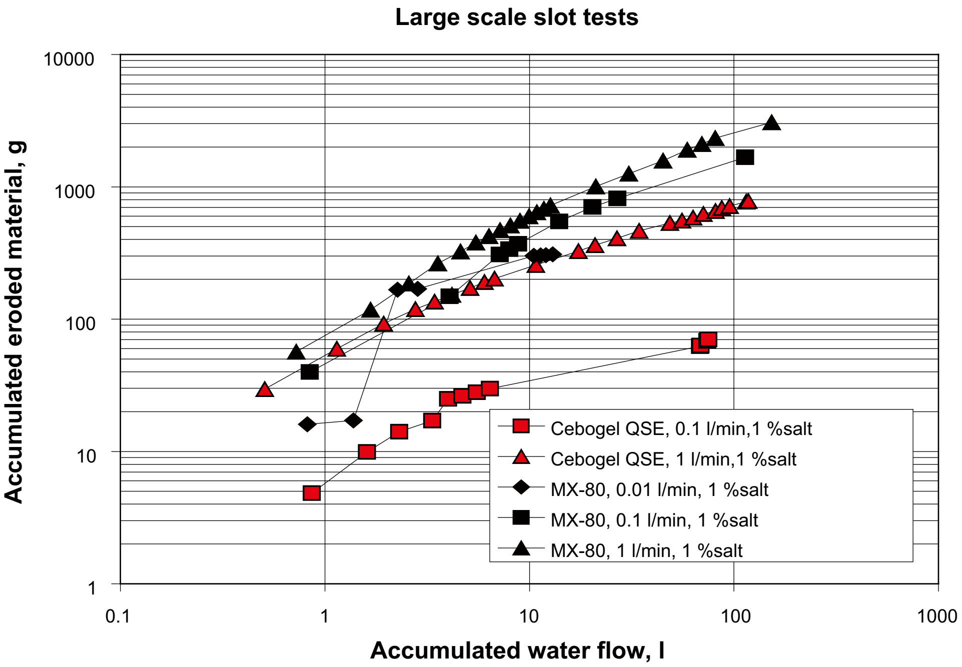


Figure 6-13. Erosion measured for MX-80 and Cebogel QSE pellets in /Sandén and Börgesson 2006, Sandén et al. 2008/.

at SKB's Äspö HRL. Depending on the KBS-3V tunnel geometry selected this represents tests at a scale of between 1/12 and 1/16. At the start of Baclo Phase III these tests represented a 1/12-scale simulation and hence for descriptive purposes in this report they are referred to as 1/12-Scale tests. Subsequent to these 1/12-Scale test even larger scale field tests, done at ½-tunnel scale were undertaken at Äspö and the results of those are described in Section 6.2.7.

Test setup

These 1/12-Scale tests were the first set of tests conducted at a scale of more than ~ 0.5% of the cross-sectional area of an actual tunnel and were done at the 420 level at SKB's Äspö Laboratory as part of the Baclo program. Although other backfilling tests have been undertaken in other Äspö Laboratory studies, these were designed to allow for real-time monitoring of flow and subsequent rapid excavation to determine where and how water moved through a pellet and block backfill system. These are also the first that examined the block-pellet backfilling concept at field scale.

The1/12-Scale tests utilized a 2 m-diameter by 1.6 m-long section of concrete pipe to simulate a section of tunnel (Figure 6-14 and Figure 6-15). Within the pipe two sub-cells were constructed, each having a cross-sectional area of approximately 0.9 m^2. This test setup was approximately 1.9 m^3 in volume and represents approximately 1/12 of the volume of a KBS-3V emplacement tunnel.

A series of 27 1/12-scale tests were done as part of this study. These tests are of particular relevance in determining what might occur in situations where backfilling operations were interrupted for some length of time, without installation of a temporary or permanent concrete plug 1/12 scale and can assist in identifying some limiting criteria for water influx rate, above which some remediation of the surrounding rock (grouting) would be necessary. Determining inflow thresholds will provide guidance to planning of repository backfill operations. This will also help to identify conditions where special water control will be necessary (e.g. drainage, grouting or alternative backfilling approach) in order to achieve effective backfill placement.

Test matrix and parameters examined

A summary of the tests done as part of this study is provided in Table 6-3. Tests operated for 5, 24, 48 or 120 hours and inflow rates ranging from 0.01 to 1.0 l/min. The range of operating times and inflow rates were intentional, allowing assessment of water uptake patterns /Dixon et al. 2008a, b/.

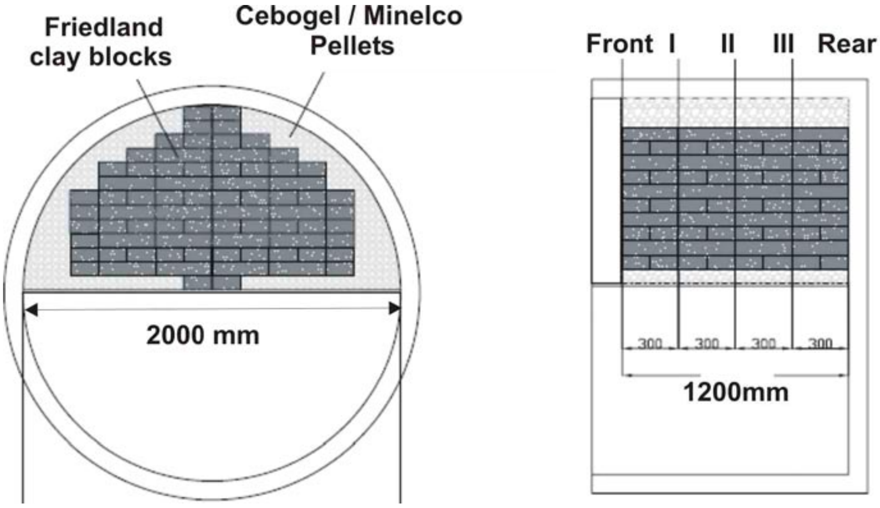


Figure 6-14. Schematic showing 1/12 scale test layout.

Figure 6-15. *Photographs showing assembly of 1/12 scale tests. (Note water inflow lines in upper left photograph, water collection buckets have load cells measuring mass of material entering the collection system.)*

Table 6-3. 1/12-Scale Tests: Parameters examined in each assembly.

Test #	Material used	Water inflow rate (l/min)	Testing time (h)	Purpose of the tests were to determine:
1	Blocks	nil	~350	Effect of humidity
2	Blocks, Granular	0.10	210	Effect of water dripping directly onto blocks
3–8	Blocks, Pellets	0.01 to 1.00	5–118	Water transfer through assembly
9–12	Blocks, Pellets	0.01 to 0.25	5–24	Water transfer through assembly, Effect of gaps between blocks
13–22	Blocks, Pellets	0.10 to 0.50	5–100	Effects of inflow rate and time on water transfer through and distribution in pellets and blocks
23–24	Blocks, Pellets	0.10, 0.25	24	Effect of water inflow from tunnel floor
27–29	Blocks, Granular, Pellets	0.25	120	Effect of water inflow on a system built using granular bentonite as a flooring material

Although the primary interest in these tests was to examine the behaviour of a completely backfilled tunnel section, the first two tests examined what would happen if backfilling operations were to be interrupted in a tunnel section prior to installation of the pellet component. The other tests examined clay block assemblies that occupied approximately 80% of the cell volume with the remainder occupied by bentonite clay pellets (or granules). In order to evaluate some of the concerns related to the influence of the thickness of the pellet-filling raised in the laboratory-scale tests care was taken to provide these assemblies with enough pellet materials to mitigate the effects of inflowing water on the blocks. The blocks were placed on a 75 mm-thick floor of bentonite and the remaining annular gap between the blocks and the cell walls was 100 mm or greater.

The test chamber was equipped with water inlet ports that supplied water (collected from a nearby fracture) to the test. Water could be supplied at a constant rate to either the floor or wall of each of the cells at the midpoint along the length of the test. Cells were separately supplied with water at a preset rate and the resistance to water inflow was constantly monitored. The downstream face was equipped with a mesh that allowed water to drain from the assembly but limited deformation. In many tests the water exiting was collected to determine total water uptake as well as allowing comparison of inflow and outflow rates at various times. Additionally, a number of the tests were operated in a manner that allowed for regular measurement of the sediment load in the outflow water. After testing, each cell was carefully disassembled and extensively sampled to determine water distribution within the test and to identify any piping or erosion.

It should be noted that the Friedland clay blocks used in all these tests were not as dense as specified in the reference design (dry density of 1,820 kg/m^3 versus 2,000–2,100 kg/m^3). This would make them weaker and more prone to erosion than would be the case in an actual repository application (see Section 6.2.5 for discussion on block erosion) /Sandén and Börgesson 2006, Sandén et al. 2008/. As previously completed using smaller-scale tests of pellets and blocks indicated that the behaviour of the pellet-block assembly will be controlled by the pellet component /Dixon et al. 2008a/, it was decided that these blocks would be suitable for use and any results where the blocks influenced the behaviour of the assembly would provide conservative bounds for performance.

Test results

The results of the 1/12-scale tests have been reported in detail by /Dixon et al. 2008a, b/ and are only briefly summarized below.

The first test was an unsupported block assembly that sat undisturbed in a "dry" tunnel environment (high humidity but no liquid water) for a period of approximately 2 weeks. This assembly was stable, showing only slight water uptake from the surrounding atmosphere by the outermost blocks.

In the second test, water dripped directly onto the clay blocks. Figure 6-16 shows the result of influx of 0.1 l/min of natural fracture water (1% TDS, mainly Na-Ca Cl), dripping from a height of only a few millimeters onto the top of a block assembly over an 8-day period. The water contacting the unconfined clay blocks rapidly caused their disruption and ultimately the assembly collapsed under its own weight. Two processes were active in this test. The first was swelling and slumping caused by clay hydration as seen in Figure 6-16. The second process was weakening of the basal blocks due to hydration as shown in Figure 6-17, a process also noted in field-scale block assembly tests done subsequent to the 1/12 scale tests /Wimelius and Pusch 2008/. This allowed the assembly to tilt, exacerbating the surface erosion and slumping of the outer portions.

Figure 6-16. *Effect of water dripping on unprotected and unsupported clay block assembly. (Water dripped from mid-point of wooden crossbars /Dixon et al. 2008a, b/).*

Figure 6-17. *Weakening of blocks due to water uptake. (Dark region at base of photo are wet blocks that have begun to deform, light-coloured material at base is wet bentonite pellet material /Dixon et al. 2008a, b/).*

Although a wide range of inflow conditions were examined in the course of this study and each of the 25 tests had unique patterns of water movement, there were general behavioural trends that could be extracted from them. Examples of the general patterns of inflow rate, outflow rate and resistance to inflow observed are shown in Figure 6-18 (for tests done at 0.1, 0.25 and 0.5 l/min inflow). It can be seen that there was rapid development of high outflow rates within a few hours of the water exiting the downstream face of the assemblies. The block and pellet assemblies were also not able to cause a substantial delay in the outflow of water form the assemblies. Observations and measurements made during disassembly of these tests showed that none of these tests were at-or-near full saturation of the pellet fill and that only a small quantity of water had been taken into the blocks at the time of first water outflow. This establishes that there is only a limited short-term storage capacity in the assembly and pore volume (either macro (between pellets) or micro (within pellets or blocks) cannot be relied on to delay water movement along the tunnel axis in the time immediately following backfilling.

In order to quantify the water distribution within the pellet-filled portion of these tests, careful sampling was done at depths of 0, 0.3, 0.6 and 0.9 m from the front face of many of the assemblies. This data was then displayed via contour plots as shown in Figure 6-19. Figure 6-20 provides the photographic record for these same contours. Although not clear in Figure 6-20, the amount of wetting of the clay blocks that has occurred is very limited, only the outer few mm of the blocks were dampened as the result of water moving along the vertical joints. In general it was found that once outflow paths are established, only a very gradual rate of water uptake by the remainder of the backfilled volume occurs (including the pellet-filled regions). There are two processes that seem to be active in water uptake and throughflow. The first is an early, advective flow that acts to fill a considerable volume of the macro-porosity in the pellets close to the inflow point. This process is dominant for only a relatively short time and as the clay pellets hydrate; they work to cut off further substantial advective water movement into the pellets.

As advective transport becomes less dominant, a second, microstructurally-controlled process becomes evident. In this water is drawn at a slower rate from the inflow region and into the smaller pore spaces of the pellets. This is driven by the suction potential of the smectite component and results in a gradual hydration of the entire clay pellet volume, and ultimately also the clay blocks. This process is of a more gradual nature and so is not likely to affect the short-term behaviour of the backfill pellets. It is also a decreasing process with time as the suction working to draw water into the core and as-yet unsaturated regions will decrease in magnitude with progressive wetting and as the volume of wet material increases, the gradient acting from wet to dry will also be decreasing.

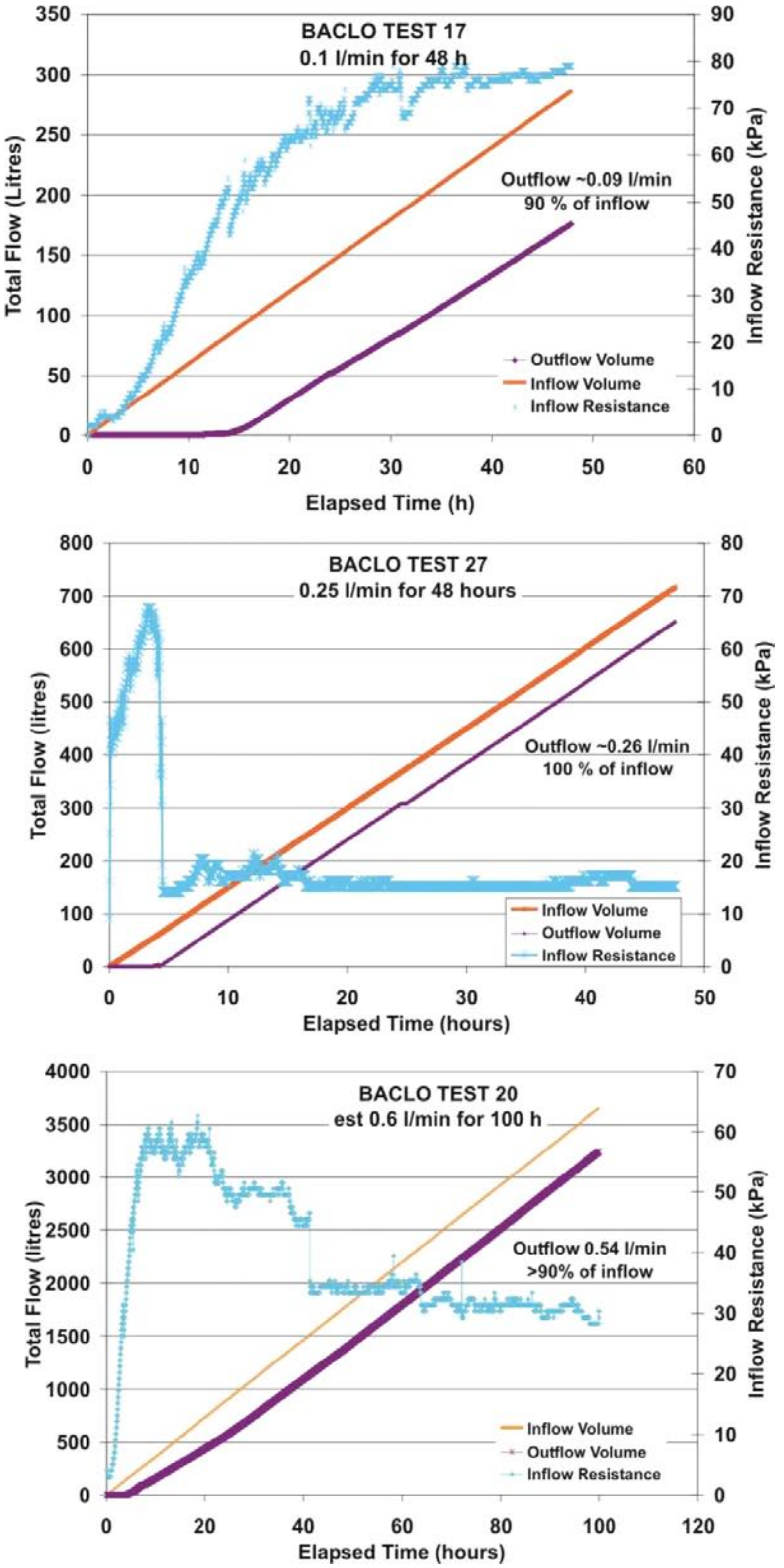
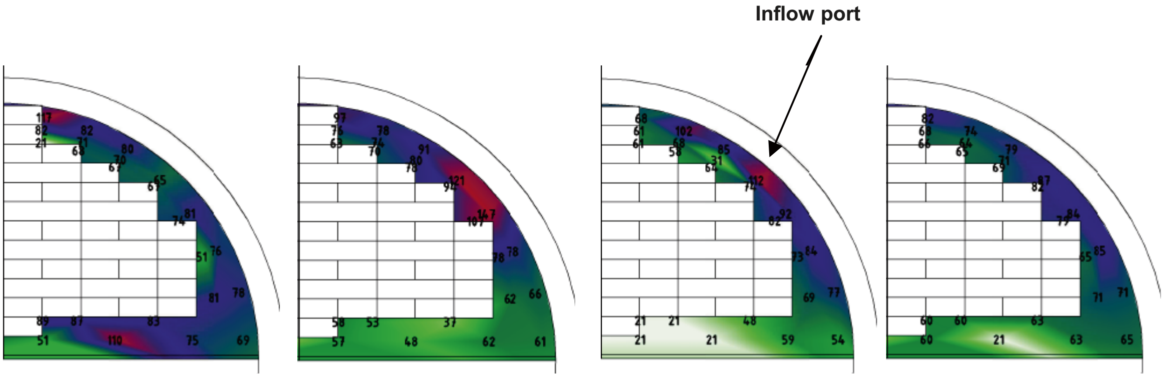


Figure 6-18. *Examples of inflow resistance and inflow-outflow balances observed in 1/12 scale tests /Dixon et al. 2008a/.*



Front 0.3 m 0.6 m 0.9 m

Figure 6-19. *Measured water distribution in pellet filling (Test 22: 0.25 l/min for 48h; red and blue regions have highest water content).*

Front 0.3 m 0.6 m 0.9 m

Figure 6-20. *Photographs showing wetting of pellets and vertical block surfaces (Test 22: 0.25 l/min for 48h).*

Ultimately, over a time much longer than evaluated in these tests, the system will achieve saturation and water will need to move through (or around) the backfill in order to exit the tunnel. Figure 6-21 shows an example of the development of a limited wetted region at the floor of the chamber that acted to channel water past the backfill and to the downstream face of the test. The regions outside the region shown at the front face were wetted largely by suction-driven water uptake by the pellet materials. These longer-term processes were not the focus of this study but appear to be significant in regions where low water influx is occurring.

Front 0.3 m 0.6 m 0.9 m

Figure 6-21. *Isolation of inflowing water by wet pellets (Test 28: 0.25 l/min for 48 h, /from Dixon et al. 2008b/).*

Time for outflow to occur, wetting of backfill and resistance to continued water inflow

Each of the tests done in the course of this study was monitored to determine the time it took for water to exit the front face of the assembly. Once water began to flow out of the assemblies, outflow rapidly increased with flow channels generally developing along the outside perimeter of the pellet fill. Compiling this information into a plot of time to outflow versus inflow rate for a 0.6 m path length produces Figure 6-22. As expected, time for outflow to occur increased with decreasing inflow rate, however, this was not a linear relationship and was especially non-linear when inflow decreased below 0.1 l/min. At such low inflow rates it would appear that suction-driven water uptake by the pellets may be the dominant process for the first few days after the backfill is placed. This has considerable significance relative to the short-term behaviour of the backfill in a relatively dry tunnel section and is further support for the micostructural influence on water uptake. The relationship between inflow rate and water outflow for different path lengths was further evaluated as part of the subsequent ½-Scale tests done at Äspö (see Section 6.2.7 and /Dixon et al. 2008c/).

Associated with the water uptake and transmission through the backfill is the resistance that the backfill provides to water entry. All of the tests done as part of the 1/12 scale series had the resistance to water input measured via pressure sensors located immediately before the water entered the test chamber. They provided a measure of how much resistance the backfill (pellets) was providing to water influx. Figure 6-23 shows the data collected for each of the tests, plotted as groups representing the same inflow rate.

The stability of assemblies exposed to very low rates of water influx was not anticipated to be problematic and the two long-duration (120 h) tests (Tests 7 and 8), conducted at 0.01 and 0.03 l/min confirmed this prediction. These tests typically showed patterns of incomplete wetting of the pellet fill, limited wetting in crown and base regions, essentially no outflow from the tests, very little wetting of blocks. Where outflow was observed, it typically occurred along the pellet-block horizontal contacts. The inflow resistance for such low water input systems showed considerable variability and this is interpreted to be the result of the wetting-plugging-pushing through to new dry region, cycle that was occurring at a very small scale in these systems /Dixon et al. 2008b/. The low resistance to water inflow was similar to systems having higher inflow rates. There was evidence of the development of new flow paths with time (sudden changes in flow resistance) as well as an overall trend towards increasing resistance to inflow with time.

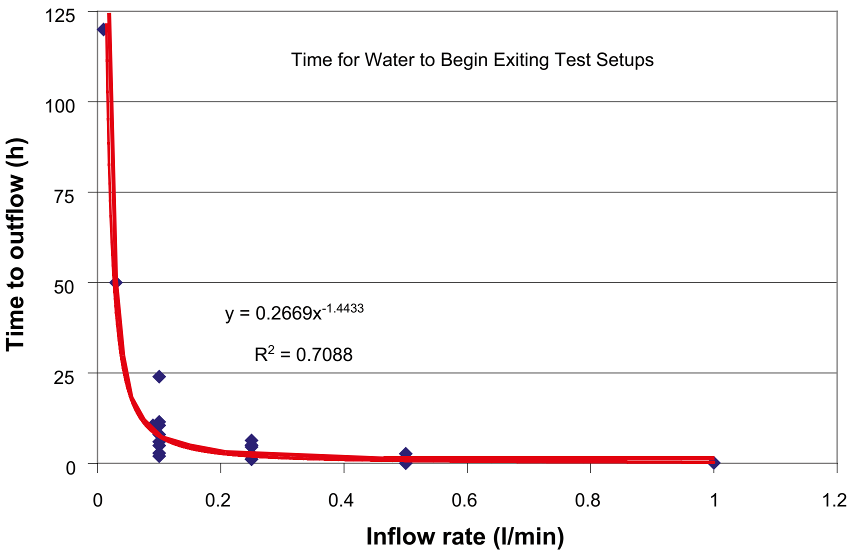


Figure 6-22. *Relationship between inflow rate and time for outflow to be established (0.6 m path-length).*

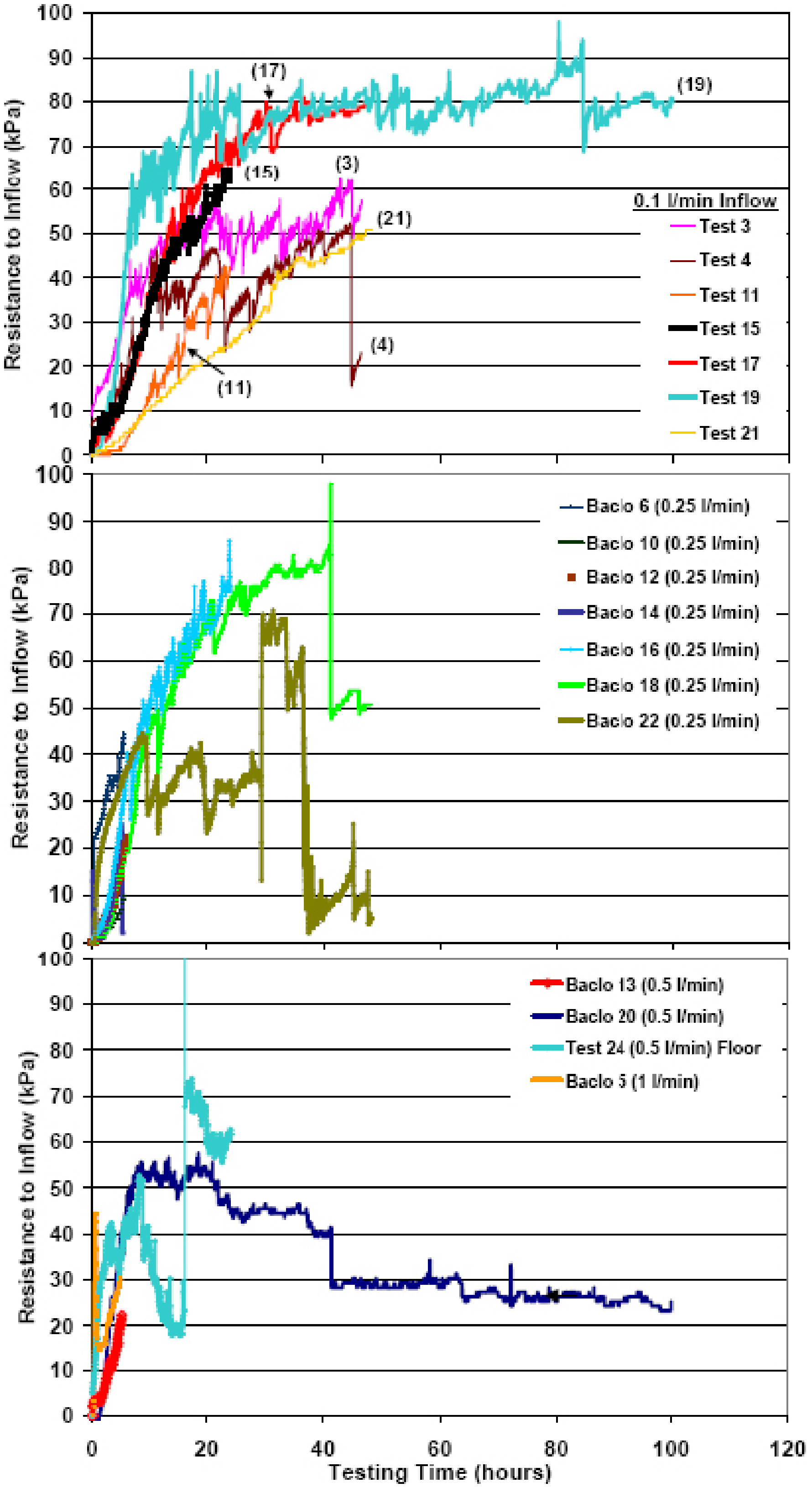


***Figure 6-23.** Development of inflow resistance in backfill block-pellet systems.*

A total of nine tests were done at a fixed rate of 0.1 l/min (6 l/h) water inflow for times ranging from 24 to 100 hours and representative tests are presented in Figure 6-23. The behaviour of these tests was strongly influenced by the location where water entered the cell, indicating that in a field situation, this will be an important consideration. Where water was entering from a floor location there was a shorter time to first exit from the system and a lower degree of overall system saturation at the time of test termination. There was considerable variation in the manner in which these systems evolved, largely associated with where and when preferential flow paths developed and how long the test operated. The general observations associated with water uptake and movement made in the course of testing systems at an inflow rate of 0.1 l/min were that:

1. Wetting generally occurs along sides of test cell (pellet-filled region) first.
2. Base of test cell is last area to wet (where inflow occurs above floor level).
3. Generally limited water entry occurs along block joints.
4. Outflow generally evolves to include the horizontal contacts between pellets and clay blocks.
5. Outflow from system (0.6 m distance from inlet) will occur in 2.8–15 h.
6. Piping can occur in and through the clay blocks (observed in 1 test of 8).
7. Piping can be highly erosive in nature.

A total of ten tests were undertaken where water inflow was set at 0.25 l/min (15 l/h), for durations of 4.5 to 48 hours. Of these, seven were constructed using a single type of pellet/granule fill and the remaining three were systems constructed using Minelco bentonite as a base material below the blocks and Cebogel in the remaining volume between the block assemblies and the wall of the 1/12-scale. The resistance to water inflow provided by these tests are presented in Figure 6-23. Those tests done using a single filler material (Cebogel pellets), between the blocks and the concrete showed a general pattern of behaviour that can be summarized as follows:

1. Rapid wetting of outer perimeter of pellet fill.
2. Subsequent wetting of pellets near crown.
3. Gradual wetting of pellet below block assembly.
4. Gradual wetting of blocks.
5. Outflow from system occurs between 1 to 6 hours.
6. Flow along block-pellet contacts is able to induce erosive flow channelling in some of the tests undertaken. Initiation of substantial erosive activity is indicated by sudden sustained decrease in flow resistance between 36 and 40 hours in Figure 6-23.
7. Ultimately, unless internal erosive behaviour develops, preferential flow path(s) will develop at the concrete (rock)-pellet contact.

Four tests were done at inflow rates of 0.5 and 1.0 l/min (30, 60 l/h) but only one test operated for more than 24 hours (at 0.5 l/min). The resistance to inflow developed by these tests is presented in Figure 6-23 and shows an ongoing reduction in resistance to water inflow, as the result of development of erosive flow paths through the system. The general evolution of the systems is as follows:

1. Rapid wetting of pellets, including materials underlying blocks.
2. Nearly complete wetting within pellet-filled volume by five hours into test.
3. Substantial water movement into joints between clay blocks.
4. A tendency for water to flow along phreatic surface of pellets as saturation progresses and pellet-block interfaces as saturation is approached.
5. Once saturation of pellet-filled volume is well advanced flow tends to channel to a limited number of flow paths at the pellet-concrete interface.

With extensive pellet wetting and extension of wetting into clay blocks there is a risk for the development of piping features and erosive water flow along the pipes that can pass through the clay-block assembly or along pellet-block interfaces.

Erosion

One of the primary concerns related to backfilling and especially situations where backfilling operations have been interrupted for a period of time beyond a few hours is the potential for erosion of the backfill by water entering the tunnel somewhere in the already filled region. Movement of water through the backfill has the potential to develop preferential flow paths, as has been clearly shown in these 1/12-scale tests, as well as laboratory tests done part of the Baclo programme /Sandén and Börgesson 2006, Sandén et al. 2008/.

Previously presented test information has established that the backfill system, or even the pellet/granular materials alone, does not have to reach saturation before water exits the system. The 1/12-scale tests provided measurements of the quantities and rates of backfill material (pellet, granular or block) removed over the period of 2 to 5 days. They also provide indications of time-dependent erosive behaviour. Flow and erosion observations allowed estimation of erosion rates and quantities, thereby providing a basis for developing predictions for behaviour in field-scale (e.g. ½-scale tests at Äspö) and ultimately in full-scale field conditions.

Erosion and erosion rates were somewhat difficult to measure and were not initially a component of this testing program, but the ability to quantify erosion rate proved to be a valuable addition to the scope to these tests. Beyond the assessment of total erosion and average rates of erosion for the various flow rates and testing times there is clear evidence that long-term average erosion rate decreases over time. Figure 6-24 shows the erosion rates recorded at various times at two inflow rates. These data indicate that the systems operated at 0.1 l/min water inflow rate trends towards stable flow and erosion rates that were less than approximately 0.01 kg/h (~ 0.02–0.05% of pellet mass per hour). Where inflow rate was 0.6 l/min (36 l/h) there was a very different pattern of erosive behaviour. These high-flow systems showed early, highly erosive behaviour as they developed flow path(s) that could transfer the water with minimal resistance to the downstream face of the backfill. This erosive behaviour persists for several hours, removing more than 1 kg/h of mass from the backfill (0.3% of pellets per hour) as shown in Figure 6-24. Development of persistent flow paths through the block materials would likely result in even more erosive conditions. Where flow developed along the pellet-concrete contact the erosion rate observed showed considerable reduction, trending towards a steady-state erosive rate in the order of 0.1 to 0.2 kg/h. This suggests that the erosion is both time- and inflow-rate dependent process.

In some of the tests, the initial movement of water through the clay pellets, along the surfaces of and into the joints between the Friedland blocks resulted in substantial internal erosion. The inflowing water was able to develop a pathway into and through the clay block assembly and the low resistance exhibited by this pathway resulted in the formation of ongoing, highly erosive flow through the test. The pellet fill was unable to provide sufficient resistance to flow to redirect the water and so flow continued. The presence of a largely unsaturated and compressible system (pellets) meant that there was little ability for the system to close off the internal flowpath. The result was the development of piping features through the clay block assembly, beginning along block-to-block contacts and progressively eroding larger flow paths. Figure 6-25 shows an example of the type of erosive paths and pipes developed when internal erosion was able to progress.

As extensive internal erosion of the clay blocks did not occur consistently and in some cases ceased after a short time, it is possible that the 0.1 m thickness of the pellet fill is not quite adequate to consistently ensure that inflowing water is sufficiently dispersed before it reaches the blocks. It is possible that a somewhat thicker pellet fill layer might be able to provide a more effective protection for the blocks. A denser clay block component will also provide a more erosion resistant core to the backfilled tunnel. These factors were examined in tests done at field-scale (½-Scale Test) at Äspö (see Section 6.2.7)

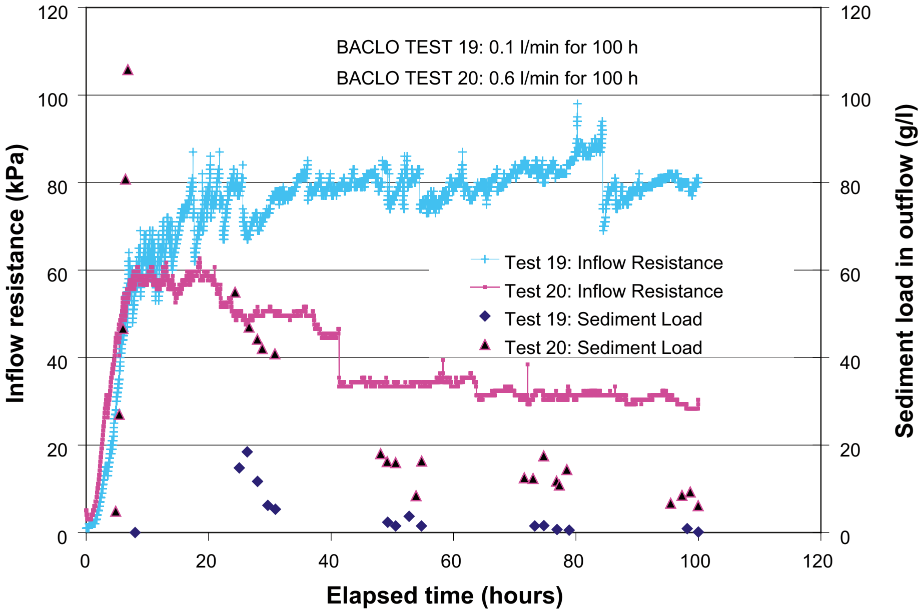


Figure 6-24. *Change in erosion rate with time.*

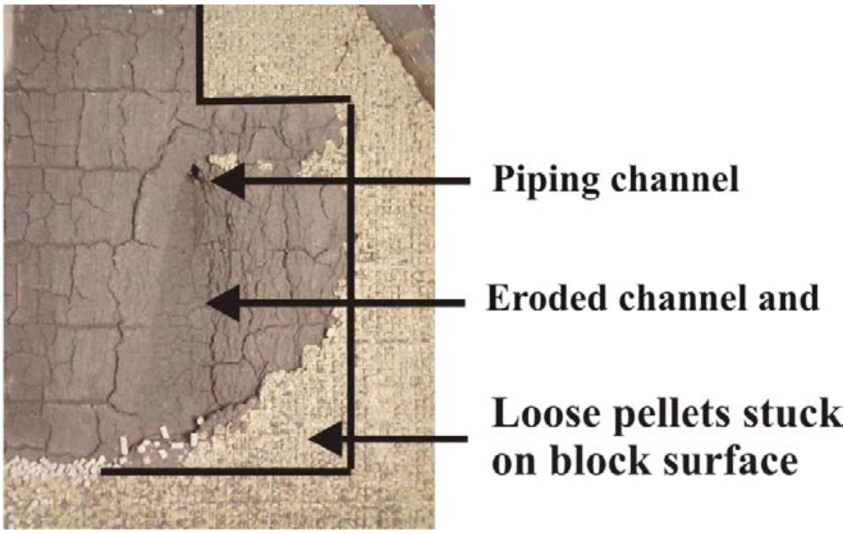


Figure 6-25. *Example of piping erosion in Friedland clay block assemblies.*

Summary

A wide range of water inflow rates has been examined, resulting in the development of a clearer understanding of the evolution of a block-pellet backfill system. The key conclusions that can be drawn from the results of these tests are as follows:

1. At water inflow of 0.1 l/min (6 l/h) or higher, the backfill block assemblies must be protected from water. If this is not done in a timely manner then block slumping and backfill disruption is likely.
2. The presence of construction gaps between blocks or groups of blocks did not affect the backfill system unless a preferential flow channel developed in these locations. Typically, swelling pressure developed by the surrounding bentonite pellets or granules resulted in compression of the block assembly and gap closure.
3. The conclusions for pellets/granules are valid for the used products and not necessarily for all pellet materials.

4. Water uptake is initially controlled by the inflow rate. High inflow rates generally result in rapid filling of the larger pore spaces of the pellet materials adjacent to the inflow point, followed by swelling of the pellets and increasing resistance to water inflow, encouraging water to find new pathways. The first flowpaths are along the horizontal pellet-block contacts but as the pellets swell constricting flow, flow paths and channels typically migrated to the cell wall-pellet interface. Once these channels were established, water moved rapidly and directly from the point of inflow out to the downstream face of the backfill. These flow paths typically showed limited and decreasing erosive activity with little hydraulic interaction with the rest of the system.
5. The mass of material removed by the exiting water (where flow did not travel through the block assembly), typically ranges from < 1 to 25 g/l (where flow > 0.1 l/min). Sediment load is mainly determined by the pathway(s) developed. This ratio tends to rapidly decrease with time during the first 48 hours of flow and reduces gradually after that. This is the same behaviour as was observed in the smaller-scale tests and is attributed to initial flushing of fines and subsequent formation of non-erosive flow paths.
6. Internal (within block assembly), flow paths developed in several tests. There was no clear linkage between their development and the water inflow rate and any test done with a flow rate in excess of 0.1 l/min could experience this phenomenon. Once established, ongoing erosion of the clay block assemblies occurred. Substantial quantities of material can be removed at relatively low water inflow rates as the clay blocks provide little resistance to interface flow. It is therefore important to try to determine a means to prevent this situation from developing.
7. Conditions that lead to internal erosive pathways developing are unclear and may be essentially random (water finds a pathway to blocks at an early stage and the flow path remains open due to the ease of movement through block assembly). No condition or mechanism that would specifically lead to their formation or prevention could be identified. However, since development of this condition was not infrequent, the 0.1 m thickness of pellets between the blocks and the rock wall is apparently not sufficient to consistently prevent formation of internal flowpaths.
8. The location of water entry appears to be important, tests where water entered the base of the cell showed rapid movement of water towards the front of the test along the block-granule interface with limited wetting of surrounding materials. This flow was typically erosive, removing a substantial quantity of granular material from a limited volume of backfill. Where flow towards the face of the test tube was restricted (possibly due to swelling of granules and plugging of flow path), water moved upwards into the block assembly, developing persistent and erosive flow channel(s).
9. Flow path(s) generally remained on the same side of the chamber as the water entry point. This indicates that for the period immediately following backfill installation that it is unlikely that flows entering from different sides of the tunnel will combine into a single flow.

The above-listed observations and conclusions from the concrete-tube tests completed at Äspö as part of the Baclo III studies represent an important step towards accomplishing the goals originally set for this project. Firstly, they demonstrated which processes are likely to be critical with respect to backfill installation and saturation prior to closure of the emplacement tunnels. It was determined that completing backfilling of the entire tunnel cross-section in as timely a manner as possible is needed in order to avoid potential destabilization of the backfill block component due to inflowing water. The importance of having a relatively thick pellet component between the rock and the backfill blocks is indicated as a thicker than 0.1 m pellet layer reduce the risk of developing extensive erosive flow both along the perimeter as well as internally through the clay block component, and that inflow rates of < 0.1 l/min will likely be tolerable based on the information provided at this test scale and geometry. These two findings begin to provide some guidance towards defining the effects of backfill geometry and tolerable water inflow rates on the backfill.

Additionally, it has been determined that the consequences of erosion on the backfill are clearly scale- and time-dependent since one litre of water can transport only a limited amount of sediment and erosion seems to decrease markedly with time, especially when flow is constrained to the pellet-filled regions. It should be noted that this was only demonstrated to be in the case in the concrete tube tests where the single-point water inflow rate to the backfill and where the rate of inflow was always less than 1 l/min. Situations where much higher inflow rates exist (potential for turbulent flow) or high inflow resistance (high water backpressure development) may result in conditions much different than observed in these studies were examined in the subsequent ½-Scale Tests.

Of particular importance in these tests was establishing that it was not practical to try and install the pellet component in a dry condition as the result was a material that exhibited very low density, gaps at the crown of the assembly and excessive dry slumping as the granular material attempts to slump to its natural angle of repose. In a repository this would result in unacceptable backfill density and swelling capacity. It will therefore be necessary to demonstrate means of achieving an adequate pellet placement process and this was one of the goals of the subsequent ½-Scale tests undertaken as part of Baclo III (see Section 6.2.7). It will also be necessary to be prepared to deal with whatever volume of water is entering the backfilled system as soon as it finds a pathway through to the working face. Minimizing water influx into the tunnel and ensuring uninterrupted backfilling occurs have been confirmed as being important to ensure smooth operations and means of achieving these conditions need to be developed and demonstrated.

6.2.7 Äspö ½-Scale tests

Background

The results of the smaller tests done at Äspö /Dixon et al. 2008a, b/ indicated that only a small proportion of the pellet fill would initially interact with the inflowing water and that for most situations, the majority of backfill block-filled region was little influenced by the inflowing water at the earliest states of hydration. The type of backfill blocks (Friedland clay), utilized in the previously completed 1/12-Scale tests were only available in limited quantities and so the construction layout developed for most of the ½-Scale tests were designed to limit the quantities needed for each assembly. To simulate the material that would be installed to provide a level and smooth tunnel floor, clay pellets were placed to a 0.1 m layer on floor of the rearmost 4 m of the test chamber (Figure 6-28). On this base the majority of the chamber volume was then taken up by either large, backfill-block sized boxes (in the first 2 assemblies, Tests 1–4), or in the 4 subsequent assemblies (Tests 5–12) by a wooden formwork. These boxes were surrounded with heavy-gage plastic sheeting to prevent water penetration into the central volume. The plastic-encapsulated volume was then covered with a bentonite geotextile in order to simulate the type of contact provided by dense clay backfill blocks.

Beyond the geotextile layer an assembly of backfill blocks of the same type as were previously used in the smaller-scale backfill and a minimum of 0.15 m width of pellets was then installed to fill the volume between the blocks and the steel walls of the chamber (Figures 6-27 and 6-28). The limited thickness of backfill blocks were deemed to be sufficient based on the experiences of the previous smaller-scale tests where water penetration into the block-filled volume was typically very limited or only for the period at the start of testing and this was confirmed by the results of the first ½-Scale test where water did not move into the block fill to any substantial degree. This construction thereby provided a reasonable simulation of a large mass of backfill blocks in a tunnel environment while minimizing the number blocks actually used. Based on the results of initial tests in this study, further modifications to the construction were done that further reduced (or eliminated) the clay block component (Figure 6-28). Details on the construction, operation and results of each of these tests are provided by /Dixon et al. 2008c/.

Previous work done at smaller scale are reported in /Dixon et al. 2008a, b/ and in /Sandén et al. 2008/ indicate that many of the early hydraulically-important responses of the backfilled volume are controlled by the pellet fill. Rather than being able to take on a considerable volume of water before clay pellet swelling occurs, there is typically a rapid development of a low-permeability region of pellets immediately adjacent to the inflow point. With this comes the formation of preferential flow path(s) along the "rock"-pellet contact. The ½-Scale tests are intended to confirm this behaviour at nearly field scale and to examine the effect of an increase in the thickness of the pellet-filled region on the potential for development of preferential flow paths through the block-filled region.

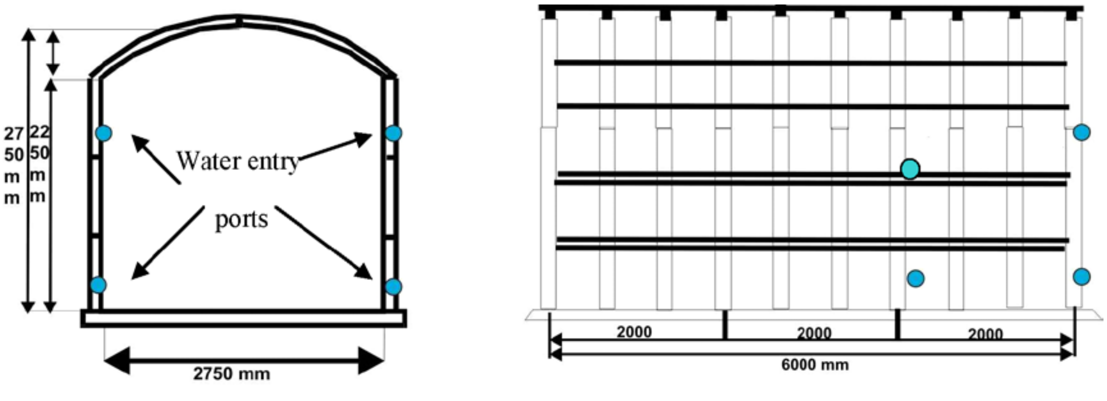
Test setup

The ½-Scale tests involved six pairs of tests. The smaller scale tests conducted previously at Äspö found that there was no hydraulic interaction between the two sides of a test setup where water was supplied to both sides independently or one side only for the initial stages of system evolution (Section 6.2.6). As a result, the new ½-Scale tests were planned to take advantage of this. Tests examining different inflow rates and locations could be run separately and without interference with one-another. Each test was intended to operate for at least five days following initiation of water supply to the setup, but some variations occurred due to excessive erosion or decisions to operate for slightly longer periods. Water was supplied to each of the tests at one of the following rates (0.1, 0.25, 0.5 1.0 or 2.5 l/min). Table 6-4 provides a listing of the tests.

Tests were done in a mock-up constructed in the Bentonite Laboratory at SKB's Äspö Hard Rock Laboratory (Figure 6-26 and Figure 6-27). A total of 12 tests, undertaken under well-controlled conditions, were completed. They examined the effects of inflow rate, inflow location and time on assemblies of blocks and pellets. Water was supplied to the assembly at rates ranging from 0.1 to 2.5 l/min and the time for water exit, the exit location, potential for erosion of backfill, the rate of water uptake and resistance of the assembly to water influx were all monitored for periods of 3 to 7 days. The testing time was selected to simulate a reasonable duration for unanticipated backfilling interruption. Longer durations were not necessary and risked both the stability of the system and the loss of the early-stage conditions through progression of swelling and homogenization.

Based on the dimensions provided in Figure 6-26, the cross-sectional area of the test chamber is nominally 7.1 m^2. The chamber length is 6 m, but only 4 m was utilized for each assembly, as shown in Figure 6-27. Since the time needed before water exits should be at least in part determined by the distance it has to travel, then path lengths of 2 m and 3.8 m would compliment the 0.6 m path length examined in the 1/12-Scale tests.

The results of the smaller tests done at Äspö /Dixon et al. 2008a, b/ indicated that only a small proportion of the pellet fill would initially interact with the inflowing water and that for most situations, the majority of backfill block-filled region was little influenced by the inflowing water at the earliest states of hydration. The type of backfill blocks (Friedland clay), utilized in the previous smaller-scale tests were only available in limited quantities and so the construction layout developed for most of the ½-Scale tests included clay pellets to a thickness of 0.1 m on floor of the rearmost 4 m of the test chamber (Figure 6-28). On this base a large number of backfill-block sized boxes were installed (in later tests they were replaced by a wooden formwork), they were surrounded with heavy-gage plastic sheeting to prevent water penetration into the central volume. The plastic-encapsulated volume was then covered with a bentonite geotextile in order to simulate the type of contact provided by dense clay backfill blocks. Beyond the geotextile layer an assembly of backfill blocks of the same type as were previously used in the smaller-scale backfill and pellet tests was installed (Figures 6-27 and 6-28). The limited thickness of backfill blocks were deemed to be sufficient based on the experiences of the previous smaller-scale tests where water penetration into the block-filled volume was typically very limited or only for the period at the start of testing. This construction thereby provided a reasonable simulation of a large mass of backfill blocks in a tunnel environment while minimizing the number blocks actually used. Based on the results of initial tests in this study, further modifications to the construction were done that further reduced (or eliminated) the clay block component (Figure 6-28). Details on the construction, operation and results of these tests can be found in the report by /Dixon et al. 2008c/.



End view

Length

Figure 6-26. Schematic of ½-Scale chamber.

Interior and side view of ½-Scale chamber, note tanks used to supply water and hold outflow

Interior of chamber during test assembly where blocks entirely surround central void

Test where mesh installed, prior to water appplication

Figure 6-27. *Chamber and restraint system /Dixon et al. 2008c/.*

Figure 6-28. *Tests where only a small volume of block materials installed. (Pellets installed into remaining volume and downstream face sealed through use of wet pellet materials.)*

Water was supplied to the test via constant-rate-of-flow pumps, each of which could be preset to supply different rates of water to the test. For the first 8 tests completed they operated at nominal supply rates of 0.1, 0.25, 0.5 or 1.0 l/min. Tests 9 and 10 examined high rate of water inflow conditions (2.5 l/min via a single inflow location at the rear of the chamber. Tests 9 through 12 provided water to the rear of the chamber, simulating a large piping feature that had reached a recently installed section of backfill.

The resistance to water inflow was monitored via pressure transducers installed at the inlet ports of the chamber (one at each inlet location). This allowed changes in water inflow resistance to be continuously monitored and since inflow resistance is known to correspond to the development of water transport channels these data provide valuable information on system performance. The water used in testing was artificial Äspö water (1% TDS as equal mass proportions of NaCl and $CaCl_2$). It was prepared and stored in a large holding tank and the pumps drew water as needed (Figure 6-29).

Test results

A summary of testing conditions and results are presented in Table 6-4 and Table 6-5. Table 6-4 shows that the average dry density of the pellets in the crown and sides is in the range of 950 and 1,080 kg/m^3. This information is very important for prediction of the likely swelling pressure and hydraulic conductivity of the system over the longer term. The use of a limited amount of water to facilitate pellet placement and reduce dust generated during placement in Assemblies 4 through 6 (Tests 7 through 12), did not result in any discernible change in the dry density of the placed materials. Additionally, the water used allowed the pellets installed at the downstream face to retain a stable, durable and nearly vertical face without adversely affecting the density achieved. As a result, any changes in the water outflow location or pattern observed must be attributable to parameters other than pellet density. Table 6-5 provides a general summary of the water inflow and resistance data for each of the 12 tests completed in this study.

Time to start of outflow

The tests done in the ½-Scale chamber had the time-lag between start of inflow and start of outflow determined as well as monitoring resistance to water inflow. These data provide valuable indirect measurement of the manner in which water moves into the pellet-filled mass and how progressive bentonite pellet saturation affects water movement. The evolution of inflow resistance also provides a measure of the timing and nature of channeled flow through the test.

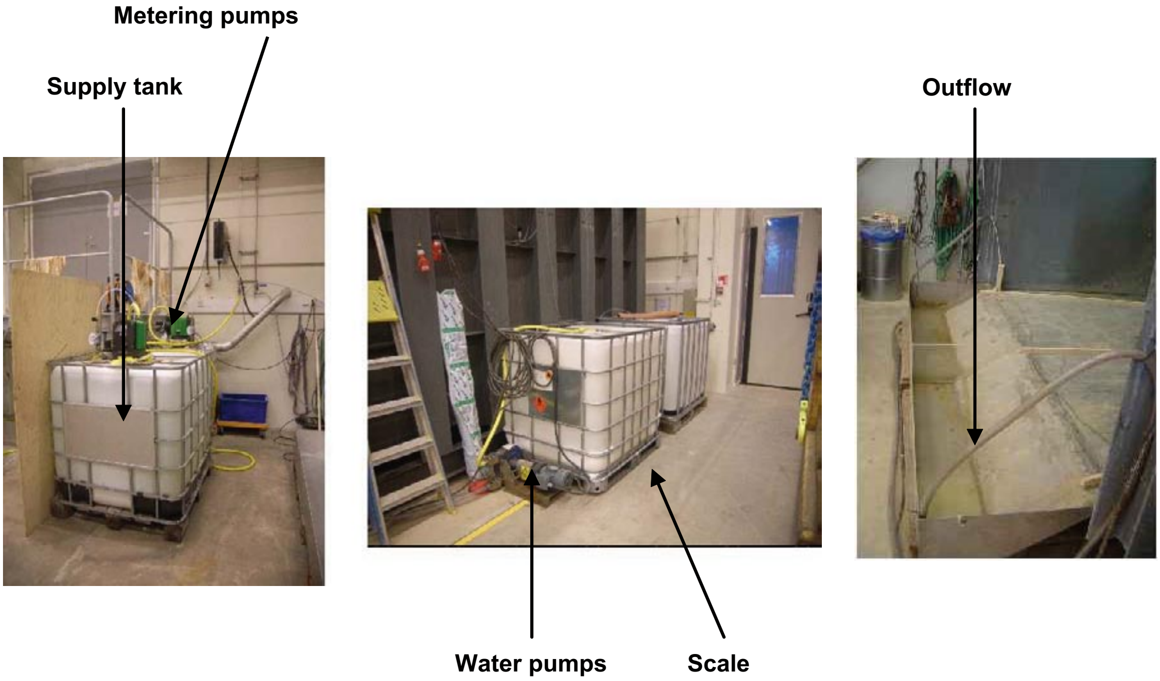


Figure 6-29. *Photographs showing water supply and collection system /Dixon et al. 2008c/.*

Table 6-4. ½-Scale tests.

Test number	Inflow location* (m)	Inflow rate (litres/min)	Test duration (days)	Percolating fluid**	Side of ½-Scale mockup (Left/Right)	Average dry density of pellet fill (kg/m³)
1	1.5 : 2.1	0.25	5	Äspö	Left	1,080
2	1.5 : 2.1	0.5	5	Äspö	Right	1,080
3	1.5 : 2.1	0.5	5	Äspö	Left	950
4	1.5 : 2.1	1.0	5	Äspö	Right	950
5	1.5 : 2.1	0.1	5	Äspö	Left	1,030
6	1.5 : 2.1	0.25	5	Äspö	Right	1,030
7	1.5 : 2.1	0.25	5	Äspö	Left	980
8	1.5 : 2.1	0.5	5	Äspö	Right	980
9	0.3 : 3.9	2.5	<1***	Äspö	Left	988
10	1.8 : 3.9	2.5	3	Äspö	Right	988
11	1.8 : 3.9	0.25	7	Äspö	Left	984
12	0.3 : 3.9	0.50	7	Äspö	Right	984

* Elevation from floor : distance from front face of assembly.

** Artificial Äspö water (1% TDS).

*** Water by-passed clay, entered core of restraint system, test ended at 17.5 h.

The tests showed a longer time between start of inflow and initiation of outflow when the path length was increased and an increase in time before outflow when inflow rates were lower. Figure 6-30 shows these trends in the path-length, inflow rate and average observed time to outflow. The general trends observed are generally as expected, but in an ideal system a doubling of flow path length should result in a doubling of the time to outflow. Similarly, a simple linear relationship between inflow rate and time to water discharge could be anticipated, but in the ½-Scale tests an increase in inflow rate resulted in a decrease in the time to outflow but this relationship was not directly proportional. Factors such as density of the pellet fill, tortuosity of the flow path, minor variations in the packing pattern of the pellets and inflow location all come into play in determining the time to outflow.

When all the data for the concrete-tube and ½-Scale tests are combined Figures 6-31 and 6-32 are produced and these figures illustrate the variability in time to outflow that was encountered in these studies. If time for outflow estimation were to be based on behaviour at higher flow rates then substantially shorter than observed times to outflow should have been observed for systems where < 0.1 l/min was supplied as can be seen in Figure 6-32. Factors of 3 to 5 difference in time to outflow for tests having applied inflow rates of more than 0.1 l/min were not unusual, but even that level of variability does not account for the type of values observed at low inflow rates.

It would seem that the effects of factors such as suction-driven uptake of water, flow path tortuosity, texture and density that are overwhelmed in situations where inflow is high, have a discernible role in determining flow and water uptake behaviour at lower inflow rates. These processes are recognized in affecting flow through soils and other porous media but given the highly heterogeneous macro- and micro-structural nature of a newly backfilled section of tunnel it is unlikely that the relative importance of each can be accurately quantified. It may be useful to examine the uptake of water by the pellet materials under low water supply rates to gain a clearer understanding of at what water uptake rate, or degree of saturation that water will begin to move in discrete flow paths rather than as a uniform wetting process.

Viewed in context with the conceptual model for system evolution provided later in this section, the outflow data indicate that the microstructurally-induced (suction) water uptake by the pellet-filled volume are a process that does not greatly affect system evolution in the early stages, unless the inflow to the pellet-fill are very low (< 0.05 l/min) at a single point. At such low inflow rates it would seem that much of the influx will be drawn into the pellet fill for a period of several days at least. Of course once the system has sufficiently saturated, water will tend to find a less resistant pathway to move along (rock-pellet contact).

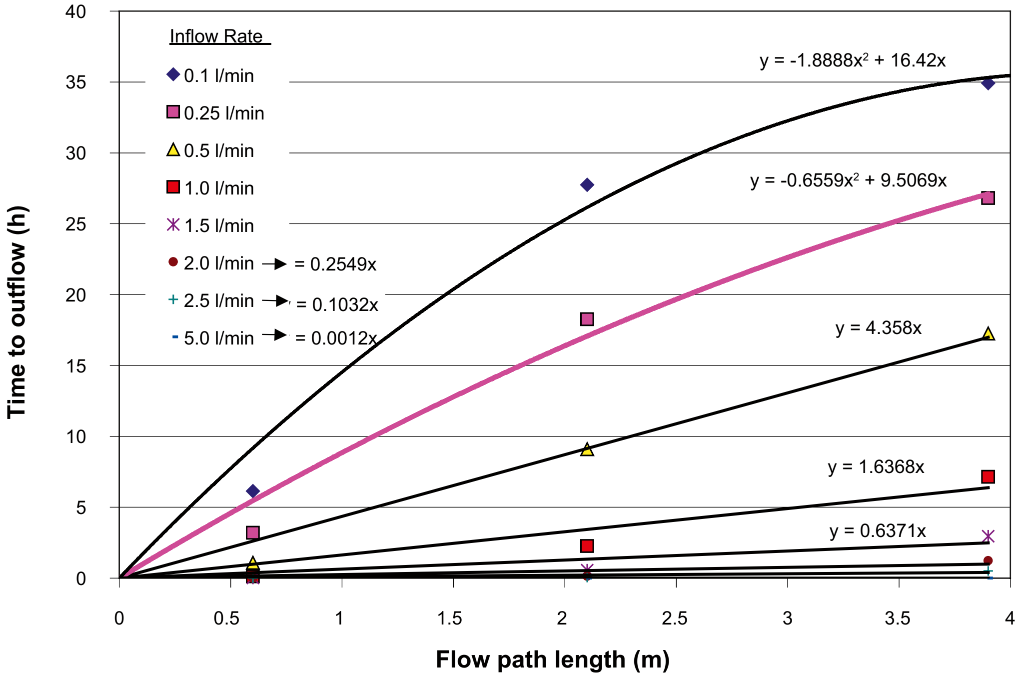


Figure 6-30. *Effect of flow path length and inflow rate on time to water discharge.*

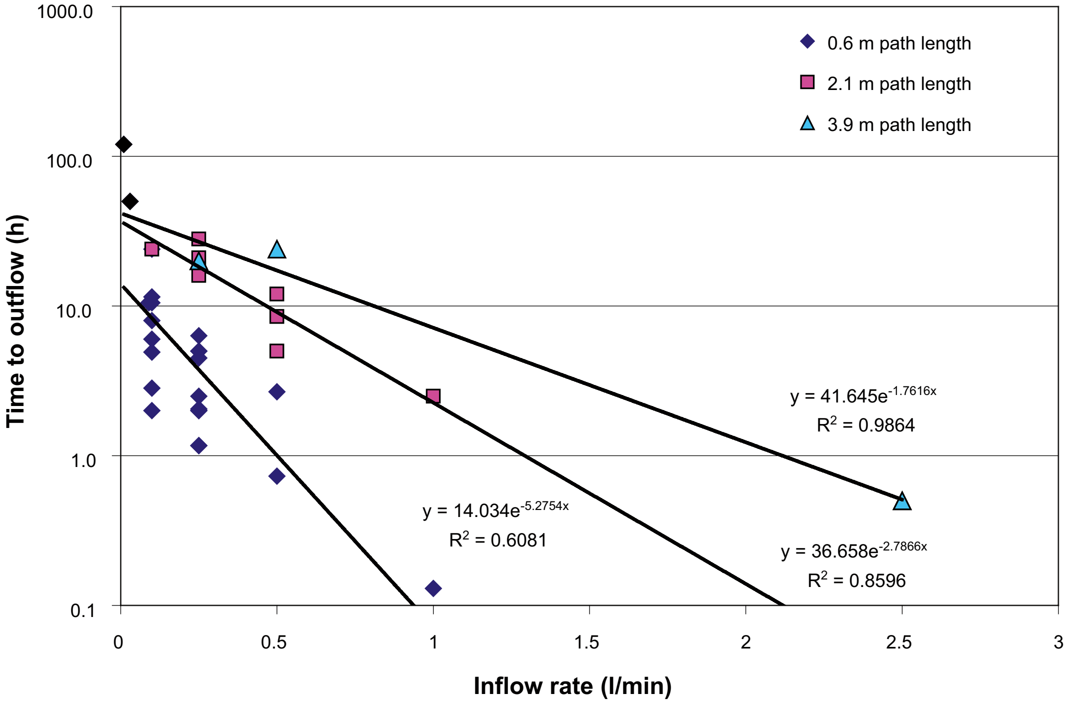


Figure 6-31. *Time to outflow for various inflow rates and path-lengths.*

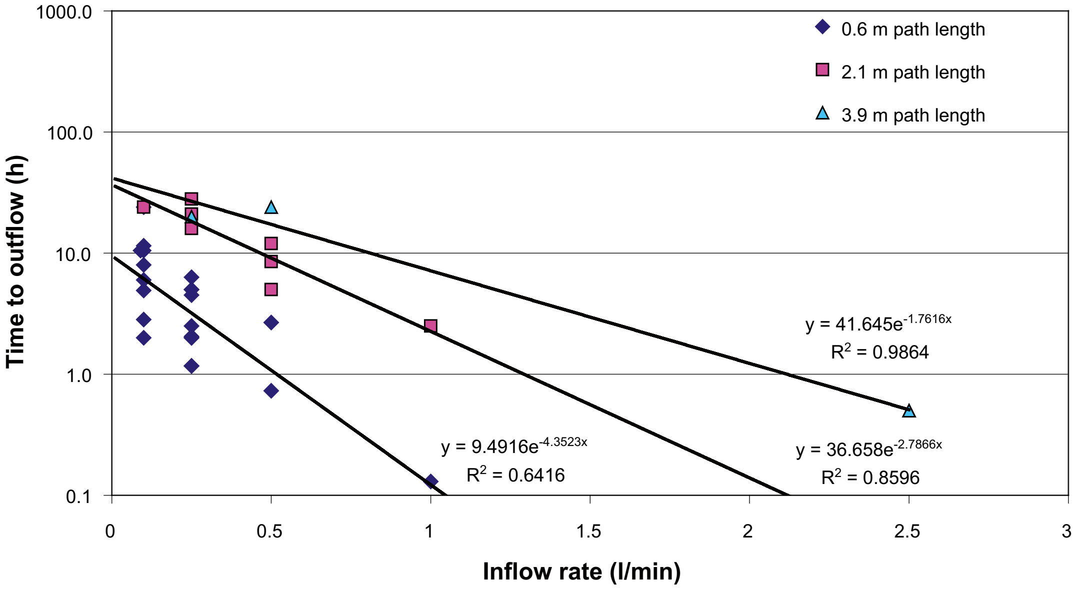


Figure 6-32. *Time to outflow from 1/12 and 1/2-Scale tests (excluding inflows < 0.1 l/min).*

Resistance to water inflow: balance between inflow and outflow

It was previously observed in smaller-scale tests (Section 6.2.6) that development of preferential flow channels resulted in a decrease in flow resistance. Erosive channelling and piping typically result in unstable resistance (pressure fluctuations) as materials are moved and removed from vicinity of the flow path. This can sometimes be associated with changes in the inflow-outflow balance but most often is seen in as a dramatic change in the inflow resistance. Non-erosive channelling is typically associated with stable inflow resistance and a steady-state flow rate (stable inflow ~ outflow).

The resistance to water inflow to the chamber for each of the twelve tests done in this study is summarized in Table 6-5 but the detailed plots of changing resistance with time provide more information with regards to the initial water movement. Figure 6-33 presents the inflow resistance data for the first 6 tests and Figure 6-34 presents the data from the last 6 tests. The inflow resistance data show the same generic patterns observed in previous smaller-scale tests. There was a fairly rapid development of resistance to inflow until the system is able to develop a preferential flow path to the front face of the chamber. The tests all showed occasions where inflow resistance changed rapidly, these changes were interpreted as channelling events. Detection of outflow from the tests is usually associated with one of these sudden drops in resistance to inflow. The magnitude of resistance to inflow for all these tests was relatively low, never exceeding 100 kPa and typically in the order of 25 to 50 kPa. In two cases (Tests 3 and 7) the longer-term inflow resistance decreased to less than 20 kPa, indicative of an open, stable flow path.

Figures 6-33 and 6-34 also provide the inflow-outflow mass balance measured for each test. Table 6-5 shows the water inflow-outflow balance at the end-of-testing for each of the ½-Scale tests where it could be determined. In all tests more than 70% was passing directly through the backfill and for high-inflow systems (> 0.25 l/min), the outflow was at least 80% of the inflow. These systems were not even close to saturated at the end of these ½-Scale tests and so less than full outflow was expected, however examination of the plots in Figures 6-33 and 6-34 show that the outflow rate developed within a few hours of the start of water outflow. This is further evidence of preferential flow path(s) dominating the backfill and that there is some degree of secondary water uptake process that continues to operate within these systems. In some of the tests (6, 7, 10 and 11) there is clear evidence that although water is predominantly moving through the piping features developed, there is discernible movement of water upwards into the crown of the chamber (pellet-filled region likely to have the lowest density of fill). Figure 6-35 shows how this water movement was occurring.

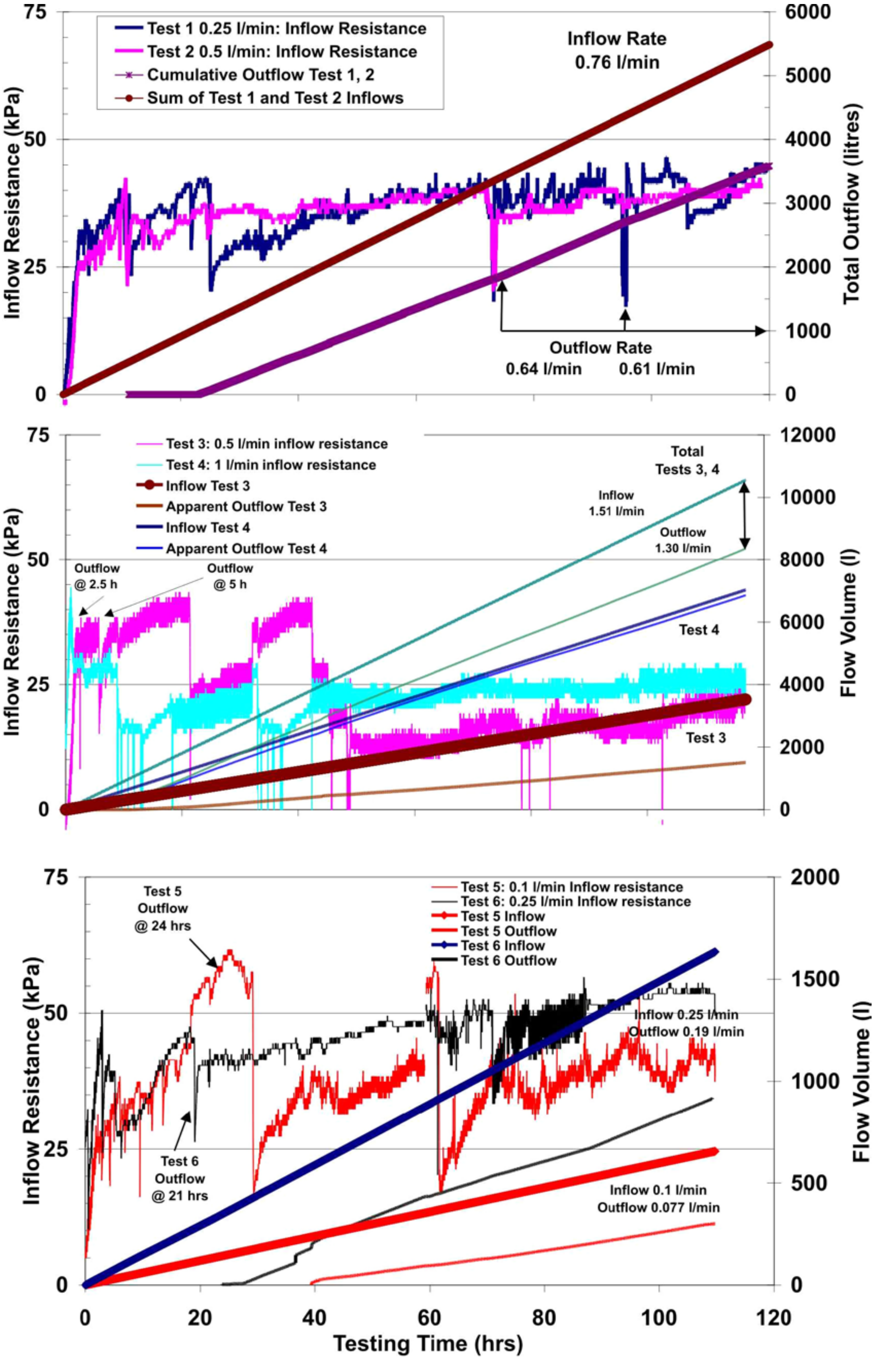


Figure 6-33. *Resistance to water inflow and inflow/outflow for Tests 1 through 6.*

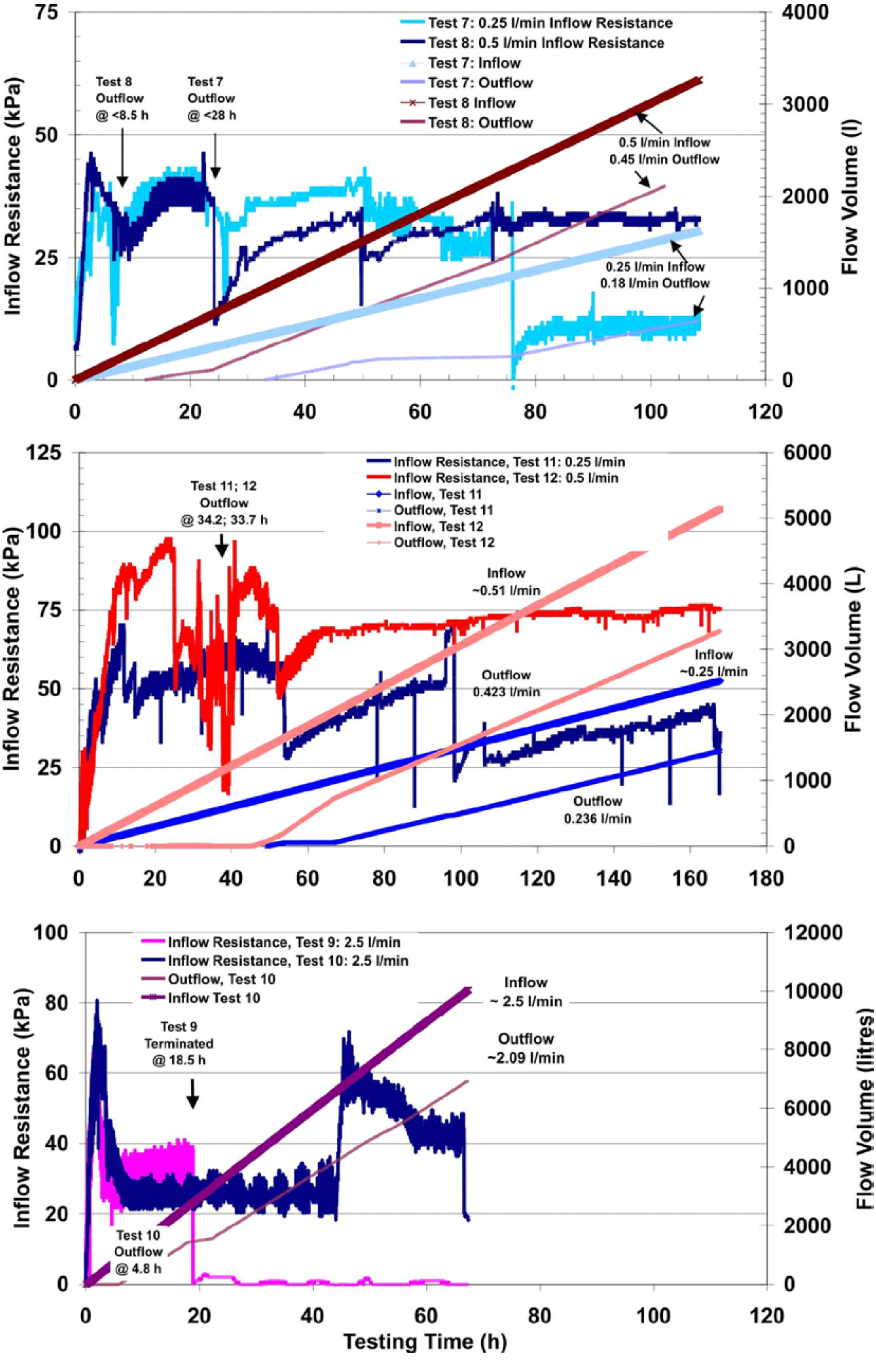


Figure 6-34. *Resistance to water inflow and inflow/outflow for Tests 7 through 12. (Tests 9–12 had water supplied at rear of chamber rather than at midpoint.)*

Table 6-5. Inflow resistance observed and break-through time for water.

Test #	Inflow rate (l/min)	Distance Inlet to Outlet (m)	Test time (hrs)	Time to first outflow (hrs) **	Highest resistance to inflow (kPa) at (@) hours after beginning of the test	Inflow resistance at end of testing (kPa)	End-of-test Flow path location	End-of-test Outflow rate (%)
1	0.25	2.1	120	(12 h?)*	44 @ 110	44	sidewall	84[+]
2	0.5	2.1	120	(11 h?)*	42 @ 110	42	sidewall	84[+]
3	0.5	2.1	117	5	42 @ 2.5	20	sidewall	87[++]
4	1.0	2.1	117	2.5	45 @ 24	25	sidewall	87[++]
5	0.1	2.1	110	24	62 @ 24	42	sidewall	77
6	0.25	2.1	110	21	55 @ 110	55	sidewall	76
7	0.25	2.1	109	28	43 @ 24	11	sidewall	72
8	0.5	2.1	109	8.5	47 @ 2.5	32	sidewall	90
9[***]	2.5	3.9	17.5	0.5	69 @ 1.5	35–40	NM	NM
10	2.5	3.9	65	0.5	81 @ 1.9	45	sidewall crown	84[+++]
11	0.25	3.9	168	20	72 @ 12.4	45	crown	94
12	0.5	3.9	168	24	98 @ 4	75	sidewall	83

NM Not measured, water supply discontinued after 17.5 hours.

* Estimated outflow time, outflow detection system not installed in Assembly 1.

** Outflow time based on signal from conductivity meter located 2 m away from face, outflow may have occurred several hours this time.

*** Test developed large leak past restraint system and was discontinued after 18.5 hours.

[+] Separate outflow collections systems not installed for Assembly 1.

[++] Mixing of outflow from two sides of Assembly 2 as result of seepage at downstream face, only overall flow quantity measurable could be made.

[+++] Large eroded sediment quantity made measurement of outflow difficult, actual amount likely higher.

Figure 6-35. *Vertical movement of water into crown regions of chamber. (Test 5–6, water is moving from right-side (Test 6) upwards along the chamber wall-pellet interface and to the left. There is no evidence of fluid outflow but extensive wetting is occurring.)*

Piping, preferential flow paths and erosion

The nature of the water outflow from the backfill assemblies, together with the water distribution at the end-of-testing and inflow-outflow balances all provide evidence of preferential flow paths past the backfilled volumes. The movement of water through the ½-Scale tests was typically forced through the pellet-filled volume, stabilizing at the chamber wall-pellet interface. In the first hours of testing, prior to this pathway being stabilized, there were several occasions where limited water flow along the pellet-clay block interface occurred, resulting in limited removal of clay from the surfaces of the blocks. There was also limited water penetration along block boundaries and in some cases very short-lived flow at those locations (as shown in Figure 6-36 and Figure 6-37). In all cases these flow paths self-sealed and water was not allowed to move along them. As a result only a few grams of material was removed from the block surfaces in the course of each test /Dixon et al. 2008c/. In none of the tests done was there any evidence of extensive water penetration past the pellet fill or erosive activity similar to what was observed in the smaller-scale tests /Dixon et al. 2008a, b/.

Most of the tests done as part of this study showed similar hydraulic behaviour with respect to erosion and flow paths developed. Flow began along either the clay block-pellet interface or else along the pellet-chamber wall contact and ultimately stabilized at the pellet-chamber wall contact, at or near the same location as they began. Figure 6-38 shows an example of this type of wetting behaviour.

The resistance to inflow, decommissioning water content samples recovered and observed wetting behaviour for these tests all indicated that flow was being directed to the contact between the pellets and the chamber wall, where resistance to water movement would be lowest. The ½-Scale tests provided an opportunity to physically confirm these indirect observations. In four of the ½-Scale tests it was possible to trace the pathway taken by water as it moved along the pellet-chamber wall contact. Figure 6-39 shows the serpentine flow path observed during dismantling of Tests 1-2 and Figures 6-40 and 6-41 shows the outflow locations and tracer-stained pathways taken by water in Tests 11 and 12. As flow continues it could be expected that the pathways become straighter and resistance to inflow would gradually decrease until steady-state was achieved. This may be the explanation for the inflow resistance patterns, non-proportional inflow-rate versus time for outflow, described above.

Piping

Piping

Sheet Erosion: block face

Figure 6-36. *Short-term erosion features observed in block-filled regions /Dixon et al. 2008c/.*

Figure 6-37. *Piping features initially present along pellet-block interface in Test 12 /Dixon et al. 2008c/.*

Initial outflow from Test 8 (right) **End-of-test outflow locations**

Figure 6-38. *Front Face of Tests 7 and 8 at the start of outflow and end of testing (0.25 l/min and 0.5 l/min at sample mid height and mid length).*

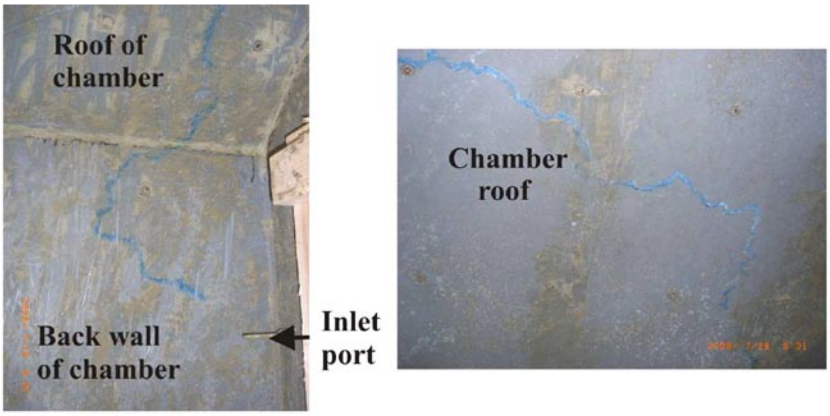
Test 1 Test 2

Figure 6-39. *Evidence of flow channels in Tests 1 and 2. (Pathway location traced with arrow showing direction of flow.)*

Erosion

As with previous, smaller-scale tests a key aspect in the conduct of the ½-Scale tests was monitoring of the amount of material eroded. In all cases where outflow occurred, there was some quantity of clay material removed. In general, the quantity of material removed by the water exiting the backfilled volume was quite small. Due to the large volumes of water passing through these tests and the tendency of this water to cause swelling of materials adjacent to the outflow locations or on the floor beyond the backfill, it was not possible to get an actual measurement of the mass of solids removed. It was possible to estimate the quantity in some cases based on the volume of materials deposited at the toe of the backfill wall. In cases where there were considerable quantities of materials removed it was not possible to do more than roughly estimate the mass removed.

Figure 6-40. Assembly 6 (Tests 11 and 12) at the end of testing Test 12. (Note blue tracer exiting a crown of chamber and pink tracer in lower right corner.)



(a) Test 11 showing flow path along back wall and roof of chamber

(b) Test 12 showing flow path along wall of chamber

Figure 6-41. Tracer-highlighted flow paths on roof (Test 11) and sidewall (Test 12) (actual dye tracks shown in photographs, pink and blue traces).

Eight of the twelve ½-Scale tests lost in the order of 1 kg (or less), of clay material over the 3 to 7 days each operated. The three tests done at inflow rate of less than 1 l/min that exhibited substantial (> 1 kg), amounts of material removal during their operation were numbers 7, 8 and 12. The quantity of material eroded in those tests was still quite limited (estimated to be 2–3 kg) as can be seen in Figure 6-42. The material removed was predominantly fines that either exited the piping features along the chamber wall, or more importantly, materials that were picked up while the water flowed down the face of the backfill assembly. In this respect erosion was very similar to what was observed in smaller bench-scale and field simulations /Dixon et al. 2008a, b, Sanden et al. 2008/.

Once flow channels were established, the erosion rate dropped off to very low levels, a process similar to that quantified in the smaller 1/12-scale field tests described in Section 6.2.6.

Test 10 demonstrated the potential risk to the backfilling system should very high, localized flow occur. Inflow of 2.5 l/min was provided at the rear of the chamber, contacting the backfill close to the interface between the pellets and the blocks. This water forced its way first along the block-block and geotextile-block contacts, then moving outwards to the block-pellet interface and into the pellet fill itself. This water rapidly formed a preferential flow path of perhaps 5 mm diameter along the cell wall (as observed at downstream face). As it exited the backfilled volume, the high flow rate removed material at the downstream face, resulting in ongoing erosion of this region. Ultimately enough material was removed to cause the physical collapse of a portion of the material above the eroded void. This represented a substantial mass of material removal but only extended about 0.5 m into the assembly (Figure 6-43).

It should also be noted that these tests have been done using artificial boundary conditions (pellet-concrete or pellet-steel). These contacts are not necessarily representative of interactions that will occur in a rough rock contact, however it is likely that interface flow will dominate even the rock-pellet systems.

28 h 70 h 97 h 108 h

Figure 6-42. *Limited erosion caused by stable piping feature (Test 8; 0.5 l/min).*

Fan of eroded material at toe of outflow point along chamber wall

Sediment washed into collection trays

Void developed

Figure 6-43. *Erosion in Test 10 (2.5 l/min inflow at rear of chamber).*

Conceptual model for short-term hydraulic evolution of backfill

The completion of the above-described ½-Scale tests as well as the 1/12-Scale tests (Section 6.2.6) and laboratory-scale studies /Sandén et al. 2008/, allows the development of a preliminary conceptual model for the evolution of the backfill system immediately after it is installed and water begins to interact with it.

As a first step in developing a conceptual model for water movement into and through a confined pellet fill immediately after it is installed, it is necessary to look at the process as an interaction of processes that have different importance at different stages of system development. Evolution of the system will depend on a range of factors including both macro and microstructural factors including (individual pellet dry density and water content, as-placed pellet-fill density, fines content and mineralogical composition of the clay). Conceptually, the basic evolution of the system can be described as follows:

- In the earliest stages, inflow will be controlled by the macro-structural features such as macroporosity and tortuosity. Thus the amount of initial water uptake can be greatly affected by rate water ingress, fines content (providing initial resistance to inflow). If water enters sufficiently rapidly and other factors are "favourable" then it has the potential to occupy a substantial portion of the macro-porosity before swelling begins.
- Once water has entered the system, secondary processes such as mineralogy and associated processes such as suction of the individual pellets will begin to affect both water movement and water uptake.
- Swelling of the pellets will reduce macro-porosity and begin to change the nature of water movement into the pellet-volume from an advection-dominated process to one dominated by suction from the as-yet unsaturated pellet mass.
- The lower permeability of the volume occupied by the swelling clay results in increasing resistance being developed to further water inflow.
- With this resistance and the heterogeneous nature of the pellet fill with respect to saturation, many changes in the pathway taken by the inflowing water will occur, resulting in oscillations in inflow resistance.
- Once a sufficient volume is wet to provide a consistent resistance to flow, water will tend to move along the next-lower resistance pathway (an interface).
- The process of wetting and swelling adjacent to the source of water will ultimately result in a system where the path for water movement reaches the downstream face of the cell.
- On reaching the downstream face hydraulic gradient will decrease due to loss of backpressure induced by low permeability clay, resulting in a decrease in inflow resistance.
- Water movement will then be dominated by the channel developed.
- Provided that inflow rate is low enough that turbulent flow is avoided, the flow path will remain relatively stable and non-erosive.
- For a period following the development of the hydrated zone around the flow path there will be further water uptake by the as-yet unsaturated clay further away from the source of free water. The quantity of ongoing water uptake will be rather small as it is predominantly driven by the suction gradient between the saturated region and the as-yet unsaturated regions.
- Ultimately, on achieving saturation there will no longer be a demand for water from the perimeter regions and all water inflowing will move along the established flow channel. This will happen so long as there is unrestricted outflow at the downstream face or the channel is not closed through other processes active in a hydrating backfill system.

This very basic conceptual model for backfill evolution is based on the results of laboratory tests on backfill components and assemblies of potential components through to ½-scale simulations of a KBS-3H emplacement tunnel. The processes identified begin to describe how the backfill system will evolve during the period immediately following materials placement and through to the time when tunnel plugging is accomplished. Actual field conditions will likely cause evolution to be somewhat more complex than described above but it is expected that the basic processes and issues identified will exist.

Summary

The ½-Scale tests provided a more realistic simulation of an emplacement tunnel than previously available and provided known and quantifiable boundary conditions for use in evaluating the behaviours observed. As noted previously these are still only simulations and not actual field-scale tests done in a natural rock environment so the results are still only indicative in nature. They do however still provide valuable information regarding likely conditions that will occur in the tunnel during backfilling operations and provided a means of evaluating technologies and materials considered for used in a repository. These tests have also provided greater confidence in the ability to place backfill in the form of precompacted blocks and pellets using technologies that are currently available or that could be developed through extension of these technologies.

In the course of completing the ½-Scale tests it was found that most of the water entering the system typically remained within the pellet-filled perimeter region or else made its way into that region during the first few days after beginning of the test. This was the case at all inflow rates examined (0.25 to 2.5 l/min single point inflows and up to 4 l/m inflow combined from two inlets) and indicates that internal erosion of the backfill clay blocks may not be as great an issue as was indicated in the previously conducted 1/12 scale tests (see Section 6.2.6). There will still be the potential for internal flow (and greater erosion risk associated with it) and so techniques to deal with such a situation still need to be developed. High localized water inflow to the backfill (e.g. 2.5 l/min) also resulted in considerable erosion of the pellet materials along its flowpath and if persistent could compromise backfill performance as well as complicating ongoing backfilling operations.

The ½-Scale tests also allowed for demonstration of pellet placing techniques and technologies that are appropriate for use in a repository. The ability to place pellets in a consistent and efficient manner was demonstrated and the densities achievable could be quantified. This provides some bounding values for the pellet fill and allows the evolution of the backfilling system to be assessed with respect to equilibrated densities, swelling pressures and hydraulic properties.

The basic operationally-important conclusions that can be derived from the inflow resistance data, water flow and emplacement technologies examined in the ½-scale tests are as follows:

1. The block and pellet assembly will remain physically stable under conditions of water inflow from a single point of 0.5 l/min or less.
2. Erosion of backfill will likely be limited and so should not adversely affect the ultimate density of the backfilled volume.
3. A pellet-block backfilling system cannot be relied on to substantially delay water movement to the front face of a backfilled section of tunnel.
4. There is unlikely to be any substantial build-up of porewater (or trapped air) pressure within the backfill close to the working face during the period of backfilling.

These conclusions are important in two ways, firstly the water entering the tunnel will need to be dealt with within a short time of backfill placement (few hours to a few days) and secondly it is unlikely that there will be substantial deformation of the backfill as there will be no build-up of water or (air compressed by water influx). This provides additional confidence in the ability to install a mechanically stable backfill system although there is still a need to ensure that there is no opportunity for internal erosive pathways to develop.

From the results of the ½-scale tests several topics have been identified that will require some further evaluation. These are largely associated with advancing the technologies associated with backfilling and conduct of field demonstrations intended to confirm the apparent significance of processes identified in Baclo III studies. Topics for ongoing examination include:

1. Developing a means of installing pellet materials to a higher dry density.
2. Developing means of controlling water influx in regions of high inflow.

Developing means of collecting water entering unfilled sections of tunnel (both from the already backfilled volume as well as the open regions) so as to minimize influence on backfill and backfilling operations.Determining the effect of dispersed water inflow into backfilled regions on saturation process, development of swelling pressures and resistance to water movement within the tunnel.

6.2.8 Installation tests that examine block placement and pellets installed on floor of tunnel

Some observations on wetting and erosion of Minelco granules and Cebgel pellets were made in conjunction with practical installation tests performed in the Bentonite Laboratory at Äspö, Sweden /Wimelius and Pusch 2008/. The objective of the tests was not to study erosion, but to study the stability of an assemblage of full-size mock-up backfill blocks (made of concrete) placed on a layer of pellets and the effect of water inflow to this system (see Figure 6-44). The observations made on saturation and erosion were an unplanned for by-product of the tests. A total of 7 tests were performed in a simulated tunnel with width of 4.05–4.65 m and height of 5.6 m. A total of 100 concrete blocks were installed and this produced a pressure on the pellet layer between 33–66 kPa depending on the block layout applied. The pellet materials used were Cebogel pellets and Minelco granules /Wimelius and Pusch 2008/.

The dry density of the pellet materials after compaction with a vibrating plate varied between 1,220–1,382 kg/m^3 depending on the weight of the vibrating plate used (50, 70, and 150 kg) and thickness of compacted layers (1×0.3 m, 2×0.15 m or 0.1 m). Some additional compression of the pellets also took place underneath the blocks. The water inflows applied to the centre of the layer were either 0.1 or 1 l/min. In addition, there was an additional inflow of 0.25 l/min located at the middle of other half of the floor filling in all of the tests. The water was fed into the assembly from beneath the bentonite bed. The duration of the tests varied between 20 and 25 hours /Wimelius and Pusch 2008/.

Some general observations were made on the saturation of the floor backfill /Wimelius and Pusch 2008/:

- Only very small movements of the concrete blocks were measured by wetting of the pellets.
- The pellets were usually wet below the block joints.
- In most cases, the water rose through the bentonite bed to the surface of the layer and from there along the surface to the front and sides of the test setup. After that, continuing wetting of the pellets took place from the surface of the layer. Wetting of Minelco granules was visually observed slower than for Cebogel pellets.
- After dismantling of the blocks, areas with dry pellets were found underneath the concrete blocks in all tests. Since the pellets had been compressed by the weight of the blocks, this indicates how construction-induced features can affect the propagation of the saturation beneath the blocks.

Figure 6-44. *Floor material tests in the bentonite laboratory at Äspö showing on the left how water moved along sides and towards front of pellet materials and on the right how saturation had propagated underneath the blocks.*

6.2.9 Erosion model developed from laboratory and field experiments

The general conclusion from the erosion and various scale tests is that there will likely be some degree of ongoing water inflow and erosion to the tunnel until the entire void space in the pellet filling is occupied with water. Once the plug is installed, the erosion process will be dominated by internal erosion (internal re-distribution of mass in the sealed tunnel) and this is not assumed to stop before the total void volume in the pellet fill is filled with water. Hence the aim of this section is to estimate the total erosion (X kg) that can take place in the backfilled tunnel before its closure and then internally after installation of the tunnel plug. Since the empty volume in the pellets filling can be estimated and equal to the total water inflow that can cause erosion, the maximum internal erosion that can take place can be calculated provided that the erosion rate is known. It should be noted that this type of assessment is extremely conservative as it assumes several unlikely boundary conditions, as outlined below, but it does provide a set of bounding calculations. These calculations were performed using erosion rates (g/l) from laboratory tests described by /Sandén and Börgesson 2006 and Sandén et al. 2008/. The data from ½- or 1/12-scale tests was not used in these calculations.

Assuming that the above hypothesis is correct, 80% block filling yields the total volume of pellets of:

$V_{pellets} = 300 \times 0.2 \times 25\ \text{m}^3 = 1{,}500\ \text{m}^3$

Assuming a 50% open space in the pellets, yields the total volume that can be filled with water:

$V_{space} = 750\ \text{m}^3$

The most extreme case that yields the largest erosion is that all water inflow into the entire tunnel comes in one point and flows towards a single location in the tunnel. Measurements from laboratory tests /Sandén and Börgesson 2006, Sandén et al. 2008/ have shown that the erosion is between 1 and 10 g per litre eroding water. With this rough estimation the consequence of erosion will be the following:

Erosion 1–10 g/l in 750 m^3 eroding water yields 750–7,500 kg eroded backfill.

If the inflow rate is 1 l/min it will take 1.43 years to fill the tunnel and stop the erosion.

Although this is an extreme scenario the example shows that the consequences of internal erosion could be considerable for the backfill and that a better understanding and an improved model of the erosion is needed in order to find the limits.

New model

All results from the reported erosion tests done at laboratory scale are plotted in Figure 6-45 with the accumulated dry mass of eroded material as a function of the accumulated water flow in a double logarithmic diagram. The diagram clearly shows that there seems to be a fairly linear relation and that most relations have similar trends.

A model can be derived from these test results assuming linear relation in such a double logarithmic diagram:

$$m_s = \beta \times (m_w)^{\alpha} \qquad (6\text{-}1)$$

where

m_s = accumulated mass of eroded bentonite (g)

m_w = accumulated mass of eroding water (g)

$\beta = 0.02–2.0$ = parameter defined by the level of erosion at a certain accumulated water flow

$\alpha = 0.65$ = parameter defined by the inclination of the straight line relation

Figure 6-45 shows that all data is limited by two lines with the inclination corresponding to $\alpha = 0.65$ and the erosion level corresponding to $\beta = 0.02$ (lower line) and $\beta = 2.0$.

$\alpha = 0.65$ yields a rather strong decrease in erosion rate with time and accumulated water flow. Constant flow rate corresponding to $\alpha = 1.0$ is also illustrated in the figure.

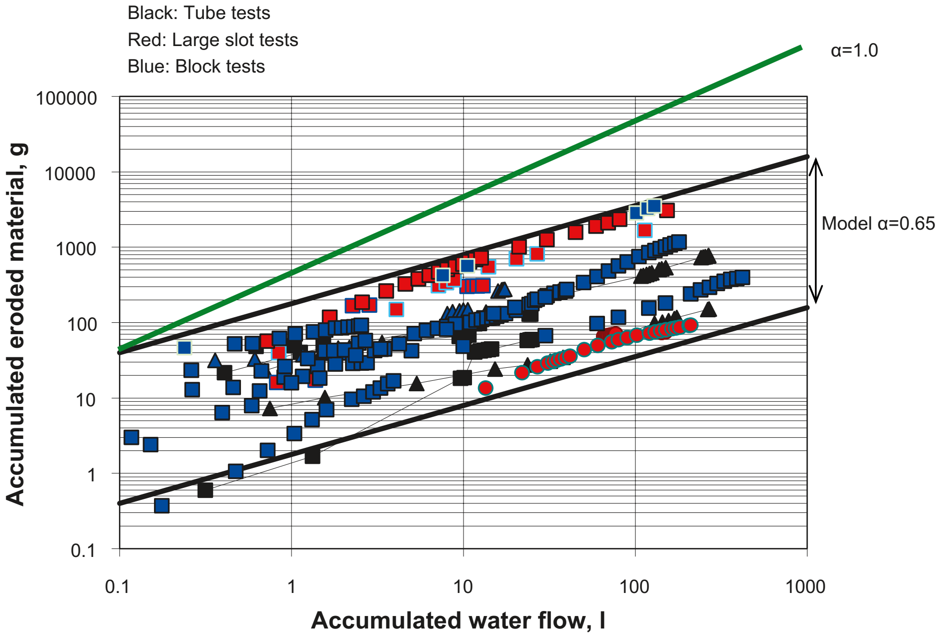


Figure 6-45. *All erosion results plotted in one diagram. The lower boundary line corresponds to β = 0.02 and the upper β = 2.0. The inclination corresponding to α = 0.65 is motivated in the figure. α = 1.0 (corresponding to constant erosion rate) is also illustrated. Data from /Sandén and Börgesson 2006, Sandén et al. 2008/.*

The model can also be used to determine the expected erosion rate:

The water flow rate can be expressed according to Equation 6-2.

$$q_w=\delta m_w/\delta t=(\text{at constant rate})=m_w/t \tag{6-2}$$

Differentiation of Equation 6-1 yields the rate of erosion as function of the accumulated mass of eroding water:

$$\delta m_s/\delta m_w=\beta\cdot\alpha\cdot(m_w)^{\alpha-1} \tag{6-3}$$

Insert $\delta m_w=q_w\delta t$ and $m_w=q_wt$ in Equation 6-1:

$$\delta m_s/\delta m_w=\beta\cdot\alpha\cdot(q_w\cdot t)^{\alpha-1} \tag{6-4}$$

$$\delta m_s/\delta t=q_w\cdot\beta\cdot\alpha\cdot(q_w\cdot t)^{\alpha-1} \tag{6-5}$$

Equations 6-4 and 6-5 thus yield the rate of erosion as function of time at constant flow rate:

$$q_{mv}=\delta m_s/\delta m_w=\beta\cdot\alpha\cdot(q_w\cdot t)^{\alpha-1} \tag{6-4b}$$

$$q_{mt}=\delta m_s/\delta t=q_w\cdot\beta\cdot\alpha\cdot(q_w\cdot t)^{\alpha-1} \tag{6-5b}$$

where

q_{mv} = erosion rate (grams dry backfill per ml eroding water) at time t

q_{mt} = erosion rate (grams dry backfill per second) at time t

q_w = water flow rate (grams eroding water per second)

t = time (s)

β = 0.02–2

α = 0.65

Application of the new model

The new model can now be applied to the extreme scenario that all inflow comes in one point:

750 m^3 (= $7.5 \cdot 10^8$ g) eroding water yields according to Equation 6-1

$m_s = \beta \times (m_w)^\alpha$

$m_s = (0.02–2) \cdot (7.5 \cdot 10^8)^{0.65} = 11.7–1{,}170$ kg

The total expected mass of eroded backfill calculated using this model be only between 11.7 and 1,170 kg, which is 1.5–15% of the erosion estimated when a constant erosion rate of 1–10 g/l was assumed.

The rate of erosion at different times can also be estimated with Equation 6-5. If the inflow rate is 1 l/min the total time will be 1.43 years:

$q_w = 1$ l/min = 16.7 g/s

$t = 1.43$ years = $4.5 \cdot 10^7$ s

Erosion rate after 1 hour: $q_{mv} = 0.28–28$ g/l (or $q_{mt} = 0.28–28$ g/min)

Erosion rate after 1.43 years: $q_{mv} = 0.01–1.0$ g/l (or $q_{mt} = 0.01–1.0$ g/min)

Although the erosion rate is similar after one hour (0.28–28 g/l) to what was assumed in the original example (1–10 g/l), it decreases with time so much that the total erosion is 7–70 times lower when the new model is used.

This example concerns the degree of block filling 80%. If it is only 60% the total erosion will be larger but the difference between the assumption of constant erosion and the new model also greater.

New tests on vertical pellets filled slots of MX-80 indicate that the erosion of pellet materials can be further reduced with a factor 10 (β=0.02–0.2) but these results cannot be used for the backfill since the tests were explicitly made for simulating vertical deposition holes.

Conclusions and comments

An erosion model based on erosion tests has been suggested. This model describes the situation where internal erosion continues to take place in the tunnel after a plug has been placed in the entrance of a deposition tunnel until the total void space of the pellet fill has been filled with water. The model assumes a linear relation between accumulated eroded material and accumulated water flow in a double logarithmic diagram. It includes two parameters: α that corresponds to the inclination of the linear relation and β that determines the level of the accumulated erosion. Application of the model on an extreme case showed that the expected total mass of eroded material was reduced 7–70 times compared to what could be expected if a constant erosion rate of 1–10 g/l was assumed. Some observations and comments:

- α seems little affected by the test material or conditions and is a constant with the value 0.65 according to the measurements.
- β must be measured and is dependent on the material type, the salt content, the water content, the pellet grain size distribution and the geometry etc.
- The model is preliminary but may be a way to put limits the erosion consequences.
- All tests have made on bentonite with low water content (10–17%) but the erosion seems to decrease with increasing water content.
- Since tests have so far only been made with short duration (less than a week) and with rather short flow paths, long term tests and tests in long tubes are ongoing in order to verify that the results can be extrapolated to actual field conditions.

6.2.10 Summary and discussion of effects of water inflow during installation and early saturation

The material presented in the preceding sections have resulted in a better understanding of the processes active in the backfilled tunnel immediately prior to completion of backfilling and in the period just after installation is completed. These results may also be relevant to tunnel sections that are initially dry but subsequently see inflow of water from either the rock or other sections of the tunnel. To facilitate summarizing of the results presented the key findings have been organized into four general subject areas a described below.

Material selection and preparation

- Friedland clay blocks are sensitive to erosion and piping, at least if blocks with low initial dry density are used.
- No formation of piping channels was observed for 30/70 mixture in block densities and water moved through the specimen as a water front.
- The quality of blocks affects the erosion resistance of the blocks. Therefore, the blocks should be prepared with compaction pressure of at least 25 MPa. The water content of the blocks may have some effect on the erosion resistance, but in practice the water content has to be set based on the optimum water content for the compaction to obtain the target density.
- Pellet fill is needed to protect the blocks from erosion by inflowing water. Without pellets the risk of block erosion increases.

Erosion

- When comparing the results from laboratory-scale tests, 1/12-Scale tests and ½-Scale tests, the test-scale seemed to have effect on the saturation behaviour and also on erosion. In laboratory scale tests the erosion rate was in most cases 1–10 g/l. In the 1/12-Scale tests, the erosion was in some cases significantly higher, the usual case being between 1 and 25 g/l. However, in both cases there was a trend that of the erosion rate decreasing with time, when a stable pathway had formed in the system.
- In the 1/12 Scale tests, whenever a flowpath was formed between the pellets and the wall of the test setup, the erosion was significantly smaller compared to a situation where the piping occurred through the blocks.
- In each of the ½-Scale tests, the total erosion observed was only a few kilograms of material, making the loss per unit volume very limited, however, locally erosion may be quite substantial.
- A model of the erosion has been suggested. This model was used to estimate the erosion before and after installation of the tunnel plug, and projections extend through until the total void volume of the pellet fill was completely filled with water. This model also assumes that erosion rate decreases considerably with time.
- Water inflow at a single point does not seem to affect the erosion very much if a preferential pathway forms in the pellet-rock contact and inflow rates are moderate (< 0.5 l/min). However, at inflow rates > 0.5 l/min the probability of erosion increases.
- Based on the tests, some erosion will take place during the installation and saturation period. However, the erosion rate seems to be limited (some tens of grams of sediment per litre of inflow water), with a tendency to decrease in time provided that turbulent flow conditions are avoided. Therefore, it can be stated that at tunnel scale under most conditions the effect of erosion on the performance of the backfill in the period immediately following installation is likely to be limited. However, locally the consequences of high inflow may be more significant.

Water influx and movement (observed in 1/12-Scale and ½-Scale tests)

- Water inflow is also important from installation point of view, because it can disturb the working process and lead to lower initial dry densities than planned. In addition, inflow will affect the installations rate.

- In general, almost all of the water that was introduced to the system (~ 90%) was coming out of the system after the first water outbreak. Outflow took place some hours after the beginning of the tests when the water inflow was > 0.1 l/min. The remaining of the water was occupying the macropores of the backfill (voids between pellets and voids between the blocks) but the water was also consumed by suction of the materials.
- Based on these ½-Scale tests, the inflow can be as great as 0.5 l/min and the point source flow can be tolerated for short time periods if the backfill placement can be advanced several meters past the inflow location and placement of block backfill does not cease for more than few days.
- The total acceptable inflow into a single deposition tunnel must still be determined.
- It seems plausible that flow pathways formed at different sides of the tunnel do not unite further down at the tunnel.

Design concept

- The scale-effect can be seen when comparing the results from 1/12-Scale tests and ½-Scale tests. In the first case, the pellet thickness between the blocks and the rock wall/roof was ~ 10 cm and in the latter ~ 15 cm. Even though the difference in the pellet thickness was not very big, the saturation behaviour was more consistent for the ½-Scale tests, where a stable pathway formed in most cases in the interface between the pellets and the wall of the test setup (and very limited erosion). However, this may also be due to different installation techniques. In the 1/12-Scale tests, the installation was made manually probably leading to arbitrary variations in the pellet density, but in the ½-Scale tests, the installation of pellets were made with a machine probably leading to somewhat more consistent density distribution. In addition, some extra water was added in the ½-Scale tests to inhibit dust generation during pellet placement and in few cases to provide steep pellet front. The higher water content may have also affected this situation.
- There needs to be some technical means of dealing with the water at the backfilling front, since the materials are not able to prevent the water from reaching the backfill front.

Recommended further work

The 1/12- and ½-Scale field tests done as part of Baclo Phase III have provided valuable guidance and understanding regarding backfill evolution and processes that might affect operations. To better understand the processes and issues identified, further testing would be of value, these might include examination of the following:

- Effects of ongoing localized erosion in larger-volume environments.
- Effect of high water pressure, turbulent versus laminar flow through piping features and effects on erosion rate.
- Erosion during installation of blocks before pellets are placed, how it can be handled or what inflow remedial actions can/should be undertaken.
- Can pellets installed at high water content be used to direct where water will flow within the tunnel during the period immediately following backfill installation?
- The manner in which water enters the tunnel and how multiple inflow points (simulating a fracture intersecting the tunnel) interact with one-another has yet to be determined.
- Verification of currently determined time and scale-effects needs to occur through further testing and modelling.

In addition, some longer-term processes not part of the scope of Baclo Phase III might affect backfill performance and should be further evaluated. Specifically:

- Erosion and mass loss via regional hydraulic gradient and natural fractures in rock intersecting the tunnel after installation of the deposition tunnel seal (long-term safety issue).
- Effect of diluted water (glacial meltwater following an iceage) on erosion through colloid formation and transport to the open void space in fractures and in the tunnels (a potential long-term safety issue).

6.3 Interaction between backfill and buffer

6.3.1 Introduction

A key requirement set for the backfill is to ensure that the swelling of the buffer into the deposition tunnel is limited, so that the buffer density remains at acceptable level. This is important because a decrease in buffer density has various consequences that are critical for the performance of the whole engineered barrier system

- Permeability of the buffer increases with decreasing density, affecting the rate of mass transfer through the buffer. This results in an increased risk of premature canister corrosion and failure, eventually allowing the migration of radionuclides through the buffer.
- Reduced density enables microbiological activity in the buffer if the saturated buffer density decreases below 1,800 kg/m^3 /Miller and Marcos 2007/. The microbiological activity increases the risk of premature canister corrosion and failure.
- Mechanical strength decreases as density decreases, which can lead to canister movements, although depending on the magnitude may be harmless to the performance of the engineered barrier system.

Since the buffer bentonite has higher swelling pressure than the backfill, it is likely that the buffer will be able intrude into the deposition tunnel until a mechanical balance is reached between the buffer and the backfill. What the magnitude of this displacement is at the buffer-backfill interface will depend on various factors such as the initial swelling pressure of the buffer, friction angle between the buffer and the rock, saturation state of the buffer and the backfill and composition of the backfill. Since a backfill consisting of blocks and pellets is initially heterogeneous, the deformation of the backfill is affected not only by the deformation properties of the materials used but also by the geometry of different backfill components. In order to evaluate this, a number of analytical calculations and numerical modelling cases were performed by /Johannesson and Nilsson 2006, Johannesson 2008, Börgesson and Hernelind 2008 and Korkiala-Tanttu 2008/. The basic assumption made in these studies was that the saturated buffer density should remain above 1,950 kg/m^3 at the level of the canister lid. The calculation cases, results and uncertainties linked to these studies are described in Sections 6.3.2 to 6.3.5 of this report.

6.3.2 Deformation of backfill due to swelling of the buffer based on analytical calculations

Analytical calculations were performed in order to assess what decrease of buffer density at the canister level would occur due to deformation of the backfill as a consequence of the swelling pressure generated in a saturated buffer. The analytical calculations were first performed in /Johannesson and Nilsson 2006/ assuming that also the backfill would be in saturated state generating some counter pressure against swelling pressure of the buffer. Later, the analytical calculations were repeated assuming that the backfill would still be in unsaturated state, while the buffer is already fully saturated, since this was supposed to present a "worst-case-scenario" /Johannesson 2008/. Based on the criteria set for the backfill, the saturated density of the buffer shall not decrease below 1,950 kg/m^3 at the level of the canister lid.

These calculations for the unsaturated backfill /Johannesson 2008/ were made for two cases: 1) assuming continuum of materials and 2) assuming that the deformations would take place only in a pillar of blocks piled on top of the deposition hole, named here as the block case. In order to develop baseline data for the dry case calculations, the strength properties of different block and pellet materials were measured via unconfined one-dimensional compression tests and with a beam test /Johannesson 2008/. Other assumptions used in these calculations were:

- The tunnel volume is filled to 78% efficiency with blocks, 2% is unfilled voids (gaps and joints) and the rest is filled with bentonite pellets having bulk dry density of 1,100 kg/m^3.
- The geometry of the backfill is as presented in Figure 6-46. Note that the thickness of the pellet layer between the blocks and the roof is defined to be 300 mm.
- The initial thickness of one horizontal joint between blocks is 4 mm and the number of joints is 9.

- The strength parameters were determined for specimens prepared using a compaction pressure of 25 MPa.
- The initial swelling pressure generated by the buffer is 7 MPa corresponding to dry density of 2,000 kg/m^3. The swelling pressure decreases gradually as the buffer density decreases.
- For the basic calculation case, the friction angle between the buffer and the rock is 10°, but calculations were performed also with 0° and 20° in order to determine the sensitivity of the system to this parameter.
- The distance between the backfill-buffer interface and the top of the canister lid is 1.5 m.

The results calculated for the unsaturated backfill are presented in Table 6-6. The strength parameters used were based on block specimens with following initial dry densities: 1,690 kg/m^3 (Asha 230B), 2,060 kg/m^3 (Friedland clay) and 2,170 kg/m^3 (30/70 mixture). Based on the results the buffer saturated density at the level of the canister lid remains on acceptable level (> 1,950 kg/m^3). However, at the buffer-backfill interface, the saturated density decreases below 1,950 kg/m^3. The results for the saturated and unsaturated backfill are compared in Figure 6-47 as a relation of the initial average backfill dry density in the tunnel and the resulting saturated buffer dry density at the level of the canister lid (after the swelling of the buffer/deformation of the backfill has reached equilibrium). Based on the results presented above, the dry backfill case proves to present the worst-case scenario with respect to risk of decreasing the saturated buffer density below the criterion of 1,950 kg/m^3. In addition, the conditions are less suitable if it is assumed that the deformations take place in a pillar of blocks placed above the deposition hole, compared to the continuum case. In reality, it is likely that the backfill will be at least partially saturated by the time the buffer has reached its full swelling pressure. However, based on current information, locally dry sections of backfill cannot be totally ruled out, which should be taken into account in the design basis.

The key uncertainties linked to these calculations are linked to the assumed tunnel geometry, block filling degree (78%) and several other assumptions made in the calculations and uncertainties of the test methods to determine the strength parameters (e.g. beam tests were not successful for 30/70 mixture).

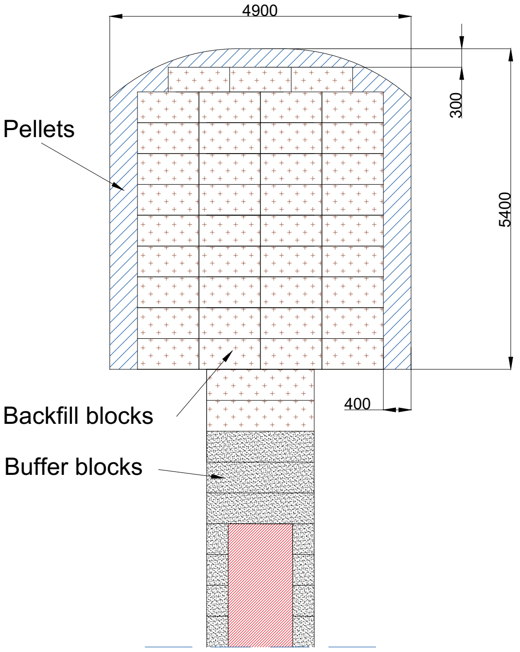


Figure 6-46. *Assumed backfill geometry for the analytical calculations performed in /Johannesson and Nilsson 2006 and Johannesson 2008/.*

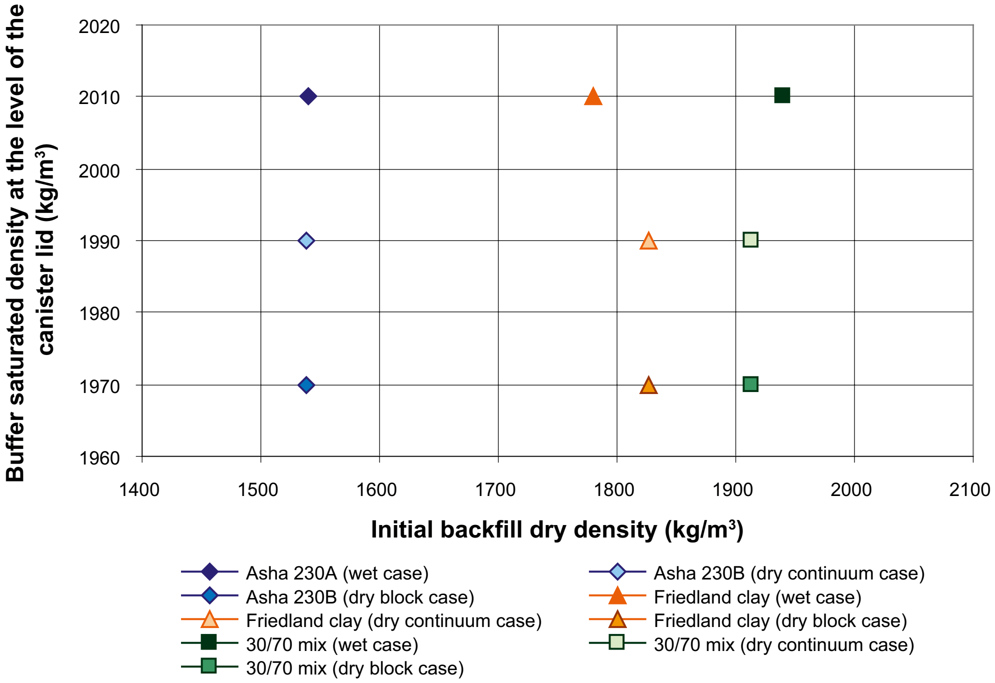


Figure 6-47. *Saturated density of the buffer at the level of the canister lid after a swelling of buffer/deformation of backfill scenario calculated assuming 1) wet backfill case, 2) dry continuum case and 3) and a dry case where the deformations take place in pillar of blocks piled above the deposition hole. The data is taken from /Johannesson and Nilsson 2006 and Johannesson 2008/. Assumed block filling degree: 78% and friction angle between the buffer and the deposition hole: 10°.*

Table 6-6. Results from the calculations of compression made for unsaturated backfill materials assuming a block filling degree of 78% and friction angle of 10° between the buffer and the deposition hole /see Johannesson 2008/.

Material	Case	Displacem. at buffer/ backfill interface (mm)	Swelling pressure of the buffer (MPa)	Buffer depth where there is no decrease in density (m)	Saturated buffer density at the canister lid (kg/m³)	Saturated buffer density at the buffer/ backfill interface (kg/m³)
Asha 203b	Contin.	83	2.95	2.14	1,990	1,940
Friedland	Contin.	78	3.00	2.10	1,990	1,940
30/70 mix	Contin.	85	2.92	2.17	1,990	1,940
Asha 203b	Blocks	133	2.37	2.69	1,970	1,920
Friedland	Blocks	130	2.40	2.66	1,970	1,920
30/70 mix	Blocks	139	2.32	2.75	1,970	1,920

6.3.3 Deformation of backfill due to swelling of the buffer: Based on numerical modelling

The deformation of the backfill as a consequence of the saturation and swelling of the buffer were also studied using numerical modelling. The purposes of the numerical calculations were to improve and complete the analytical calculations for more realistic simulations. The cases modelled represented two extreme cases where the saturation state of the backfill was supposed to be either the initial (dry case) or that it had reached full saturation (wet case). In both cases the buffer was assumed to be fully saturated generating an initial swelling pressure of 7 MPa. Both dry and wet backfill cases were studied by /Börgesson and Hernelind 2008/ via a 3D model (using a programme called ABAQUS). In order to evaluate effect of using different modelling tools, a parallel 2D modelling study was performed with a programme called Plaxis 2D (version 8.6) by /Korkiala-Tanttu 2008/.

In the basic modelling case studied, the tunnel and backfill dimensions were the same that were used in the analytical calculations by /Johannesson and Nilsson 2006 and Johannesson 2008/, see Figure 6-46 and Section 6.3.1. Since this tunnel geometry is based on a Swedish deposition tunnel design that has since been altered, the dimensions of a Finnish deposition tunnel were also used by /Korkiala-Tanttu 2008/ to study the effect of the tunnel geometry. The assumptions used in the numerical modelling performed in the Baclo programme are summarized in Tables 6-7 and 6-8.

Table 6-7. Summary of comparison of assumptions made for the basic modelling case and parameters varied in the sensitivity analysis performed in /Börgesson and Hernelind 2008/.

Assumptions used in /Börgesson and Hernelind 2008/	Basic modelling case	Varied in sensitivity analysis
Basic assumptions		
Material	Friedland clay	–
Model	Continuum (wet and dry cases)?	Block case (dry case)
Material model (backfill)	Linear elastic?	
Material model (buffer)	Porous-Elastic (D-P plasticity)	
Material parameters		
E-modulus of Friedland clay backfill (wet case)	50 MPa	25 MPa, 100 MPa
E-modulus of Frieldand clay blocks (dry case)	500 MPa	
E-modulus of pellets	3.24 MPa	50 MPa
Poisson's ratio (v) of Friedland clay blocks	0.2	
Poisson's ratio (v) of pellets	0.3	
Friction angle between the buffer and the rock	8.7° (between all surfaces)	0.0°, 4.4°, 17.0°
Swelling pressure of the backfill in (wet case)	0 MPa	1 MPa, 3 MPa
Geometry		
Width of horizontal and vertical gap elements between blocks	4 mm, closed at 10 MPa	
Block filling degree (volume-%)	78%	
Thickness of pellet filling at the roof	0.3 m	–

Table 6-8. Summary of comparison of assumptions made for the basic modelling case and parameters varied in the sensitivity analysis performed in /Korkiala-Tanttu 2008/.

Assumptions used in /Korkiala-Tanttu 2008/	Basic modelling case	Varied in sensitivity analysis
Basic assumptions	**Friedland**	**Asha**
Model	Axisymmetric, continuum	
Material model (backfill)	Linear elastic	
Material model (buffer)	Linear elastic	
Material parameters		
E-modulus of Friedland clay backfill (dry continuum case)	92–264 MPa	
E-modulus of Asha clay backfill (dry continuum case)	100–251	
E-modulus of pellets	20 MPa	
Poisson's ratio (v) of Friedland clay blocks	0.28	
Poisson's ratio (v) of Asha blocks	0.1	
Poisson's ratio (v) of pellets	0.12	
Friction angle between the buffer and the rock	0.0°	10°
Geometry		
Width of horizontal gap elements between blocks	4 mm × 9	
Block filling degree (volume-%)	70%	60–80%
Thickness of pellet filling at the roof	0.3 m	

Results for the wet case (fully saturated buffer and backfill)

Based on the results from the 3D modelling for the base case, the buffer-backfill interface will be move 102.9 mm upwards from its original position due to swelling of the buffer /Börgesson and Hernelind 2008/ (see Table 6-9). The resulting changes in the location of the buffer/backfill interface and swelling pressure and void ratio of the buffer in the basic case is presented in Figure 6-48. In addition, according to the 3D model, a canister heave of 5.5 mm will also take place as a consequence of the changes in the buffer density.

Assuming that the density changes in the buffer would take place uniformly in the whole buffer volume above the canister, the acceptable displacement upwards into the backfill is only ~ 47 mm. However, based on the model, uniform density change will not occur, since the buffer will loose more of its density nearer to the buffer/backfill interface than in the vicinity of the canister. Whether this situation changes in the long term, remains as an uncertainty that needs to be studied in the future. It should be also noted that in the basic case it was assumed that no swelling pressure exist from the backfill rather than the 0.2+ MPa that will actually develop. From the results of the sensitivity analysis performed in /Börgesson and Hernelind 2008/, the swelling pressure of the backfill (p_0), acts as a counter pressure for the buffer swelling, leading to somewhat smaller displacements than in the assumed basic case. The other parameters affecting the magnitude of displacements are the friction angle between different surfaces (ϕ_c) and assumed E-modulus for the backfill and pellets (see Table 6-9). The main conclusions concerning the effect of different parameters are that:

- The friction angle between buffer and backfill has a significant effect on the density of the buffer and on the canister movements. However, the case where the friction angle would be 0 is not considered as a realistic case.
- The stiffness (E-modulus) of the backfill blocks has a strong effect on the displacement at the backfill-buffer interface. The effect of stiffness of pellets is not significant in this model, since in the assumed geometry there were no pellets at the floor.
- The swelling pressure generated in the backfill is an important factor in the wet case. Since no swelling pressure was assumed for the reference model, it can be considered as a conservative approach.

Table 6-9. Sensitivity analysis aimed at studying the effect of friction angle, E-modulus and swelling pressure of the backfill on the displacement at the buffer/backfill interface for the wet backfill case /Börgesson and Hernelind 2008/. ϕ_c = friction between buffer and rock, p_0 = swelling pressure of the backfill.

Model	**Characteristic** Deviation from reference model	Buffer swelling (mm)	Canister heave (mm)
Baclo3b	**Reference model**	**102.9**	**5.5**
Baclo3b1	ϕ_c = 4.4°	116.1	8.0
Baclo3b2	ϕ_c = 17.0°	94.3	3.5
Baclo3b3	ϕ_c = 0°	153.9	50.0
Baclo3b4	$E_{pellets}$ = 50 MPa	94.4	5.0
Baclo3b5	$E_{backfill}$ = 25 MPa	145.7	7.0
Baclo3b6	$E_{backfill}$ = 100 MPa	74.1	3.7
Baclo3b7d	p_0 = 3 MPa, $E_{pellets}$ = 50 MPa	23.9	0.8
Baclo3b7e	p_0 = 1 MPa, $E_{pellets}$ = 50 MPa	44.4	1.7
Baclo3b8	p_0 = 3 MPa, $E_{pellets}$ = 50 MPa, ϕ_c = 0°	58.4	17.0

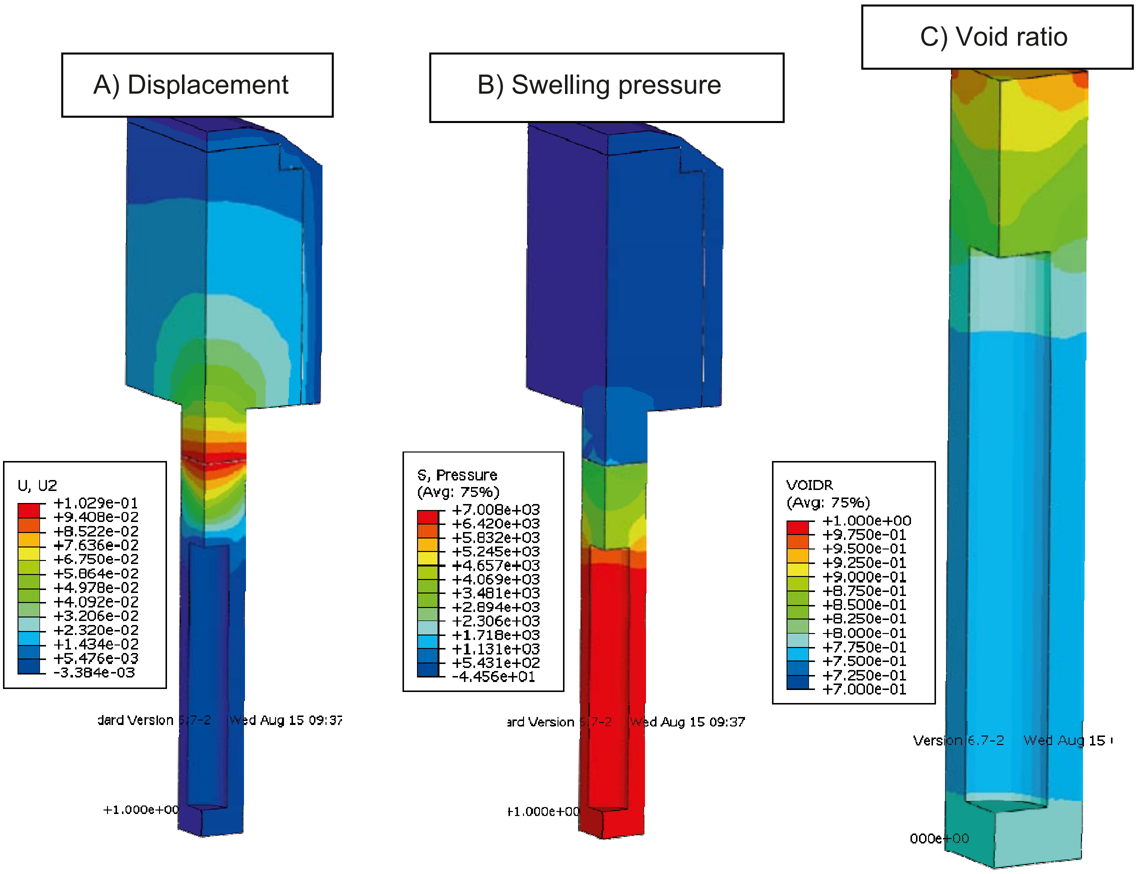


Figure 6-48. *Results from the 3D modelling for the basic case assuming that both buffer and backfill are in fully saturated state /Börgesson and Hernelind 2008/.*

Results for the dry case (unsaturated backfill, fully saturated buffer)

The dry case was studied with two different modelling approaches and programmes. An approach assuming continuum of materials was studied using Plaxis 2D by /Korkiala-Tanttu 2008/. In this case, the block-block interfaces were added to the displacement estimation in a manner similar to the analytical calculations by /Johannesson 2008/ by assuming that all horizontal joints between individual blocks would close as a consequence of the buffer swelling (9×4 mm). The results gained for the basic modelling case assumed in /Korkiala-Tanttu 2008/ with block filling degree of 70%, Swedish tunnel geometry and friction angle of 0°, the vertical displacement at the buffer/backfill interface is ~ 60 mm. In this (continuum of) material modelling approach, the stresses distribute both towards the roof and the walls of the tunnel. This is different from the approach studied with 3D modelling by /Börgesson and Hernelind 2008/, where vertical block-block surfaces also affected the stress re-distribution so that most of the stresses are exerted on a column of blocks placed above the deposition hole (see Figure 6-49).

Based on the results by /Börgesson and Hernelind 2008/ for the dry case, the results for the wet basic modelling case and the dry case were relatively near each other (the displacements were 90 and 100 mm respectively). The small difference was mainly because no swelling was assumed in the basic modelling case and the average stiffness of backfill materials was almost the same for the wet and dry cases (in the assumed backfill geometry).

A comparison of the results from the dry backfill case with the previously-described modelling approaches and analytical calculations was made in /Korkiala-Tanttu 2008/ where it was assumed that the friction angle between the buffer and the rock is 0°. Based on this comparison, the results are in relatively good accordance with each other, thus the results gained with analytical calculations and the two different numerical modelling approaches can be considered to be comparable.

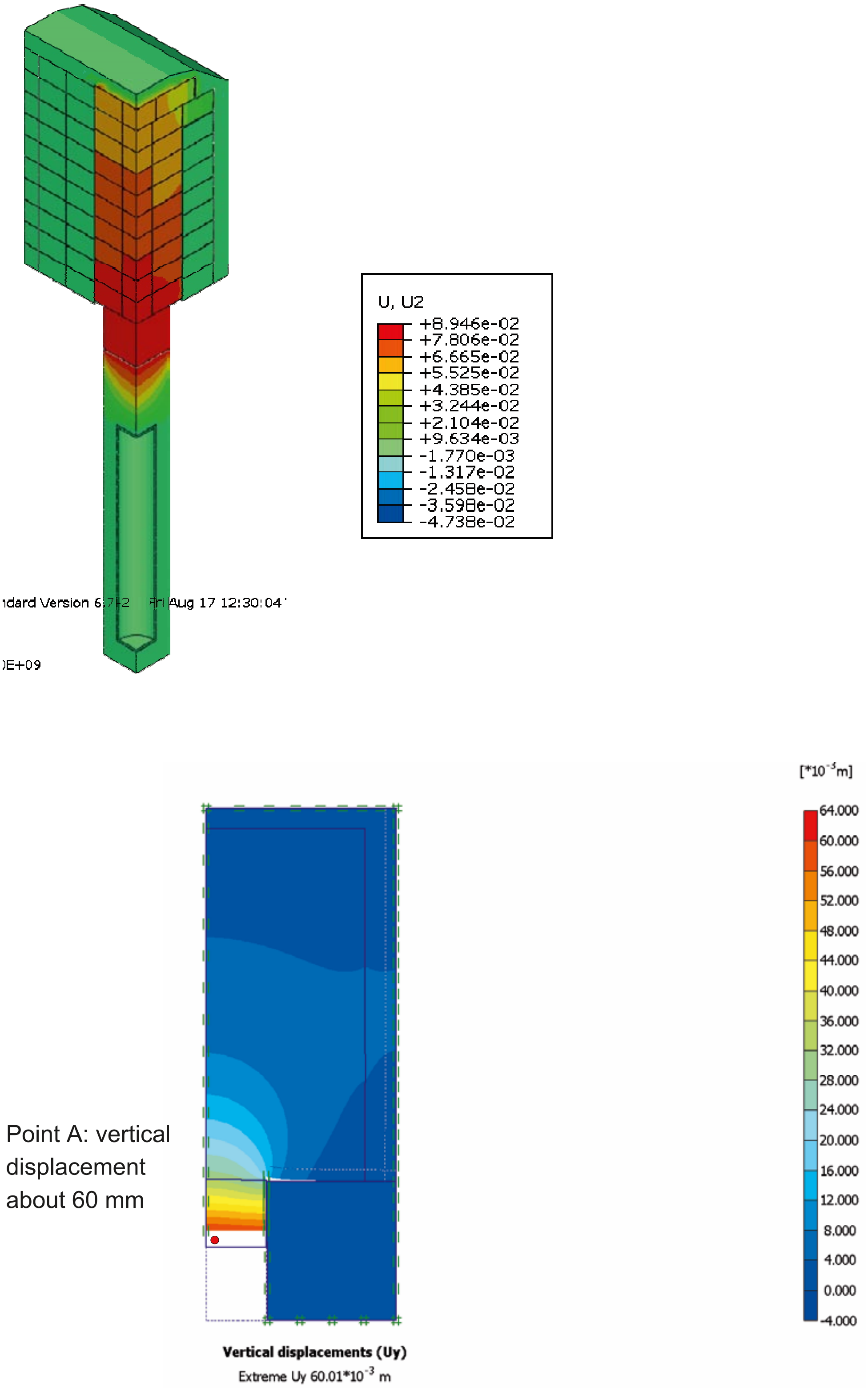


Figure 6-49. *The difference in the stress redistributions between the two modelling approaches for the dry backfill case. The situation in the model by /Börgesson and Hernelind 2008/ is shown in the upper figure and the situation in the model by /Korkiala-Tanttu 2008/ in the lower figure.*

Effect of different variables for the dry continuum case

Assessment of the effect of different variables for the basic modelling case (presented in Table 6-8) was performed in a study by /Korkiala-Tanttu 2008/ by varying the following parameters

- tunnel/buffer geometry (Finnish tunnel and buffer geometry versus the Swedish geometry),
- block material (Asha 230b bentonite versus Friedland clay),
- block filling degree (60, 70 and 80%), and
- effect of free space/gaps around the backfill blocks/pellets (varied only assuming Finnish tunnel dimensions).

In the Finnish case, the thickness of the buffer above the canister lid is 2 m, which is 0.5 m more than in the Swedish case. In addition, the volume of the tunnel is somewhat smaller than in the Swedish case. The main conclusions of this study into the effects of varying materials and proportions was that the deformations are more than 10% smaller in the Finnish case as compared to the Swedish case. According to /Korkiala-Tanttu 2008/ one reason for this is the thicker buffer layer above the canister that mitigated the amount of density loss that can occur as the result of buffer swelling.

The results obtained through evaluation of an alternative block material (Asha 230b bentonite) show that the deformation of the backfill was approximately 10 to 13% larger than for Friedland clay installed in exactly the same geometry. This was due to the smaller compression modulus (M) determined for Asha using the results of uniaxial compression tests provided by /Johannesson 2008/.

The effect of varying the degree of block filling from 70 to 80% had a relatively small effect on the deformation of the backfill (less than 1% change in calculated deformations). Such results imply that the proportion of pellets has a relatively small influence in the continuum of material approach, where the deformations take place mostly by blocks. For the Finnish case, the variation in the block filling degrees examined were 60, 70 and 80%. The differences in the deformation were small for those variations as well.

In order to study the effect of settlement of the pellets in the uppermost part of the tunnel, a numerical simulation where a 20 mm thick air filled gap has formed at the roof was performed by /Korkiala-Tanttu 2008/. The results show that this type of settlement can increase the compressibility of backfill (> 10%). This is one issue that should be considered in developing the method for pellet installation. In contrast, a case where it was assumed that all the pellets would have flushed away due to erosion did not result in an increase the deformation of more than 13% (when the block filling degree was 70%). This behaviour needs to be further examined using other modelling methods to rule out the effect of uncertainties linked to the program used and the continuum of material approach.

Uncertainties

The numerical modelling to study the deformation of the backfill, due to upward swelling of the buffer, showed that backfill deformation depends mainly of 3 factors:

- friction angle between the buffer and the rock,
- stiffness of the backfill materials, and
- swelling pressure generated in the backfill.

The cases studied present two extremes with respect to saturation state of the backfill but in practice conditions will likely be somewhere between these two cases. However, since the occurrence of dry tunnel sections cannot be ruled out, the dry case may need to be used as the base case since it provides the most conservative results. Regardless, it is recommended that the saturation process of the backfill be further investigated by combining experimental data and modelling to ensure that the numerical simulations can capture actual physical behaviour.

One of the biggest uncertainties linked to these modelling cases is that based on current data, the backfill geometry will be different than what was assumed when the first analytical calculations were initiated. The main difference between the geometry assumed in the modelling and the updated backfill design is that no layer of pellets beneath the blocks were assumed in the modelling. In addition, the thickness of the pellet filled section on the roof was assumed to be only 0.3 m, and the pellet thickness may be larger in reality. Locally thicker pellet fills may exist due to high outbreak percentage of the excavated tunnel (see Section 7). Because results from the analytical calculations were compared to those obtained through numerical modelling, the geometry of the model was kept the same as in the original geometry, in spite of changes in the actual backfill and tunnel designs.

Another issue in developing an estimate of backfill behaviour is the block filling degree, in the original base case and geometry this was 78% which has since proven to be higher than is expected to be achievable with the backfill technique chosen by SKB (see Section 7). Therefore, the modelling work should be extended to include the updated backfill designs, ensuring that the deformations remain under the specified limit. In addition, the method of how the upper section of the deposition hole will be filled is something that needs also to be taken into account in the further modelling cases. Yet another issue that should be studied are the influence of different block stacking techniques on the deformation of the backfill.

The modelling approaches used (continuum case, block simulations) include limitations and assumptions that may affect the results. However, comparing the results obtained using different calculation cases/modelling it can be concluded that the results are in relatively good accordance with each other.

6.3.4 Other types of interaction

The other types of backfill-buffer interactions that need to be considered in the design are the:

- effect of backfill material on the saturation process of buffer bentonite, and
- chemical interaction, i.e. the amount of oxidizing substances and stray materials in the backfill material.

Baclo Phase III did not study these issues, excluding chemical analyses done as part of characterizing the candidate materials (see Section 5).

The type of backfill material installed may affect the saturation process in the backfill itself but also the saturation of buffer. The time needed for the backfill to reach full saturation depends on various factors such as the material properties of the backfill material (hydraulic conductivity and suction) but also the free void volume in the backfill after installation, the water inflow to the tunnel and frequency of water conducting fractures as well as water chemistry /Börgesson et al. 2006, Miller and Marcos 2007/. For more information see /Börgesson et al. 2006/.

What is currently known regarding the basic chemical composition of the candidate materials is presented in Section 5.2.2. The clays considered as block or pellet materials have relatively low content of organic carbon and sulphur ≤ 0.5%. However, with the enormous total mass of clay used for backfill, the total amount of these impurities is considerable /Hagros 2007/. The iron content in Asha 230b is 14%, which may have some effect on the mineralogical transformations of smectites. The composition of the crushed rock component in the 30/70 mixture should also be considered, especially if very fine fractions are used and the material is stored for long-time after its crushing allowing it to expose to contamination, e.g. vegetation.

6.3.5 Summary and discussion (interaction between backfill and buffer)

The mechanical interaction between buffer and backfill was studied using both analytical calculations and numerical modelling. In the calculation cases it was assumed that the backfill would be either in a fully saturated and homogenized state (wet case) or in an unsaturated state (dry case), while the buffer would be in fully saturated state.

Based on the analytical calculations and numerical modelling, the deformation of the backfill is affected by a number of factors, e.g. the swelling pressure generated in the backfill, the friction angle between the rock and the buffer, deformation parameters (E-modulus) of the materials and tunnel/backfill geometry. The type of the modelling code used to assess these mechanical processes has been found to result in only small differences on the results obtained. For the wet case the displacements varied between 44–154 mm, 102 mm being the assumed basic modelling case (assuming Swedish deposition tunnel dimensions). In practice, this means that the dry density of the buffer remains above 1,950 kg/m^3 at the level of the canister. The conclusion was the same from both analytical calculations and numerical modelling. However, excluding the cases where the backfill generated a counteracting pressure of > 1 MPa (displacements smaller than 47 mm), the buffer density decreased locally below 1,950 kg/m^3. This decrease seemed to take place mainly at a limited volume of the buffer located near the buffer-backfill interface.

The nature of the mechanical interaction between the backfill and the buffer needs to be re-assessed using the updated backfill and tunnel geometries. The limitations of the calculation methods and modelling approaches are discussed in more detail in Sections 6.3.1 and 6.3.2. Other buffer-backfill interaction issues are linked to chemical interaction between backfill and buffer and the effect of saturation of the backfill on the saturation of the buffer. These issues also need to be studied further, at least for the reference materials chosen as the block/pellet materials.

6.4 Homogenisation and self-sealing

6.4.1 Introduction

It is essential to know how the whole backfill, consisting of backfill blocks and pellets behave during and after saturation. For this purpose, tests were initiated to study whether the backfill system is able to homogenize as a consequence of water saturation with respect to a) dry density and b) hydraulic conductivity. One aim of these studies was to determine a target block filling degree (and density) where the system seems to be able to homogenize in density with sufficient safety margin. Another question studied was that whether the materials are able to self-seal after a piping case/scenario.

6.4.2 Average densities after saturation

In theory, the performance of the backfill can be estimated through use of the average dry densities achieved by the backfill after reaching full saturation. This includes an assumption that the material will have sufficient volumetric swelling capacity to ensure that the system will homogenize perfectly with respect to dry density and there will be no macro-voids (e.g. gaps between blocks, open space between individual pellets or between the backfill and the rock) left in the system. Whether this is the case in reality is discussed in Section 6.4.3.

Theoretical calculations that assume an average dry density can be used to evaluate at which minimum average dry density and minimum block filling degree the system has a *theoretical* chance to fulfil the dry density criteria set for the material (see Section 5.2.5). The dry density criterion was determined for the materials by establishing the minimum dry density where the material meets the requirements set for hydraulic conductivity, swelling pressure and compression /Johannesson and Nilsson 2006/. However, it is important to note that the dry density criteria was determined assuming saturated backfill materials and that the density criterion concerning compressibility is not valid in unsaturated state (as shown in Sections 6.3.1 and 6.3.2), and because those calculations were based on compression properties determined for saturated block materials with oedometer tests /Johannesson and Nilsson 2006/. The result may also be misleading for cases where the proportion of pellets is very high, since the assumption in the analytical calculations by /Johannesson and Nilsson 2006/ was that proportion of pellets is 20% by volume. This also assumed that the thickness of the pellet layer at the roof was only 300 mm, there were no pellets on the floor and the compressibility of pellets was taken into account only as reduced density of the blocks.

The average dry densities achieved with different block filling degrees for the materials studied are presented in Figure 6-50. The dry densities in the chosen block filling degrees were calculated assuming that the backfill blocks have a dry density that is 97% of the maximum dry density achieved with compaction pressure of 25 MPa /see Johannesson and Nilsson 2006/, the volume of free space in the tunnel is 2% and the volume occupied by the bentonite pellets has a dry density of 1,100 kg/m^3.

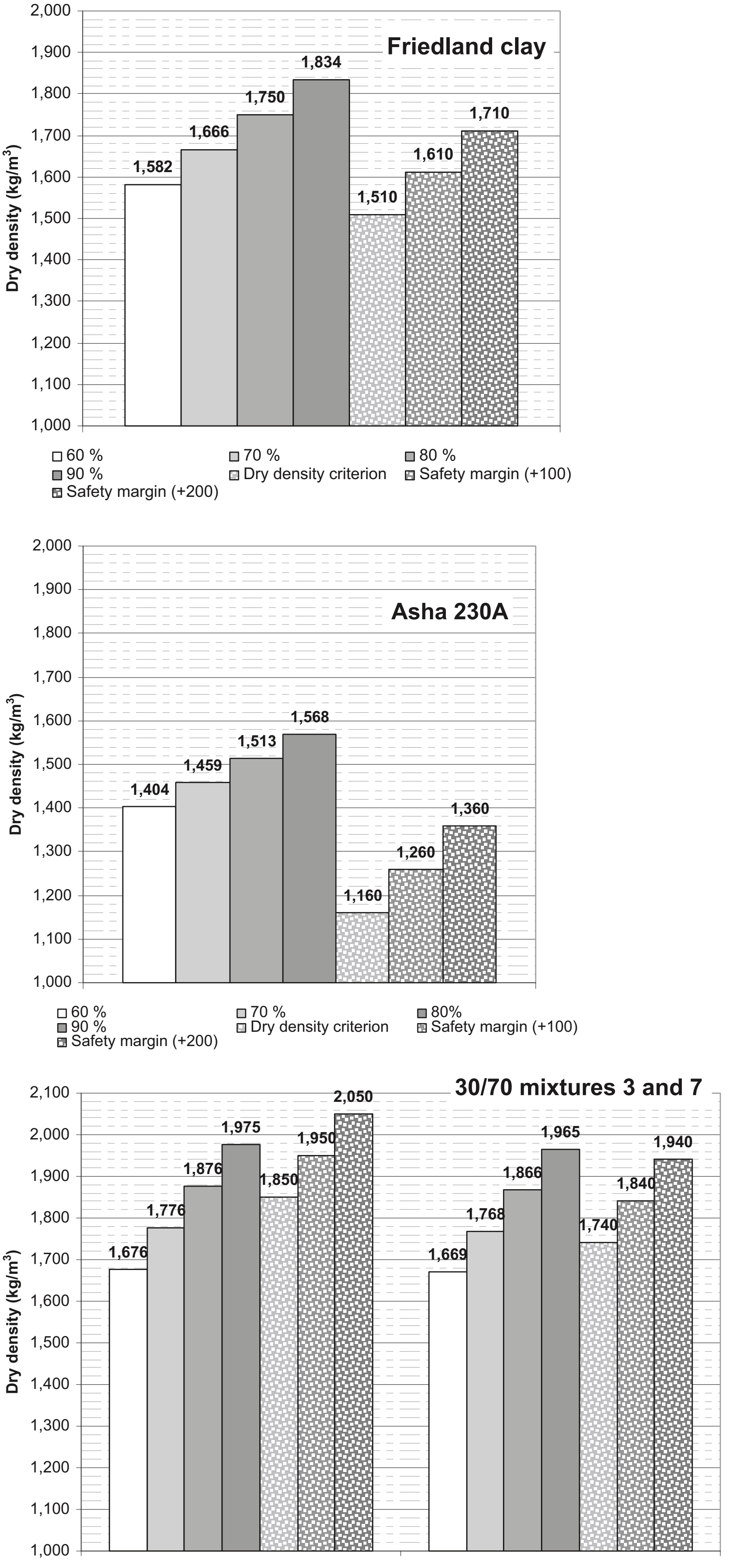


Figure 6-50. *Dry density criterion versus the average dry densities for different block filling degrees (60, 70, 80 and 90%). As an example, it is also shown what the dry density should be to reach safety margins of +100 or +200 kg/m^3.*

Assuming an ideally saturated and homogenized backfill (same density along the whole tunnel cross-section), the minimum required block filling degrees to reach the dry density criteria is < 20% for Asha bentonite backfill, ~ 50% for Friedland clay backfill and 67–77% for the 30/70 bentonite/crushed rock backfill. However, taking into account the unsaturated situation and uncertainties linked to compressibility of pellets, these block filling degrees are not adequate, since low percent of block requires additional conditions to fulfil the requirements. Therefore, the average dry density comparison should be used only as a tool for comparing different material alternatives. In addition, it has been discussed that a *safety margin* (defined as extra density in /Gunnarsson et al. 2006/), is needed to be sure that the system is able to perform despite small disturbances in the manufacturing or installation processes, erosion or variations in the mineralogical composition of the materials. In Figure 6-50 it is shown also as an example of what the average dry density should be in order to reach safety margin of +100 kg or +200 kg per m^3.

How big the safety margin (in terms of required dry density) should be is as-yet undefined. One possible approach suggested has been that the safety margin should be 10% by mass of that is required to fill a volume of 1 m^3 with backfill as presented in Figure 6-51. Based on this approach, only the Asha 230 bentonite clay backfill is able to fulfil the average dry density requirement also at a block filling degree of 60%. For Friedland-clay backfill the block filling degree should be > 70% and for the 30/70 mixture backfill > 90%. However, in practice a safety margin of 10% may be over conservative in extra mass per 1 m^3 for some of the studied materials.

Another approach is to present the safety margins as extra mass (kg) per volume of 1 m^3 compared to the required minimum mass (kg) per 1 m^3 as presented in Table 6-10. From this table it can be seen that as an example for 70% block filling degree the amount of extra mass for Friedland clay is almost 160 kg and in 60% almost 72 kg per 1 m^3. Based on the Äspö field tests, it is not probable that such high amount of material would be eroded during the time that the deposition tunnel is open, thus the safety margin of 10% may be somewhat over-conservative when looking only at the resulting average densities and erosion.

Table 6-10. Safety margins as extra mass (kg) per 1 m^3 for different materials and in different block filling degrees (volume-%).

Block material	60%	70%	80%	90%
Asha 230 bentonite	244 kg	299 kg	353 kg	408 kg
Friedland clay	72 kg	156 kg	240 kg	324 kg
Mix 3 (30/70)	–174 kg	–74 kg	26 kg	125 kg
Mix 7 (30/70)	–71 kg	28 kg	126 kg	225 kg

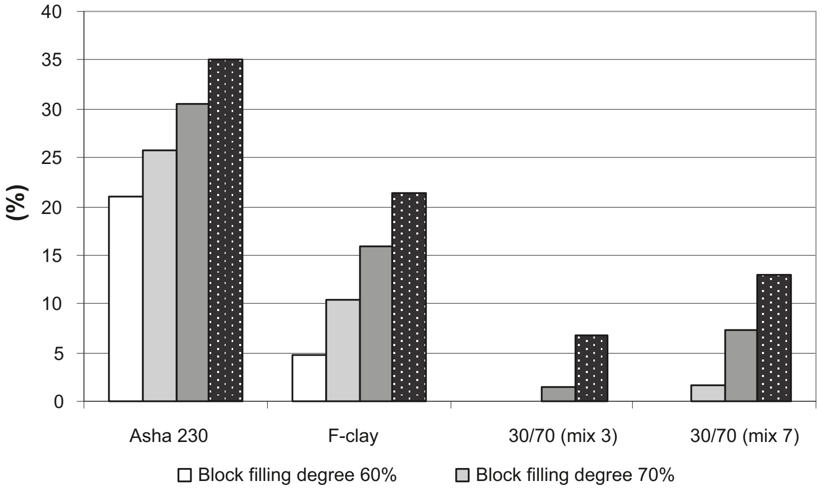


Figure 6-51. *Safety margins in percent (ratio of extra mass of backfill per 1 m^3 and the mass that is needed to reach the criteria dry density determined for the material).*

Looking at the actual material properties (see Section 5.2), compressibility is the defining parameter for Asha 230 bentonite and Friedland clay. Therefore, the target block filling degree for these clay backfill alternatives should be chosen based on the following issues.

- Pellet proportion/geometry the compressibility of the backfill above the deposition hole is at acceptable level. As discussed in Section 6.3, more studies are needed on this subject.
- Homogenization of the block + pellet backfill (see Section 6.4.3).
- Self-sealing properties of the backfill (see Section 6.4.4).

For the 30/70 mixtures, the performance seems to depend strongly on the relation of dry density and hydraulic conductivity. Based on data presented in Figures 5-3 and 5-4 (see Section 5.2.3), the hydraulic conductivity varies quite much depending on the mixture type, and it can be determined that to remain well within the margin of safety, the dry density for any mixture should be at least 1,950 kg/m^3. This means that the safety margin should be at least +100 kg/m^3 for mixture of type 7 and +160 kg/m^3 for mixture of type 3 used as an example in this report. In practice it means that for 30/70 mixture type 3, the block filling degree should exceed 90% and for mixture type 7, a block filling degree of ~ 80% should be sufficient. However, the homogenization (see Section 6.4.3) and self-sealing properties of the materials (Section 6.4.4) also need to be taken into account, as well as the geometry of the pellet fill. Discussion related to block filling degree(s) needed is found in Section 6.5.

6.4.3 Homogenization with respect to dry density and hydraulic conductivity

The homogenization of the backfill consisting of pre-compacted backfill blocks and bentonite pellets as a consequence of water saturation have been investigated in laboratory by /Johannesson et al. 2008/ and by /Kuula-Väisänen 2008/. The main parameters of interest in these investigations were the effect of proportion of blocks and pellets on the resulting dry density distribution.

Homogenisation with respect to dry density

In the first approach to studying the evolution of the homogenization process, described in /Johannesson et al. 2008/, the tests were done in a confined test cell with a diameter of 50 mm (see Figure 6-52).

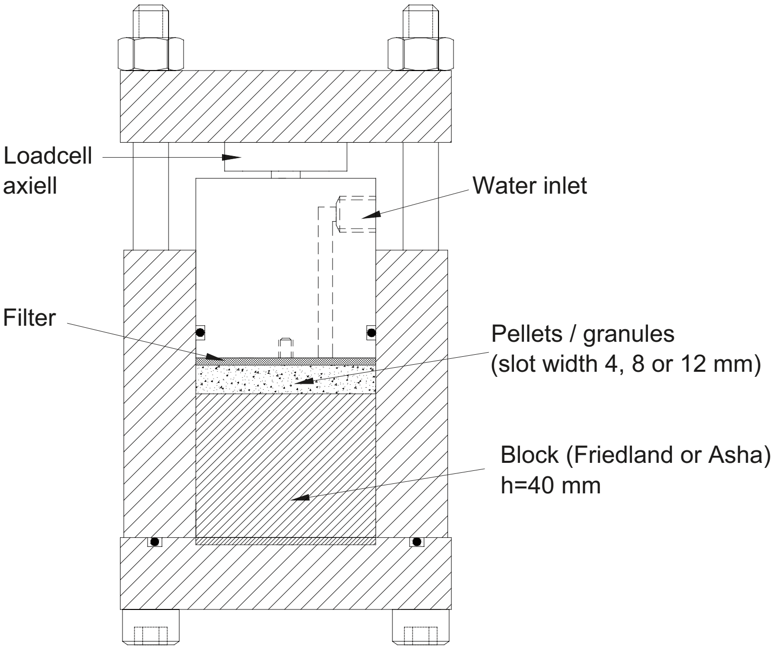


Figure 6-52. *A schematic cross section of the test equipment /Johannesson et al. 2008/.*

The block materials tested were Friedland clay and Asha 230B bentonite. The pellets/granules tested in the study were MX-80, Cebogel pellets, Friedland clay and Minelco granules. This provided a wide range of potentially usable materials and allowed for assessment of the effects of material on system evolution. The height of the sample was determined so that the height of the block portion of the sample was always 40 mm and the height of the pellet filled part of the sample was 4, 8 or 12 mm corresponding to block filling degrees of 70, 80 and 90%. However, the objective of the study was not to examine the effect of the block filling degree, but to study the general homogenization process and to produce experimental data for modelling of the process.

Saturation was performed from the pellet side of the specimen, simulating the expected direction of water influx. The salinity of the water was either 1 or 3.5% ($NaCl:CaCl_2$, 50:50 in weight-%), simulating the range of salinity conditions that might be encountered in a repository in Sweden. During the test, the only measured parameter was the axial load from swelling of the specimen. After the test, the specimen was sliced in layers with thickness of 5 mm and the dry density; water content and degree of saturation were determined from these samples. Only the main findings from these tests are discussed below. The results are described in detail in /Johannesson et al. 2008/.

- The specimens were saturated up to 95–100% during test periods up to four months long. The water contents and degree of saturation were highest at the pellet side of the specimen.
- In the basic case studied (corresponding to 80% block filling degree, Friedland clay blocks and pellets), the dry density of pellets increased from 1,100 kg/m^3 to 1,400 to 1,600 kg/m^3 and the dry density of blocks decreased from 2,000 kg/m^3 to 1,600 to 1,800 kg/m^3, the densities being lowest at the near the block-pellet interface (see Figure 6-53a).
- If the particle density, grain-size distribution and mineralogical composition of block and pellet materials is very different, it is impossible for them reach uniform density over the total volume of the specimen after saturation (see Figure 6-53b). However, this should not be automatically considered as a negative feature, since if the material parameters in the resulting dry densities are sufficient (e.g. hydraulic, mechanical and mass transport), then non-uniform dry density distribution should not be an issue.
- The pure bentonite pellets and granules tested in systems having an 80% degree of block filling had an initial dry density between 900 kg/m^3 and 1,000 kg/m^3 respectively After the tests, the dry densities were between 1,200 kg/m^3 and 1,300 kg/m^3 for both systems (Figure 6-53b), meaning that the material properties in this outer margin after saturation are likely to be sufficient with respect to hydraulic properties, compressibility and swelling pressure.
- The results of tests at varied block filling degrees (70, 80 and 90%) imply that there is a clear difference between the 80% and 90% but no significant difference exists for block filling degrees of 70% and 80% (see Figure 6-53c). The latter result may be somewhat misleading due to difficulties in recovering samples in tests done at this scale and the fact that the test was not originally designed to study the effect of block filling degree but to examine the homogenization process in general.
- Salinity of the water (1% or 3.5%) did not have significant effect on the homogenization.
- The Asha 230 blocks and bentonite pellets homogenized very well. The resulting dry density was approximately 1,400 kg/m^3 through out the specimen. This behaviour is because the smectite contents and particle densities were almost the same for the materials making up the bentonite pellets and the Asha 230 bentonite blocks /Johannesson 2008/.

Uncertainties associated with the results described above are linked to the relatively small number of test replications and the relatively small test scale. As an example, it may be difficult to avoid small variations in dimensions and densities when preparing the specimen or some material could have been lost during the sampling after the tests easily affecting the density measurements in small assemblies.

Based on the results obtained for this test series it seems that sufficient homogenization takes place at 70% block filling degree for all of the studied material combinations. However, further tests and modelling are needed to verify this conclusion. Since the homogenization of 30/70 mixture was not studied, it is impossible to present any conclusions for that material. In addition, it is not possible to conclude anything assuming smaller block filling degrees than 70%.

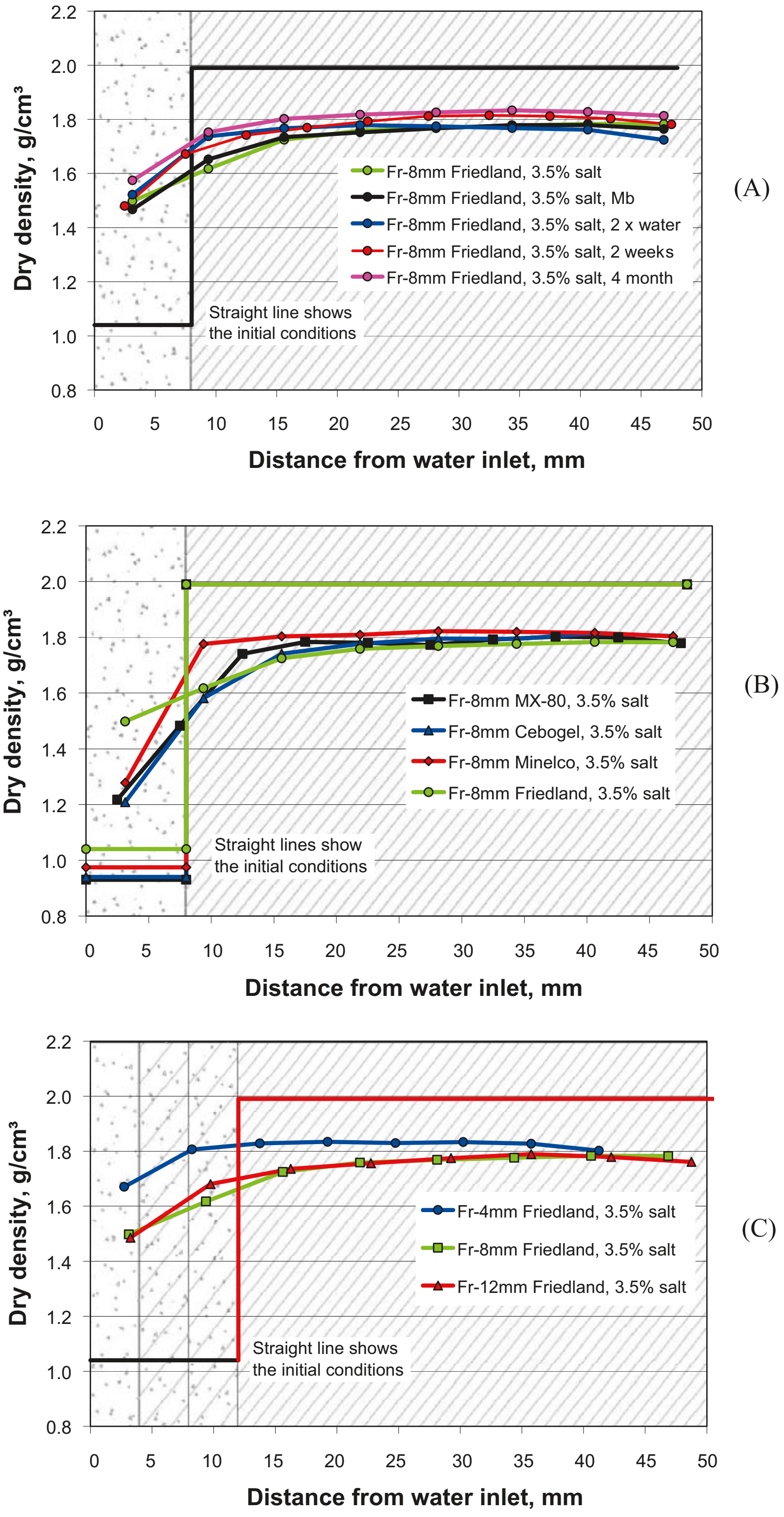


***Figure 6-53.** Effect of test duration (A), pellet type (B), and proportion of blocks and pellets (C) on the resulting dry density distribution of a backfill consisting of Friedland clay block and different pellet materials (Friedland clay granules in A and C).*

Homogenisation with respect to hydraulic conductivity

A set of homogenization tests done has also been performed by /Kuula-Väisänen et al. 2008/. These tests assessed homogenization of Friedland-clay blocks and Friedland clay granules (or bentonite pellets) with respect to hydraulic conductivity. The objective of the test was to observe how the permeability of the backfill evolves during the saturation process.

A schematic cross section of the test setup is presented in Figure 6-54. The idea was to place blocks in the middle and pellets in the outer region to simulate the situation in the tunnel. The principle of the test setup is the same as in so called CUR-cells used for studying the permeability of land-fill liner materials in somewhat more realistic conditions compared to confined small-scale laboratory test cells /see Hämäläinen et al. 2005/. The block filling degrees examined were 70, 80 and 90%, determined as the (initial) volume of blocks compared to the (initial) total volume of the specimen. Originally it was assumed that the blocks would expand mostly towards the pellet filled zone since a 50 mm thick confining layer of sand was placed above the specimen. Later, this layer was proven to be insufficient to limit the upward swelling of the specimen, significantly affecting the resulting dry densities. However, due to this test geometry additional information was made available regarding the swelling capacity (in volume) of the tested materials.

The homogenization of the specimen during the test was recorded by measuring the water outflow of the specimen at different times during the saturation process. The water outflow was measured from two locations, simulating the situation in the middle of the block fill and at the pellet filled zone. These areas were separated with a ring mounted on the bottom of the test cell. At the top of the specimen, the water level was kept constant during the whole testing period (0.43 m). The hydraulic conductivity was calculated based on the cross section areas occupied by the inner cylinder and outer the ring. In between the measurements (performed only at specified intervals) outflow was prevented so that the specimen had a chance to saturate without any disturbance.

The blocks used in these tests were produced in three different places: Bjuv brick factory in Sweden, Kiikala brick factory located in Finland and at Alpha Ceramics in Aachen, Germany. The initial dry densities, water content and dimensions of the blocks are presented in Table 6-11.

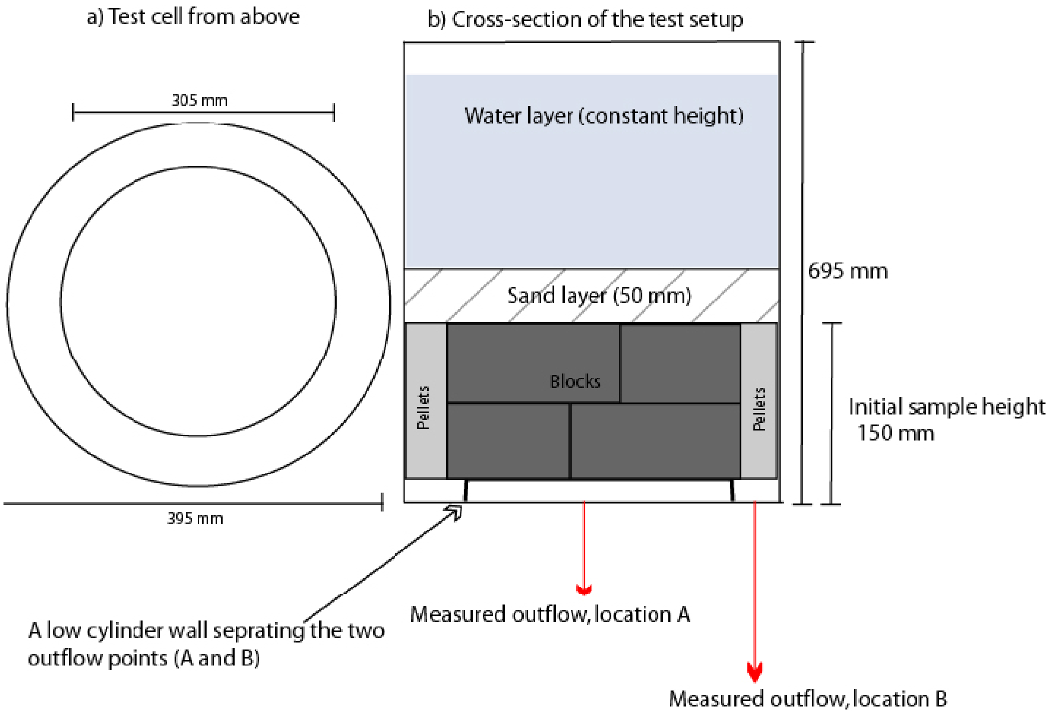


Figure 6-54. Schematic figure showing the principle of the test setup /Kuula-Väisänen 2008/. The hydraulic conductivity was measured from two different locations, one in the middle and one from the margin zone mainly filled with pellets. The test method is based on hydraulic conductivity measurements in a CUR-cell /see Hämäläinen et al. 2005/.

Table 6-11. Initial dry densities of pre-compacted Friedland clay blocks used in homogenization tests by /Kuula-Väisänen 2008/.

Block manufactured at:	Water content (%)	Compaction pressure (MPa)	Dry density (kg/m³)	Dimensions (mm)
Bjuv (Sweden)	6.3	7	1,820	300×150×75
Kiikala (Finland)	6		2,021	Small pieces of blocks were used in the test
Alpha Ceramics (Germany)	<10	25	2,080	300×300×150, only one intact block was used in the tests

The pellets materials used in the majority of the tests were Friedland-clay granules and in the remainder Cebogel pellets. The test materials are described in detail in Section 5 (Backfill materials).

A total of 7 tests were performed with Bjuv blocks combined with Friedland-clay pellets to achieve block filling degrees of 70, 80 and 90%. These specimens were allowed to saturate for 1, 2, 4 and 12 months (the 12-month test is still ongoing during writing of this section) to study the effect of saturation time. Four additional tests were performed with Kiikala blocks (2 tests at 80% block filling degree combined with Friedland clay pellets) and Alpha Ceramic blocks (2 tests 80% block filling) combined with Cebogel pellets.

The results show that the hydraulic conductivity of the Bjuv blocks combined with Friedland clay pellet remained relatively high (1×10^{-5} and 2×10^{-7} m/s) after 4 months of testing. Based on the density measurements after the test, this high hydraulic conductivity is mainly due to the significant increase of the volume of the specimen during the test (because the sand layer was not thick or heavy enough to keep the specimen in its place). The dry density of the Bjuv blocks decreased from 1,700–1,735 kg/m³ to 1,230–1,260 kg/m³ while the pellet densities only increased from 900–980 kg/m³ to 1,050–1,080 kg/m³. However, the differences between the measured hydraulic conductivities from the inner cylinder and the outer ring did not differ significantly indicating relatively good homogenization with respect to hydraulic conductivity.

The results with higher density blocks (Kiikala and Alpha Ceramics blocks) indicate the dependence of the results from the initial dry density of the blocks. The best results gained with high density blocks produced in Germany combined with Cebogel pellets ended up with hydraulic conductivity between 1×10^{-9} and 7×10^{-8} m/s, which may be explained by higher initial block density but also by better pellet material, since the decrease in block density was also significant in this case (2,070 to 1,235 kg/m³).

The volume expansion calculated for the specimen were > 50% for the Bjuv blocks and 70–80% for Alpha Ceramic and Kiikala blocks showing the influence of initial block dry density on the swelling capacity of the material.

The uncertainties linked to this testing method comes mainly from measuring the change in the specimen height during the test, difficulties in recording the density changes during the tests and in general the uncertainties in determining of density from loose samples. In addition, some extra boundary flow may take place in the outer ring (margin flow) and it cannot be ruled out if the hydraulic conductivity is measured at the outer ring (not the procedure in standard CUR-cell measurements). The advantages of this size of test setup is that the different interfaces (block-block, pellet-block) can be taken better into account than in very small laboratory scale tests. Therefore, similar tests are recommended for conduct in future if a solution to limit the upward swelling of the specimen can be found.

6.4.4 Self-sealing of piping channels

Self-sealing capacity is a material property that is required from the backfill materials. If an open, water-conducting pathway is generated in the backfill (piping channel), the material is expected to be able to seal the channel by swelling after the tunnel has been sealed and the backfill has reached full saturation. The formation of piping channels may take place during the installation period when there can be high water gradients over the tunnel that is being backfilled /SKB 2006, Miller and Marcos 2007/. The gradients in the backfill expected to decrease after the deposition tunnel is sealed with a water resistant plug and eventually reach zero when the whole repository has been closed and sealed /see e.g. Pastina and Hellä 2006/.

The self-healing of piping channels was studied with laboratory-scale tests by /Sandén et al. 2008/. In these studies the hydraulic conductivity of the specimen was measured in constant volume oedometers (Figure 6-55), before and after drilling a through-going hole of 5 mm or 10 mm diameter through the 50 mm or 101 mm diameter specimens respectively. Following drilling of the hole the specimen was allowed access to water for 3 weeks without a hydraulic gradient being applied across the specimen, enabling further water uptake and saturation. This test method was used to attempt to quantitatively assess how a pre-existing piping feature will respond to subsequent water movement through it.

The selected dry densities (2 measurements made per material) for the studied block materials were determined based on the fact that the dry density of the blocks decreases gradually due to water saturation and homogenization, as shown in Section 6.4.3. The pellet materials tested were not compacted at all. The results from the tests are presented in Table 6-12 and in Figure 6-56.

The main conclusions from the self-sealing tests are:

- The self-sealing capacity of MX-80 pellets is insufficient at the density examined (~ 900 kg/m^3). However, after homogenization of the backfill the dry density of the pellet is expected to have increased from 900 kg/m^3 to > 1,200 kg/m^3, which is adequate for self-sealing (see Section 6.4.3).
- The self-sealing properties of Asha 230B seems to be sufficient at the dry density corresponding to the average backfill dry density of 1,440 kg/m^3 and a block filling degree of ~ 65%.
- The self-sealing of Friedland clay seems to be sufficient at a dry density corresponding to the average dry density achieved for a block filling degree of 70% (1,780 kg/m^3). However if the dry density was decreased below this value, the self-sealing properties were barely sufficient to achieve the properties defined as being required.
- The 30/70 mixture did not seem to have any self-sealing capacity. This may be due to erosion of clay particles from the void space of ballast grains near the drilled hole when a gradient was applied across the specimen. Another possible explanation is that the plasticity of the material is not sufficient due to large proportion of ballast grains in the mixture giving the material high internal friction.

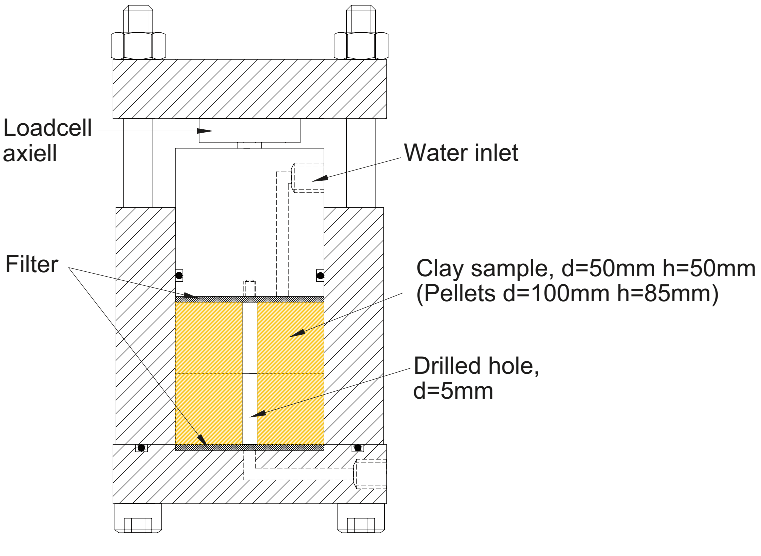


Figure 6-55. *Schematic cross section of the test setup used in /Sandén et al. 2008/.*

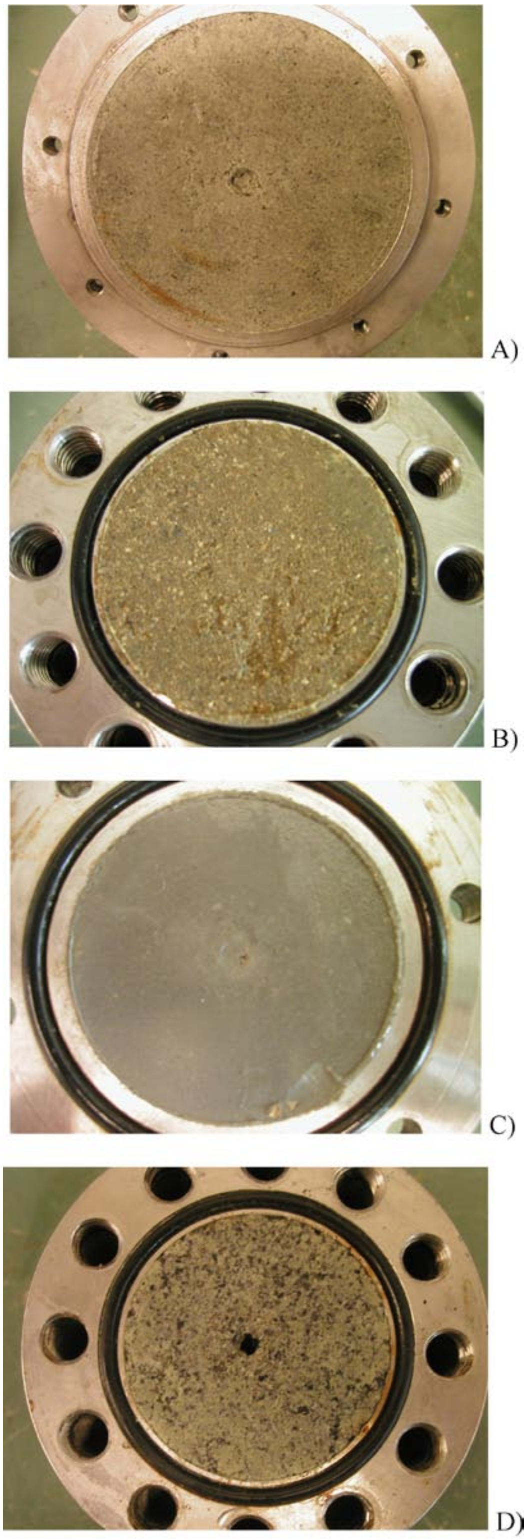


Figure 6-56. *The figure illustrates self-sealing samples photographed after the test. A) MX-80 pellets (10 mm hole), B) Asha 230B bentonite, C) Friedland clay and D) bentonite-ballast mixture 30:70.*

Table 6-12. Results from the self-sealing tests performed by /Sandén et al. 2008/.

Material	Calc.dry density / sat. density kg/m^3	Measured sat.density kg/m^3	Water	Applied water pr. kPa	H.K. before drilling m/s	Healing time	H.K. after healing m/s	Remark
MX-80 pellets	980 / 1,627	1,595	1% salt	20	2.1×10^{-11}	3 weeks	7.7×10^{-11}	5 mm hole
MX-80 pellets	980 / 1,627	1,595	3.5% salt	20	9.6×10^{-11}	3 weeks	1.3×10^{-8}	10 mm hole
MX-80 pellets	980 / 1,627	1,562	3.5% salt	20	1.2×10^{-10}	3 weeks	5.4×10^{-9}	5 mm hole
Asha 230	1,440 / 1,922	1,927	3.5% salt	500	2.8×10^{-13}	3 weeks	3.3×10^{-13}	5 mm hole
Asha 230	1,540 / 1,986	1,945	1% salt	500	9.7×10^{-14}	3 weeks	1.5×10^{-13}	5 mm hole
Asha 230	1,540 / 1,986	1,987	3.5% salt	500	1.3×10^{-13}	3 weeks	1.4×10^{-13}	5 mm hole
Friedland	1,680 / 2,076	2,064	3.5% salt	500	3.2×10^{-12}	3 weeks	1.4×10^{-10}	5 mm hole
Friedland	1,780 / 2,140	2,120	Tapwater	500	1.0×10^{-12}	3 weeks	1.2×10^{-12}	5 mm hole
Friedland	1,780 / 2,140	2,114	1% salt	500	1.2×10^{-12}	3 weeks	1.6×10^{-12}	5 mm hole
Friedland	1,780 / 2,140	2,130	3.5% salt	500	1.2×10^{-12}	3 weeks	2.2×10^{-12}	5 mm hole
Mix.30/70	1,800 / 2,153	2,100	3.5% salt	20	1.1×10^{-10}	3 weeks	2.6×10^{-7}	5 mm hole
Mix.30/70	1,900 / 2,217	2,151	1% salt	20	8.7×10^{-12}	3 weeks	4.2×10^{-9}	5 mm hole
Mix.30/70	1,900 / 2,217	2,164	3.5% salt	20	9.5×10^{-11}	3 weeks	6.4×10^{-8}	5 mm hole

The uncertainties linked to this testing method are mainly due to the relatively low number of tests completed (there were no parallel specimens having exactly same materials, material parameters and test conditions). In addition, the behaviour of the material should be checked for a situation when a hole is drilled through an unsaturated specimen. This would allow the potential for sealing of a piping channel that has formed in a partially saturated backfill (the most likely situation to exist in the backfill), to be evaluated.

6.4.5 Summary and discussion (saturation, homogenization and self-sealing)

The block and pellet combinations tested (Asha 230 and Friedland clay block combined with different type of pellets and granules) showed reasonable homogenization with respect to dry density when the proportion of pellets from the total volume of the specimens was 10, 20 or 30%. If the block and pellet materials differ very much in mineralogy, the backfill material will not be able to homogenize with respect to dry density (in cases where the block materials has significantly lower content of clay minerals than the pellet material). However, the results show that the material properties (hydraulic conductivity and swelling pressure) remain at acceptable levels at the density states ultimately achieved for the individual components. Continuing studies are needed in order to better characterize the homogenization process where block filling degrees lower than 70% are present. This will provide a better understanding with respect to the robustness of the design and to evaluate the effect of local variations in the tunnel dimensions.

When testing the homogenization of Friedland clay blocks and Friedland clay granules at a slightly larger laboratory scale than the tests described in Section 6.4.4, the results were less consistent. The main reason for this is that the specimens expanded in the axial direction more than was expected and the resulting dry densities decreased significantly, which obviously influenced the permeability of the block-pellet specimen (see Section 6.4.3 and results by /Kuula-Väisänen 2008/). The swelling of the specimens in the axial direction showed that the high-density Friedland clay blocks were able to swell more than 70–80% in volume, verifying that the material has sufficient swelling capacity to accommodate initial heterogeneity of the block backfill.

Based on tests by /Sandén et al. 2008/, self-sealing ability of the block materials consisting of clay that have thus far been examined seems to be sufficient. However, if Friedland clay blocks are used, the recommended block filling degree is > 70%, since at lower densities the self-sealing capacity may be inadequate. In that geometry the pellets don't have sufficient self-sealing capacity at the dry density present after their emplacement. Therefore, the proportion of the pellets and blocks needs to be optimized so that compression of the pellets is sufficient to ensure adequate system performance. As the homogenization with respect to dry density has only been tested at 70, 80 and 90%, the conclusions are not necessarily valid for systems with block proportion less than 70%. Further tests where block proportions less than 70% are used are recommended in order to study the robustness of the system, the effect of local variations in the tunnel dimensions and block proportions.

The uncertainties associated with self-sealing were discussed in detail at the end of Section 6.4.4. If mixtures of bentonite and ballast are to be considered, it is recommended that further studies with higher bentonite content than 30% be made in order to find out what bentonite content is required to provide the mixture with sufficient plasticity and self-sealing capacity.

6.5 Summary of findings from laboratory tests, field trials and numerical simulations

The studies described in Section 6 have provided an extensive body of information regarding the behaviour of blocks, pellets and assemblies of these materials at laboratory through to ½-Scale simulations. Studies conducted, focussed on the hydraulic and mechanical characteristics of the materials studied. From these physical studies, conceptual and numerical simulations of system evolution and performance were developed. In addition to assessing materials performance and system evolution this work has identified processes that require further investigations to develop methods to prevent adverse effects on system behaviour during the backfill installation through to sealing of the tunnel with a low permeability plug.

The results that can be drawn from this work are summarized as follows:

- effect of water inflow during the installation phase,
- self-sealing capacity,
- homogenization,
- dry density requirement, safety margins and block filling degrees, and
- design and materials-selection considerations arising from results of these studies.

Each of the above-listed topics and conclusions are briefly discussed below.

6.5.1 Effect of water inflow during the installation phase

Water flowing into a backfilled tunnel has the potential to generate piping features and these may prove to be erosive in nature. In the studies done as part of the Baclo program it was found that in most cases, the measured erosion rate rapidly decreased within the first 1 to 4 days, with equilibrium erosion rate apparently depending on rate of water flow along the piping feature. The sediment load per litre of outflow was between 1 and 25 g/l of water exiting the backfilled volume after the first day of water outflow at 0.1 and 0.6 l/min of applied water inflow respectively. These rates seemed to be fairly consistent, regardless of the size of the simulation (although slightly lower erosion rates, 1–10 g/l were observed in laboratory scale studies).

Erosion of backfill is clearly associated with individual piping features and does not extend to the entire backfilled volume, making it potentially easier to deal with in an operational setting. Erosion rate tends to decrease with time, especially after stable water transport pathways form at the interface between pellets and other materials. This is also a desirable situation as it indicates that erosion will remain consistent along that pathway and not accelerate with time, at least in the limited time that a tunnel will remain open.

The results of the 1/12-, ½-Scale and laboratory tests to examine water movement and erosion in backfill highlight the importance of determining a means of controlling the location of flowpaths developed by incoming water. If the outflow channel is located between the pellets and the rock and the rate of flow is less than that required to initiate turbulent flow along the piping feature, it is probable that the erosion from the backfill will be limited. Specifically, it would appear that single-point inflow features in the order of 0.5 l/min (or less) that establish pathways along the rock-pellet interface do not tend to be highly physically disruptive to the backfill. The water exiting into the as-yet unfilled sections of tunnel will still need to be dealt with so as to prevent operational difficulties in installing flooring and a subsequent sections of backfill.

At high inflow rates at a single point or along a single flow path, turbulent flow conditions may exist, inducing a much higher rate of erosion within the backfill pellets or blocks. The ½- and 1/12-Scale tests described previously show that at inflow rates exceeding 0.5 to 1 l/min have a greater potential to develop extremely highly erosive flowpaths. At 2.5 l/min the ½-Scale test showed extensive erosive activity.

Of note is the fact that for a small diameter inflow location or pipe turbulent flow processes may develop (high Reynolds number). Turbulent flow may take place if the diameter of the inflow/flow channel is small compared to the inflow rate. This was discussed with respect to flow through soils by /Cedergren 1967 and Lambe and Whitman 1979/. Within the backfill the nature of the flow path is unlikely to be pipe-like but along the smoother clay-rock surface the contact will be much closer to a smooth-walled pipe. As a result ongoing flow along such an interface may have conditions that will allow Reynolds concept for turbulent flow to be relevant. In the ½-Scale test where turbulent flow existed as well as other tests where single outflow pathways were developed, the diameter of the inflow pipe was estimated to be 0.01 m (test at 2.5 l/min inflow), meaning that the inflow rates of > 1 l/min may already lead to turbulent inflow (Reynolds number > 2000). While the backfilled volume is not a true pipe geometry, such turbulent flow conditions may exist for portions of the pathway and if so then the potential for erosive activity through sediment suspension in the turbulent flow may cause greater erosion to occur. This is a process that will need further consideration and evaluation as limitations to water inflow begin to be developed. Additionally, if the water outflow channel is through Friedland-type blocks, the erosion is potentially more substantial and disruptive to the backfill as a whole. These conclusions all need to be confirmed for systems where high-density clay blocks are present rather than those used in most of the Baclo tests and under field conditions that more accurately simulate a repository tunnel.

Preliminary definition of acceptable rate of water flow along a single channel through the backfill, or along the backfill pellet-rock contact has occurred as the result of Baclo Phase III investigations. These studies provide guidance with regards to excavation design and preparation of tunnels so as to limit water inflow to acceptable levels prior to backfill installation. Excessive water movement through the backfill and into the as-yet unfilled regions can be problematic with respect to installation of flooring materials, clay blocks and safe operation of installation equipment. There is a need to more clearly define what throughflow rates are unacceptable for backfilling operations and means to control/reduce inflow to the tunnels need to be available.

6.5.2 Self-sealing capacity

An extensive set of tests was completed as part of a preliminary assessment of the ability of block, pellet and composite systems. Although done at a small, laboratory-scale these tests have provided some initial guidance on the ability of these materials to self-seal should a through-going penetration (pipe) form. The Asha230B bentonite material performed well and showed complete, or nearly complete self-sealing, which was not surprising taking into account the high amount of swelling minerals (~ 85%) within the material (see Section 5.2.2). Friedland clay materials showed considerable self-sealing behaviour over the short duration of the tests completed and provided that there was a sufficiently high degree of block filling (> 70%). Only the compacted bentonite-crushed rock material showed very limited (essentially no) short-term self-sealing behaviour.

6.5.3 Homogenisation of materials and properties

An important assumption in the backfilling concept for the KBS-3V repository is that like the buffer material, the backfill will eventually evolve into a homogeneous mass with uniform hydraulic, mechanical and mass transport characteristics. These assumptions have been used in the performance assessment models as well as a variety of other studies, but have not been demonstrated as being entirely valid. The studies done as a part of Baclo has begun the process of quantifying the rate and degree of homogenization that will occur as the backfill matures.

The preliminary results, described in Section 6.4 found that the Asha 230 blocks combined with bentonite pellets showed a considerable degree of homogenization. Similar results were found for Friedland clay blocks and granular bentonite systems at densities corresponding to block filling degrees of 70, 80 and 90%. It should be noted that in many cases there was not a perfect density homogenization but rather volumetric strains that resulted in systems that are able to provide hydraulically and mechanically uniform behaviour. In addition, the time limit in these tests may not have been sufficient to allow homogeneous behaviour to develop. This needs to be verified with continuing studies and modelling concerning the homogenization of the backfill, to which these preliminary tests work as valuable starting data.

It should be noted that studies related to the time-dependant volume strain of block and pellet/granule systems initiated by Baclo Phase III and other projects are ongoing in a variety of laboratories. It is expected that the results of these will provide valuable information on the longer-term evolution of the backfill system.

6.5.4 Dry density requirement, safety margins and block filling degrees

In backfilled tunnels there are density requirements for the backfilled system that are associated with both the hydraulic, mass transport and mechanical behaviour of the system. Assuming a dry backfill case where swelling of the backfill does not provide sufficient restraining-pressure to entirely prevent buffer expansion it is important to ensure that the system retains sufficient density (and hence stiffness) to be able to adequately resist the compressive forces generated by the buffer as it hydrates. If the density/stiffness of the backfill is insufficient then there may be an unacceptable decrease in the density of the buffer (saturated density < 1,950 kg/m^3), potentially resulting in inadequate buffer performance. The issue of backfill deformation needs to be addressed in the ongoing backfill design development, especially with respect to the thickness and density of pellet layers placed immediately above the deposition hole.

The studies described in Section 6.3 indicate that for Asha 230B bentonite blocks + pellets, the proportion and geometry of the pellet fill is crucial in order to ensure that the decrease in buffer density as the result of upwards swelling and compression of the backfill remains at an acceptable level. In addition, since the pellets in their as-placed state seem to have limited self-sealing capacity, the block filling degree should be sufficient to ensure compression (density increase) of the pellet fill is sufficient. This combination of clay materials has a great potential to fulfil the requirements set for the backfill. It still requires study and should be further modelled to evaluate the mechanical interaction between buffer and backfill especially with respect to homogenization under a range of backfill geometries. In particular, the effect of pellet layers placed directly above the deposition hole need to be taken into account in further studies.

For Friedland clay backfill systems, the situation concerning the proportion and geometry of the pellet fill is similar to that observed for Asha material. Based on self-sealing tests the block filling degree should be ~ 70%, or even more in order to ensure adequate system density.

For a 30/70 bentonite-aggregate mixture, the block filling degree should be > 80–90% (> 80% assuming mixture type 7, and > 90% assuming mixture type 3), based on theoretical calculations and sensitivity of the hydraulic conductivity of the material to decrease in the density of the material (see Sections 5.2.3 and 6.4.2). However, even in this density state, the material does not seem to have sufficient self-sealing capacity. Therefore, it remains to be determined as to what bentonite content would be required to allow this type of material (mixture of bentonite and ballast) to perform adequately.

With regards to safety margins that allow for some erosion (as extra mass in kilograms per 1 m^3 versus the dry density criteria) some initial calculations have been completed. It would seem that both Asha 230 B bentonite and Friedland clay installed at a block filling degree of 60% would have sufficient margin to allow material loss by erosion. However, this block filling degree is not necessarily sufficient to ensure sufficient stiffness for the backfill as a structure. In addition, due to homogenisation, the block filling degree for Friedland clay backfill is recommended to be > 70%. For a 30/70 bentonite-crushed rock mixture the block filling degree should be 80–90% in order to allow for some material loss by erosion.

6.5.5 Design and material selection considerations arising from results of these studies

The results and observations made in the course of Baclo Phase III studies described above provide valuable guidance with regards to materials selection and the impact of material selection on the backfill design and installation. The factors arising from these findings include the following:

- If mixtures of bentonite and ballast are to be considered for backfill, the smectite content of the mixture of bentonite and ballast should be > 30%.
- The lower the block filling degree, the higher the smectite content needed for the backfill material. E.g. for Friedland clay with estimated amount of swelling minerals of on average 30% (Section 5.2.2), a block filling degree of > 70% is recommended, corresponding to average backfill dry density of > 1,660 kg/m^3.
- Preliminary results suggest that the thickness of the pellet fill between the blocks and the tunnel walls and roof may have importance on the system behaviour during saturation of the backfill. The results from the ½-Scale tests with pellet thickness of 15 cm showed more consistent system behaviour compared to the 1/12-Scale where the pellet thickness was 10 cm. Another factor that could affect the behaviour is the pellet installation technique. The higher amount of water used in the ½-Scale tests appeared to have some influence on subsequent water movement but further confirmation is required before it can be incorporated into backfilling design.
- The upper part of the deposition hole should be filled with a suitable material and adequately compacted so as to minimize the upward swelling of the buffer (e.g. dry and loose pellet fill is not necessarily the best alternative for this purpose).
- The quantity of dry pellets placed right above the deposition hole should be minimized due to risk of upward swelling of the buffer and excessive compression of the backfill before the backfill has reached full saturation. This may be problematic with regards to other operational requirements associated with canister installation.
- Technical means of controlling the discharge water coming to the backfilled front was not part of Baclo Phase III but will need to be developed. An increased initial degree of saturation of the pellets seems to have positive influences regarding water outflow and material installation: a steeper friction angle can be gained for the pellet fill and saturated pellets seem to direct the water flow in the pellet/wall contact decreasing the risk of block erosion. In addition, saturated pellets may be able to better mechanically support the rock than dry pellets.

The above-listed points identify some of the guidelines and considerations that have been developed as part of the Baclo programme. From the results of laboratory through to ½-Scale tests valuable information has been developed regarding materials behaviour, technological needs and processes active in a newly backfilled tunnel. From this information a number of critical processes or questions have been evaluated and further ones identified. Most importantly, these studies begin the process of identifying what materials are suitable and what physical and mechanical constraints might be encountered during backfilling operations. The following Section 7 takes this information and begins the process of developing an operationally-viable means of installing the backfill.

7 Development of backfill-related technologies and designs accomplished during conduct of Baclo Phase III

7.1 Introduction

The hydraulic and deformation behaviour of the backfill components and assemblies of these components were examined at laboratory through to large field-scale simulations as described in the preceding sections of this report. Once some degree of confidence regarding the likely behaviour of the individual components had been developed it was important to examine if these materials and concepts could actually be constructed at repository-scale. Together with this is the evaluation of processes that would be active in an actual tunnel (e.g. water influx, deformation of flooring materials, installation of pellet fill materials). These demonstrations are key to developing and demonstrating that the backfilling concepts being developed can be put into practice.

Most of the work performed to develop and test installation of backfill blocks and pellets is described in /Wimelius and Pusch 2008/. The Swedish tunnel dimensions and design requirements were used as a basis of this work. Therefore, the results summarized in this section are case specific for the Swedish deposition tunnels, although to large extent they are also applicable to the Finnish case. The main differences between the Finnish and Swedish case are between the expected rock quality, tunnel size and capacity demands.

Tests concerning manufacturing of tests blocks were made at Sweden (Bjuv brick factory), Finland (Kiikala brick factory) and Germany (LAEIS Bucher GmbH), the latter two being part of Posiva's own investigations and not formally part of Baclo.

7.2 Tunnel dimensions

The theoretical cross section of the deposition tunnels considered in Baclo Phase III is 4.2 m in width and 4.8 m in height, corresponding to a cross section area of 18.9 m^2 for the Swedish deposition tunnel. The cross section of the Finnish tunnel is 14 m^2. The tunnels have a slope of 1% towards the central tunnels in order to provide for self-drainage.

The most important difference between planned and actual tunnel geometry is expected to be caused by the characteristics of the local host rock and orientation of natural fractures. In addition, the excavation method itself has effect on the resulting tunnel geometry. These effects combine to cause considerable variations in the actual degree of block filling that is achieved.

In order to evaluate the *average* cross section of the Swedish deposition tunnel, the following assumptions were made by /Wimelius and Pusch 2008/:

- The average excavation blast round length is 4.5 m
- At the end of the round, the cross section extends out +0.2 m to +0.3 m from the theoretical excavation line, meaning in practice that the look-out angle of the blasting holes varies from 2.5° to 3.8° (Figure 7-1).
- The total overbreakage shall be less than 30% of the nominal tunnel geometry per blasting round.

The contour of the floor depends on the method employed in preparing the tunnel floor. If it is made by traditional, careful blasting, the floor will be irregular with lookouts of about 0.3 m for each blasting round.

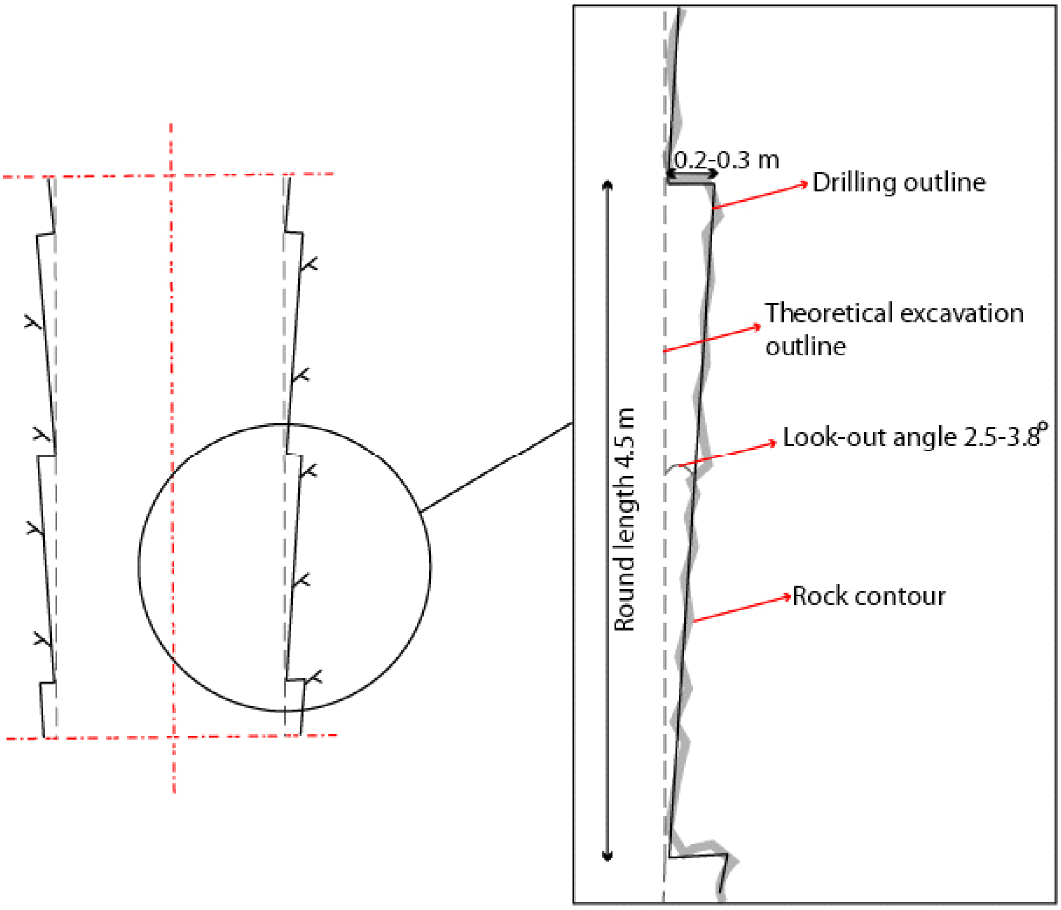


Figure 7-1. *Schematic drawing showing the basis for assessing the relation between the theoretical excavation outline and the realized tunnel contour for the Swedish deposition tunnel.*

The look-outs[1] in the roof must not extend by more than 200 mm from the theoretical tunnel profile. This is because the thickness of the pellet fill between buffer and the backfill and between the blocks in the backfill and the tunnel roof must be limited. These tunnel filling materials will be compressed by the upward expanding buffer, which will thereby become less dense. The amount of over-excavated rock contributes to the reduction of buffer density and should not be higher than 30% for each blasting round. In practice it is estimated to be about 20%, which hence provides sufficient margins taking deviations from the intended blast hole orientation and spalling rock into consideration.

The generation of extra tunnel volume can be minimized by optimizing the excavation technique including:

- Careful drilling of the blasting holes to remain within the design look-out angle.
- Optimization of the round length.
- Using the correct loading pattern and explosive type to minimize excavation damage.

7.3 Block manufacturing

The manufacturing of backfill blocks in industrial-scale was tested already in Baclo phase II (reported in /Gunnarsson et al. 2006/). Based on the tests done with compaction pressures of 25 and 50 MPa, it was estimated that blocks with maximum dimensions of 800×600×500 mm can be manufactured with a similar type of equipment using a compression pressure of 30 MPa.

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[1] Outward extension of blast holes from the axial direction at the tunnel, expressed in mm.

This block size was used as a starting point in assessing the achievable block filling degree for the deposition tunnels.

The block sizes are dependent on several factors. First the block compaction unit's limitations will determine what sizes that can be manufactured. Second, the size must be adjusted to the actual tunnel dimensions and finally, on the installation method used (discussed in Section 7.5). It is considered possible to design a compaction unit to produce backfill blocks optimized based on the tunnel dimensions.

Maximum dry densities achieved for the different block materials with compaction pressure of 25 MPa is presented in Table 7-1. These densities were achieved in laboratory scale pressing tests by /Johannesson and Nilsson 2006/ and used in /Gunnarsson et al. 2006/ for assessing the achievable dry densities for the block backfill concept. However, for conservative mass and density estimation purposes, /Gunnarsson et al. 2006/ assumed that blocks can only be pressed to 97% of their maximum density, and this assumption has also been used in this report. The achievable dry density would have to be tested at industrial scale.

In a previous block backfill design report for the Finnish case /Keto and Rönnqvist 2006/, the block size considered was 300×300×400 mm. This was chosen based on technical descriptions and an offer from a press manufacturer (LAEIS Bucher GmbH) and an assumption that a total of only 16 blocks would be installed at a time. The press type considered was LAEIS HPF III 630 with maximum pressing force of 6,300 kN and operating pressure of 32 MPa (320 bar). The description of the whole manufacturing process is presented in /Keto and Rönnqvist 2006/. The reference concept for the Finnish deposition tunnels will be updated during 2009 and will take into account more recent developments in compaction technology.

7.4 Block layout

The two main design requirements for the block layout design are to:

- Fill a sufficiently high volume of the tunnel to gain sufficient backfill density. This is especially important if the thickness of the pellet fill required right above the deposition hole is greater than in the current design concept as the risk of compression of the backfill due to swelling of the buffer increases.
- Allow installation of the pellet fill.

The basic assumption made in the block and pellet filling concept presented by /Wimelius and Pusch 2008/ was that there needed to be a minimum of 100 mm wide installation tolerance between the backfill blocks and the rock (theoretical tunnel contour) to enable efficient and controlled installation of pellets. The irregular contour of the tunnel walls and floor will cause variation of the width of the pellet fillings along each blasting round from 100 mm at minimum to 400 mm or locally even more, depending on the influence of blasting and geological features.

Table 7-1. Results from compaction tests in /Johannesson and Nilsson 2006/.

Material	Compaction pressure (MPa)	Water ratio at max density	Maximum dry density (kg/m^3)
Asha 230	25	0.173	1,700
Asha 230	50	0.176	1,790
Friedland	25	0.110	2,000
Friedland	50	0.070	2,090
30/70-Mixtures	25	0.07–0.08	2,000–2,160
30/70-Mixtures	50	0.065–0.070	2,070–2,240

The allowable content of voids and the dry density of the pellet fill are directly determined by the degree of block filling, which in turn is controlled by the amount of over-excavated rock. Taking into account the 100 mm installation tolerance, the maximum block filling degree achievable is 89%, based on the theoretical tunnel volume. However, the actual block filling degree depends on how much extra volume is present outside the theoretical tunnel outline. The maximum percentage of over-excavation of rock is set at 30% with respect to the earlier defined theoretical tunnel section. This gives a block filling degree of 67% with the selected method. For 20% over-excavation block filling increases to 73%, improving the net bulk clay density and reducing the demands of precision block fitting and high degree of pellet filling.

Different types of block layouts were studied by /Wimelius and Pusch 2008/. For example, if the backfill block placement geometry were adapted to the geometry of the rounds (flexible stacking), higher block filling degree could be achieved than with "static" system (Figure 7-2). However, the conclusion of /Wimelius and Pusch 2008/ is that the advantage of using flexible stacking was small when considering the advantages gained and the placement-rate demands (6–8 m day for the Swedish system). In addition, it was evaluated that installation of pellets is easier when using the static method compared to the flexible system.

The block assemblies can be constructed with continuous joints or overlapping joints as shown in Figure 7-3. Overlapping joints have the advantage that they would give more stable block assemblies. Water uptake and erosion may differ between the different configurations, but no special studies have been carried out to examine the importance of overlapping block joints. The first alternative (continuous vertical and horizontal joints) has been selected because this will make the stacking process simpler, which is preferred considering the Swedish requirement on the backfilling rate. The tests described by /Wimelius and Pusch 2008/ have shown that this configuration is stable and can be performed in full scale.

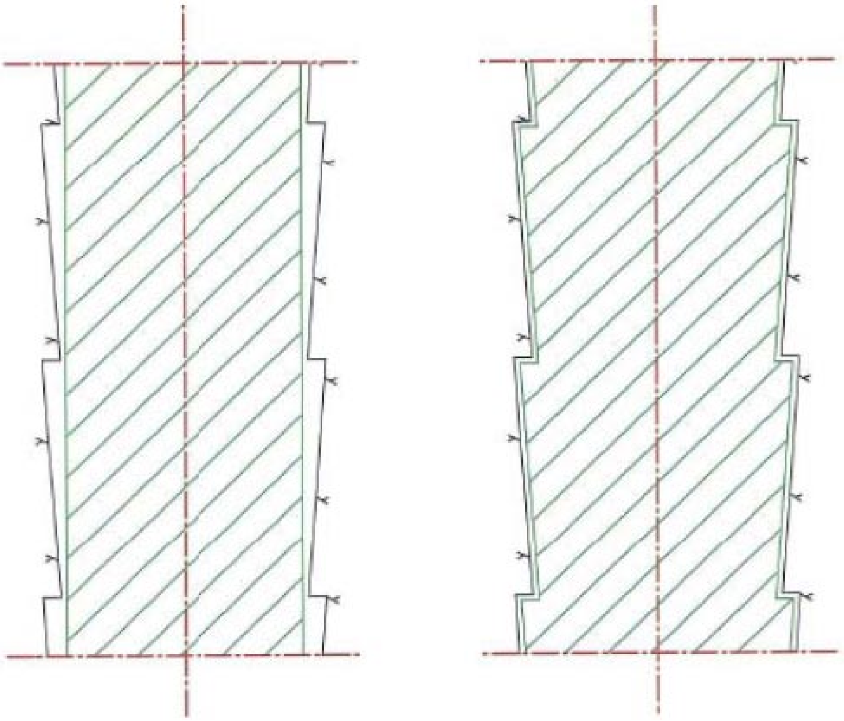
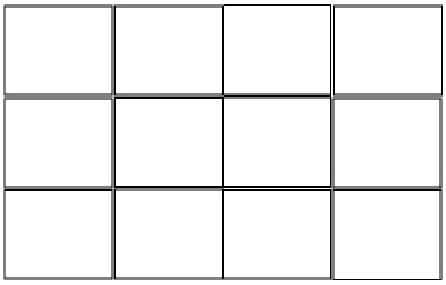


Figure 7-2. *The principle of two different stacking methods considered in /Wimelius and Pusch 2008/. Left: Static system. Right: Flexible system adapted to the rock contour.*

Alternative 1)
Block layout pattern with continuous horizontal and vertical joints between the backfill blocks



Alternative 2)
Block layout pattern with no continuous vertical joints between the blocks

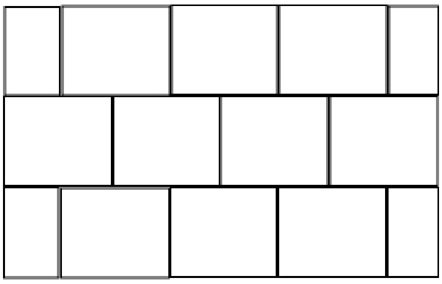


Figure 7-3. Block layout patterns.

7.5 Installation methods and rates

7.5.1 Sequence for deposition and backfilling

The sequence for preparation of tunnels, deposition of canister, placement of buffer and backfill are described in /Wimelius and Pusch 2008/. The sequence contains the following steps.

1 Preparative work such as draining, rinsing and cleaning of deposition holes, installation of drainage and pump alarm, installation of buffer protection sheet.
2 Temporary installation for ventilation, electric power, compressed air, illumination etc.
3 Placement of buffer in the deposition holes.
4 Placement of canisters.
5 Placement of upper buffer blocks.
6 Removal of temporary installations.
7 Removal of buffer protection and filling of pellets in the deposition hole.
8 Construction of foundation bed.
9 Installation of one advance of backfill blocks.
10 Pellet-filling of one advance.

Steps 6–10 are repeated until the entire tunnel is backfilled. The steps are described in more detail in /Wimelius and Pusch 2008/. It is important to have an understanding for the sequence since these activities influence the required backfill rate.

The backfilling rate is theoretically determined by the deposition of canisters and therefore the backfilling shall have the same rate as the deposition of canisters. In the Swedish case one canister shall be deposited each day, this gives a backfilling rate of 6–8 meter per day depending on the distance between the deposition holes. As the backfill sequence contains several steps, the duration of each step needs to be known in order to determine the time available for backfilling. The total number of canisters in Finland is smaller and the plan is to deposit on average 40 canisters per year.

The effect of different types of working sequences for the Finnish case is discussed in /Keto and Rönnqvist 2006/. Another issue determining the required backfill rate and sequence is the water inflow rate and distribution in the tunnel (see Section 6.5.5.).

7.5.2 Foundation bed

Blasting will give an irregular floor topography that requires filling and compaction of a suitable clay material to yield a planar surface before placement of blocks can start (Figure 7-4). In addition, the bearing capacity and evenness are important parameters for the placement of blocks. The stability of the bed as a function of time and water inflow must be known for planning of the placement of blocks and pellets.

The presence of a foundation bed is independent of the method for installation of blocks and pellets. In the study by /Wimelius and Pusch 2008/ the flooring material consisted of smectite-rich (> 70%) bentonite granules or pellets. This material was chosen for its hydraulic properties in order to prevent permanent pathways in the floor. The disadvantage is the mechanical stability and the sensitivity to water of bentonite-based materials; therefore the foundation bed must be prepared in short sections. Other materials have been considered in earlier studied presented in /Keto and Rönnqvist 2006/.

In order to ensure sufficient bearing capacity, compaction of the flooring material is needed, for this purpose a vibrating plate can be used. Another factor is the granule size distribution that should be optimized to gain better compaction properties. A series of loading experiments using concrete blocks of similar dimensions and density to backfill blocks have been performed using Cebogel pellets and Minelco granules /see Wimelius and Pusch 2008/. The process of levelling of the foundation bed for testing is shown in Figure 7-5.

Optimal compactability, according to /Wimelius and Pusch 2008/, is obtained by sieving the Minelco granules to generate a material that contains 7% powder finer than 0.125 mm and no grains larger than 30 mm. The bed should, if needed, be constructed with several layers; the thickness of each layer should be at least 5 times the maximum granule diameter.

Some water will be sprayed on the material to avoid dust generation during compaction. The final surface should be parallel to the tunnel floor, i.e. inclined by about 1% towards its outer end, and fitted to the upper surface of previously placed beds. The bed has to be prepared rapidly in 2 m long units in order to minimize problems with water flowing along the floor from regions previously backfilled. Such water can cause problems in the preparation of new beds and a technique must be worked out for removing water from the construction area. The range of the block- and pellet-placing equipment available is also one determining factor related to the length of foundation bed units. One should also note that since traffic cannot be allowed on the pellet filled floor, the length of the floor layer can not in practice be very long.

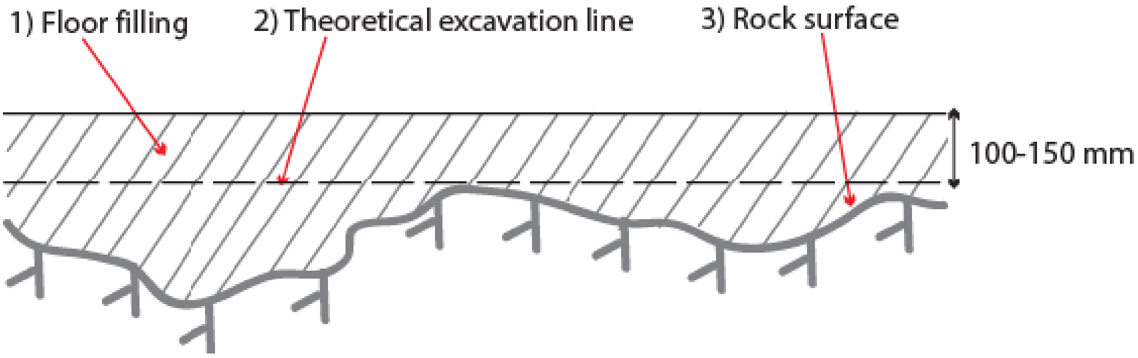


Figure 7-4. *Blasted floor with pellet filling. The maximum thickness of the layer depends on the excavation result (up to 400 mm). The minimum layer thickness is estimated to be 100–150 mm in places where the rock surface is near the theoretical excavation line. This minimum is because compaction of a thinner layer would be difficult.*

Figure 7-5. *Preparation of the bottom bed using Minelco granules.*

In the plan by /Keto and Rönnqvist 2006/ for the Finnish case, the average thickness was estimated to be 250 mm (150 mm above the theoretical floor level). As-yet the effect of this much-thicker flooring layer needs to be evaluated on the mechanical and hydraulic behaviour of the backfill system.

7.5.3 Installation of blocks

In developing concepts for backfilling the manner in which the blocks are installed is a key item. As part of Baclo and Baclo-related activities several basic approaches to block installation have been developed. These approaches all assume that the blocks are stacked from the foundation bed up to the roof. The construction length of each unit should be the same as that of the foundation bed, i.e. 1–4 m, with a probable average length of 2 m.

From the above-listed basic guidelines for backfilling, three static stacking techniques for placing blocks and pellets have been assessed based on experience from backfilling tests and theoretical considerations /Wimelius and Pusch 2008/. The three alternative installation methods for placing blocks are:

- The “Block” method.
- The “Robot” method.
- The “Module” method.

Block method

The block method involves a block-by-block installation method. From the foundation bed up to the breakpoint (location where roof curvature influences ability to emplace blocks used in basal region) (Figure 7-6) the blocks have the dimensions 667 mm by 700 mm and 510 mm height. Above the breakpoint they are 600 mm wide, 700 mm long and 250 mm high. The blocks, between the breakpoint and the roof, should be laterally offset 300 mm from the lower blocks in order to stabilize the masonry and prevent the front from leaning out towards the as-yet unfilled tunnel volume (Figure 7-7).

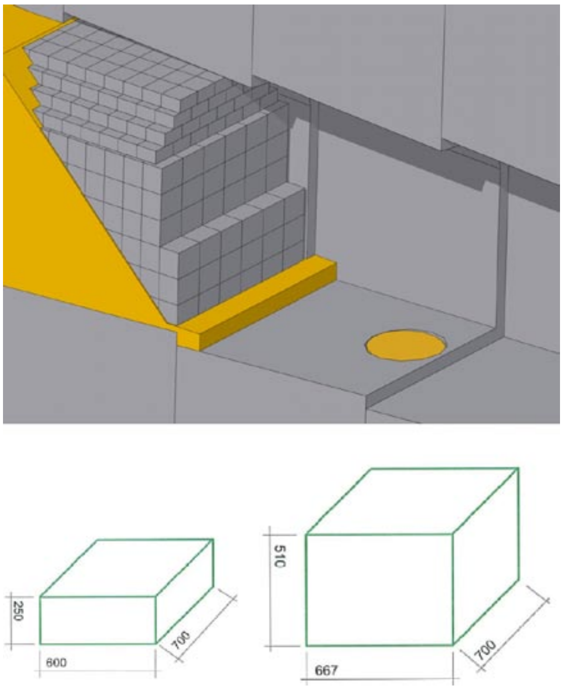


Figure 7-6. *Stepped front of the block assembly resting on the foundation bed with above breakpoint blocks (left) and below breakpoint blocks (right). The dimensions of the blocks shown are deemed suitable from practical points of view.*

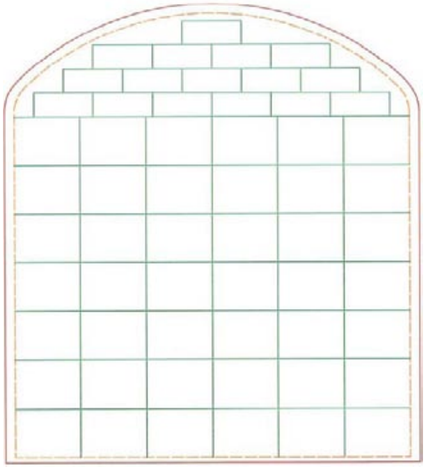


Figure 7-7. *Stacking according to the block method.*

This method was the only one that was tested at full-scale in the Äspö Bentonite Laboratory. The experiments show that placing of blocks would be possible under certain repository conditions. Following the principle that was selected for the planning of the experiments, i.e. that 60% of the volume of the up to 300 m long blasted tunnels shall be filled with clay blocks, the experiments showed that this can be achieved even if the topography of the floor, walls and roof is rather irregular. The tests have shown that it will take about 60 seconds to pick up a block and place it accurately. However, the conditions were rather ideal for the experiments and may explain the good results. On the other hand more efficient equipment can probably be developed for the purpose. Therefore, the 60 seconds per block can be considered as a fairly good approximation on the installation capacity. The geometry of the 100 blocks stacked in this trial was recorded by point-wise laser measurement. The size of the void space that can be accepted between the blocks depends on the block filling degree.

Robot method

The Robot method is also a block-by-block placing method. In this approach only one block size is planned, for example 308×500 mm with 300 mm height. The smaller size of the blocks means that the number of joints is higher for assemblies constructed by application of the “Robot” method, which means that the number of vertical joints will be higher. This implies that the requirements on minimizing the joint widths will be higher as compared with the block method.

Block placement starts by stacking blocks in the centre and then sideways, one arm serving the left half and the other the right half (Figure 7-8). No placement tests have yet been made to test this concept and so the time schedule for backfilling has been estimated based on experience from various industrial projects where comparable tasks were robotically accomplished. Additionally, as previously noted, the required rate of backfilling is 6–8 m per 24 hours for the SKB concept. Thus, for backfilling of the tunnels at a rate of about 6 m per day, 2,208 blocks must be placed per day, each placement requiring 30 seconds with two parallel working robots.

Module method

The main difference of the module method as compared to the other methods discussed above is that a module is pre-built with blocks at the surface and not at the location/depth where backfilling is occurring. Once built, the entire module is transported down and placed into the tunnel.

The stacking principle for the module concept is shown in Figure 7-9. Three big bottom blocks with smaller blocks stacked over them form units termed “modules” that are mechanically held together during transport and placement. The units are kept stable once they are assembled by orienting some blocks so that they serve as binders. The placement of these modules has been investigated in theoretical studies based on different presumptions concerning the way in which the modules are delivered from the central storage in the repository /Wimelius and Pusch 2008/. Tests have been done using stacks with 4 bottom blocks; these modules are apparently stable (Figure 7-10) although more thorough evaluation is still necessary. Investigations on producing backfill blocks with larger dimensions (bottom blocks) are ongoing.

Based on the installation concepts developed, the required number of modules needed to fill the cross section of the tunnel is 9.

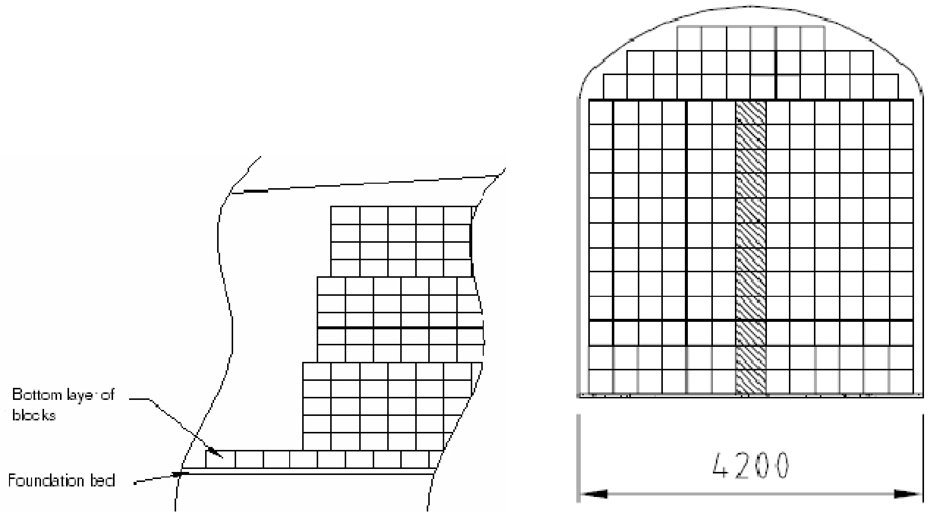


Figure 7-8. Stacking mode for the “Robot” method.

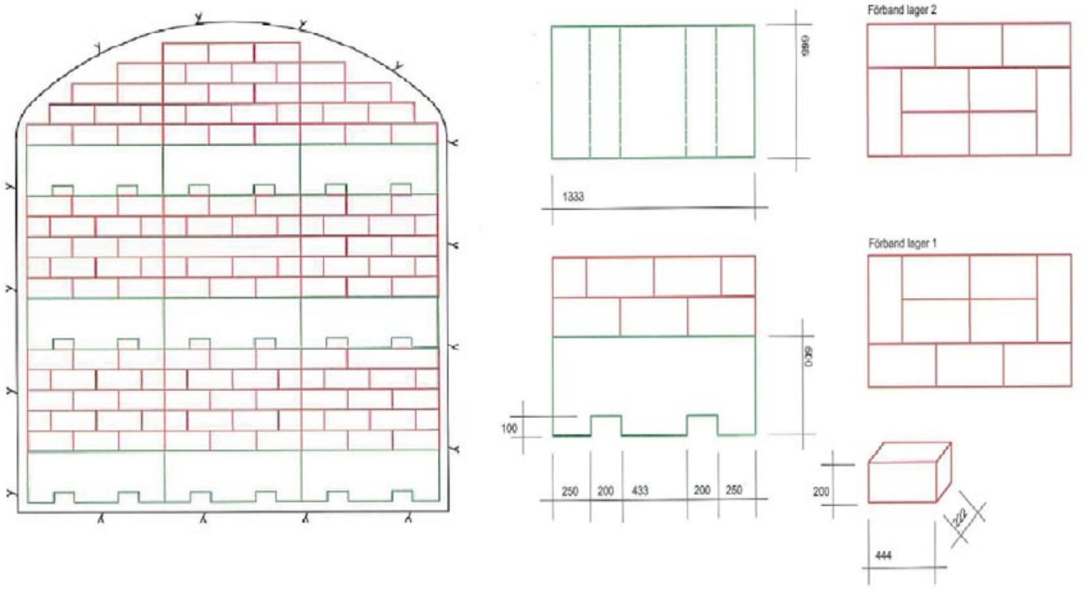


Figure 7-9. *Stacking of modules consisting of blocks. The bottom blocks are large and serve as a base of smaller blocks of one size.*

Figure 7-10. *Testing of the stability of a module. Notice the larger bottom blocks and layers of differently placed and oriented blocks for increased stability.*

The three methods for block placement onto a level floor consisting of compacted bentonite pellet materials are compared in Table 7-2. The prerequisites are the same for all methods, a foundation bed is needed and pellets are filled in the gap between the rock and the blocks. All methods need development of equipment for pellet filling and construction and levelling of the foundation bed.

7.5.4 Installation of pellets in non-floor regions

The block assemblage must remain stable until the pellets in the space between the blocks and the rock have been filled. If the blocks settle or shift, gaps between the blocks may be created and it may be difficult to install the amount of pellets needed to reach the required overall density for the backfill. The pellets should therefore be installed immediately after completion of the associated block assembly.

Table 7-2. Comparison of different backfill installation methods.

	Block method	Robot method	Module method
Installation principle	Block by block placement	Block by block placement	Placement of modules with blocks
Block size	667×700×510 mm and 600×700×250 mm	308×500×300 mm	666×1,333×500 mm and 444v222×100 mm
Needed equipment	1. Block placing unit	1. Robot-based block placing equipment (two robots)	1. Block placing equipment (fork truck)
Estimated rate	60 s for placement of one block Possible to backfill 6 m/24 hours	30 s for placement of one block Possible to backfill 6–8 m/24 hours	5 min for placement of one module Possible to backfill up to 10 m/24 hours
Advantages	Shown that 60% block filling degree can be reached and that one block can be placed in 60 s	Quick automatic handling of blocks	Block placing equipment is available with only limited development required
Disadvantages	There are only small margins if problems occurs in the process It has not been shown that blocks of this size can be pressed (the tests were done with concrete blocks)	Not tested in practice	It has not been shown that bottom blocks of this size can be pressed

The length into which pellets can be placed can be up to 4–5 meters, depending on the inflow of water. The technique for placing the pellets can be simple pouring through a tube to the lowest part of the space, moving and pushing by use of augers, mechanical throwing via conveyors, or blowing by use of a suitably adapted shotcreting technique. The latter technique was chosen in this study as it has the advantages of speed and ease of material movement. The capacity of the pellet installation device used at the trials conducted in the Bentonite Laboratory at Äspö was about 5 m^3 per hour. Figure 7-11 shows the nozzle of the blowing tube, which had an outer diameter of 70 mm. Figure 7-12 shows the pellet-filling test performed at the Bentonite Laboratory at Äspö. An amount of 1% of water by mass was to be added at the nozzle to reduce dust generated during the installation of the pellets.

***Figure 7-11.** The picture shows the nozzle of the tube for blowing pellets with holes for adding water for reducing generation of dust.*

***Figure 7-12.** Pellet filling in the most narrow tunnel section.*

The intended bulk density of the pellet fill was 1,000 kg/m³, which, for the Cebogel pellets with 16% gravimetric water content, implies a dry density of about 975 kg/m³ and a density at water saturation of about 1,600 kg/m³. The actual dry density of the fill was, however, found to be only 907 kg/m³. This may at least partly be explained by the fact that the space immediately below the artificial rock contour was not filled. Another possible reason may be the pellet granule size distribution that was not necessarily optimal for producing high as possible density. It was also concluded that although the pellet fill was in contact with the tunnel roof it will undergo some self-compaction leading to a gap that will remain open until the fill is contacted with water and it swells into any adjacent openings, this is a scenario that needs to be modelled. Other trials, done using slightly different placement equipment in the ½-Scale tests at the Bentonite Laboratory Äspö achieved the dry densities required for the pellet fill as described in Section 6.2.7 /Dixon et al. 2008c/. This indicates that the target density is likely an achievable value once the placement process and equipment undergoes further development.

A vertical front of the applied pellets would also be advantageous but it requires adding more water at the nozzle of the tube to induce pellet adhesion as they are blown into place. This technology has been successfully tested but requires further technical development to improve the homogeneity of the placed materials.

7.5.5 Quality control

Quality controls are performed during the whole chain in order to ensure that the raw materials and the manufactured backfill blocks fulfil the acceptance criteria set to them and the backfill will be installed with adequate density. Quality control was not a topic studied in Baclo Phase III, but the main principles for the quality control concerning materials, manufacturing and installation of sealing materials are described in /Ahonen et al. 2008 and Keto and Rönnqvist 2006/.

7.5.6 Efficiency with respect to costs and raw material

The requirement has been set for the backfill design to be efficient with respect to costs and raw materials. No detailed cost comparison was made in Baclo Phase III between the alternative materials considering these two issues.

All of the backfill materials are produced overseas and need to be transported by shipping, India being the furthest location and Germany as the closest. Recently, fluctuations in shipping costs have been large, making price estimations difficult. In any case, it is recommended that the shipping be made in large batches (e.g. once a year), since the costs and environmental impact is higher if the shipment is made more often. Therefore, the capacity of raw material storages needs to be sufficient to be able to handle the amount of material shipped at a time.

In the production of raw materials there is assumingly little difference between alternatives, although in Germany pre-drying of raw material outside by sunlight cannot be done as extensively and reliably as is possible in Greece or India. In general, the more processing the product is required to undergo, the more energy is used in its production and the higher the costs. For example, the use of pellets is less effective in this respect than non-processed bentonite granules.

If a mixture of bentonite and ballast would be used, the mixing will add costs compared to the pure clay materials. In addition, crushing of ballast material at the site will have impact on the surrounding environment in form of noise, dust and space needed for storing the crushed rock. On the other hand, the storage space required for clay materials may accordingly be smaller.

7.6 Summary of technical advances

The series of tests and investigations at Äspö have shown that a block-filling degree of 60% can be achieved with the "static" type installation method. In this installation method, straight, continuous joints form between the blocks without adaptation to the actual rock contour. The Äspö test also showed that it is possible to backfill a tunnel (with a filling degree of 60%) at a backfill rate of 6–8 m per 24 hours. Other installation methods have been considered but not yet tested with similar full-scale installation tests.

The block filling degree depends strongly on the tunnel excavation. In a test tunnel (TASS) at Äspö the overbreakage was found to be 20% which would enable a block filling degree of 73% with the static method /Karlzén 2008/.

The block filling degree is one factor determining the average density of the backfill along with density of backfill blocks and the pellet fill. Based on the studies by /Wimelius and Pusch 2008/ there is a range of installation and design possibilities available to optimize the block filling degree if needed due to long-term safety issues.

The block sizes must be adapted to each case depending on the tunnel dimensions and the installation method.

All block installation methods described in this section can probably be successfully used to install the backfill, but the robot method and module method need practical testing. Results shows that the modules are fairly stable, but it remains to be shown that the large bottom blocks can be manufactured.

Technically it is possible to install pellets between the block assemblies and rock, however it should be investigated as to if the filling density can be increased if the grain size distribution differs or if the installation methods itself can be developed further. It was shown in Äspö, that the pellet filling can be installed almost to a vertical front when the water content of the pellet fill was increased /Dixon et al. 2008c, Wimelius and Pusch 2008/. This seems to be preferable from practical point of view, although the higher the water content the lower the initial pellet density will be (however, this density decrease is partly compensated by better packing).

The effect of water inflow to the tunnel needs to be assessed independent of the backfill sequence. It is expected that water will eventually come out in the front of the backfilled volume, potentially wetting the foundation bed or accumulating where the foundation bed has yet to be prepared. Therefore, there is a need to develop methods to deal with water, and to test those methods in practice.

8 Discussions and conclusions

In this section a short summary of the results from the performed work is provided. Potentially critical processes and important technical issues are listed and described. The resulting knowledge and experience is used for making recommendations on reference backfilling concept and for identifying areas for further work.

8.1 Influence of critical processes and technical issues on design basis

As the result of the extensive suite of studies done as part of the Baclo programme a great deal of knowledge has been gained regarding the evolution and behaviour of a range of potential backfill compositions and installation options. Based on this knowledge, several processes and technical issues have been identified as being potentially critical in determining the viability of the backfilling materials and approaches examined in this report. Table 8-1 identifies some of the main topics of concern and how they arose from the studies described in this report.

Interaction between backfill and buffer

Two types of interaction between the backfill and buffer components in the KBS-3V geometry were identified as potentially critical processes with respect to the performance of the backfill. These interactions consist of the swelling of the buffer upwards into the deposition tunnel (Section 6.3 Interaction between the backfill and buffer) and the second is chemical interactions between the components of the buffer and backfill. Only the first one was studied in Baclo Phase III.

The issue of mechanical interaction between the buffer and backfill was studied via analytical calculations and numerical modelling using the known characteristics of these materials. In the calculation cases it was assumed that the backfill was either in unsaturated state (dry case) or in fully saturated and homogenised state (wet case) the buffer being always in fully saturated state. The results of assessments where initially water saturated buffer and backfill are assumed were found to produce fairly comparable results. As a result, reasonable confidence can be attached to these analyses. Based on these analytical results, which take into account the restraint to buffer swelling caused by the swelling of the backfill and its relatively stiff nature, the dry densities of the buffer at the level of the canister will remain adequate (> 1,950 kg/m^3). This provides a degree of confidence in the system provided that the assumed conditions can be achieved in practice. The main sources of uncertainties come from the saturation state of the backfill, the block and pellet layout assumed in the analysis and effect of bentonite pellets placed on the floor and in the upper part of the deposition hole.

Homogenisation of block and pellet backfill

Homogenisation tests (Section 6.4) done to examine the density and deformation of backfill systems have shown that if the blocks and pellets consist of materials with different mineralogical compositions, it is unlikely that a uniform dry density will develop in the backfill. However, as long as the combination of backfill material and backfill layout yields low enough hydraulic conductivity in the entire tunnel volume this type of heterogeneity is not a critical issue (the pellets will be compressed during the saturation process improving their properties). For example, in a test with combination of Friedland clay blocks and bentonite pellets, the dry density of the bentonite pellet fill increased from 900–1,000 kg/m^3 to 1,200–1,300 kg/m^3 (in a test setup corresponding to block filling degree of 80%). This type of density increase results in a very substantial reduction in the hydraulic conductivity of the pellet-filled volume and an increase in the strength of that material with only a nominal reduction in the initial properties of the block materials. It was also demonstrated that although the initial dry density of the pellet fill installed in the bench-scale tests did not provide the required degree of self-sealing properties (Section 6.4.4). This subsequently compressed material is likely to exhibit adequate hydraulic properties, compressibility, swelling pressure and self-sealing.

These findings have yet to be verified by a larger number of lab scale tests, field demonstration and modelling but these initial results are positive.

The homogenisation tests described above were done to study the basic behaviour of the block and pellet combinations and not to determine what the block filling degree should be. However, the volumes used corresponded to block filling degrees of 70, 80 and 90%. Further homogenisation tests should be undertaken for systems having a block filling degree smaller than 70% in order to study the robustness of the system taking into account the possible irregularities of the tunnel geometry.

Average installed density/fraction of the tunnel filled with blocks

A variety of block layout options and installation methods are discussed in Section 7. So far, it has been shown with full-scale installation tests that a block filling degree of 60% can be achieved with a "*static installation system*" fulfilling also the capacity demands set for the backfill in Sweden (6–8 m/day). In this system the block layout will always be the same regardless of the variations in the tunnel geometry. Therefore, the extra volume remaining outside the theoretical volume of the tunnel (overbreak %) will affect the achieved block filling degree and hence system density. Using the TASS tunnel as an example, it has been estimated that if the excavation overbreak is at maximum 20%, the achievable block filling degree is 73%. If the overbreak is more than 20%, only block materials with relatively high amount of swelling minerals are recommended, with the requirement that the compressibility of the block/pellet structure remains at acceptable level.

The other installation system considered for backfilling and discussed previously in this document (the "*flexible method*"), takes into account the geometry of the tunnel. This approach has not yet been tested at full scale but it was assessed as not being able to fulfil the installation-rate demands set for the backfilling process. However, this method should be re-considered if it seems that the pellet geometry achieved with the static method leads to unacceptable deformation of the backfill.

Rate of wetting, formation of piping channels and erosion

A variety of wetting, erosion and piping tests were performed in Baclo Phase II and III in laboratory and in field-scale tests (Section 6.2). In most cases the block material used in these tests was Friedland clay tested in association with different types of bentonite pellets.

It was found that in direct contact with leakage waters, Friedland clay blocks tended to loose their mechanical stability and are prone to erosion and piping. Therefore, bentonite pellets are needed to protect the blocks from direct contact with flowing water. Based on the Äspö field tests, the wetting and erosion behaviour seemed to be scale- and time-dependent processes. In addition, the water salinity seems to affect the process. The measured erosion in laboratory tests varied typically between 1–10 g/l and in Äspö field tests 1–25 g/l. A tendency for the erosion to decrease with time was also observed in most of the tests. In the 1/12-Scale tests (with applied inflow rates ranging from 0.01–1 l/min), erosion was especially evident in cases where a piping hole had formed in the Friedland block filled volume. In the field-scale tests (½ tunnel scale with applied inflow rates of 0.25–2.5 l/min) the wetting and formation of preferential flow paths took place in a more consistent manner. In majority of the cases tested at ½ tunnel scale, the water exited through a pathway at the pellet-concrete wall and very little erosion was observed in these tests, excepting for the highest water inflow rates examined. Since it was not considered a critical issue, no actual analysis on how much backfill will be eroded in a deposition tunnel was made in Baclo Phase III, but should be a topic for future study taking into account site specific conditions (water pressure, water inflow rates and locations and water chemistry). The information gained on the mass solid particles that can be transported by a unit volume of water can be used as a basis for designing and evaluating the results of erosion studies.

Water management

Results from field-scale mock-ups undertaken at Äspö indicated that the backfill system should be able to tolerate a single-point water inflow of 0.5 l/min (or less) without significant erosion and mechanical instability being induced in the backfill when the inflow point is located few metres behind the backfilling front. This condition does however require that backfilling to few meters past the inflow point is made rapidly and that the interruption of the backfilling process not exceed a week (the time limit thus far examined). It should be noted that these mock-ups did not attempt to simulate the more complex geological and hydrogeological processes that would be encountered in the field. The more irregular rock surface results in longer flow paths in the rock/pellet interface and thereby in more water being absorbed by pellets. The hydrogeology of the rock probably leads to the water being distributed over larger areas that should also increase the water being absorbed by the pellet fill. Hence the conditions in the test set-up should be considered to be conservative. However, this remains to be verified with further studies. How much inflow can be accepted into the entire deposition tunnel is a complex issue and no exact limits can be given based on the existing Baclo data although some bounding values have been indicated from the results obtained. Much depends on how the water inflow is distributed throughout the tunnel, in few single fractures or more uniformly and the rate at which it enters the tunnel. Therefore, continuation of field-scale (e.g. ½-Scale) testing is needed to determine how multiple inflow points affect the system. This issue should also be studied further looking at the site dependent data, prediction of water leakage and analysis on how much material is eroded during the installation phase.

Another design factor that may depend on the water inflow rate is the required backfilling rate (m per day), which in turn affects the chosen installation sequence. If backfill installation is disrupted due to water inflow, it cannot be ensured that the assumed/required initial state of the backfill is achieved. Based on current knowledge, gained through testing done in Baclo Phase II and III, if there are interruptions with durations of more than a week, some loosening of the materials placed at the open face of the backfilled volume will almost certainly occur, and this section would have to be replaced before backfilling operations restart. Methods of dealing with the water coming towards the backfilling front and what the optimal backfill sequence would be (taking into buffer related operations) needs to be studied further.

Performance of the current design and alternative backfill compositions

The backfill concept investigated in this study is the block concept based on filling the majority of the tunnel with pre-compacted backfill blocks and the remaining volume with bentonite pellets. The majority of the investigations discussed in this report were performed for three alternative block materials: Asha 230 bentonite, Friedland clay and mixture of bentonite and ballast (30:70). The pellet materials used to fill the remaining spaces between the blocks and the surrounding rock consisted either of pure Ca- or Na-bentonite (with varying granule size distributions) or of Friedland clay fragments (granules). In the Baclo studies it was assumed that pellets/granules are used both in the void between the blocks and the rock wall/roof but also underneath the blocks to provide a low-permeability foundation layer for the block assemblage.

Combination of Asha 230 bentonite blocks (with estimated smectite content between 60 and 80%) and bentonite pellets seems to be able fulfil all the requirements set for backfilling at block filling degrees of 70, 80 and 90% if the geometry of backfill components is also taken into account in the backfill design (upward swelling of the buffer). This material also has the potential to fulfil the requirements for backfill at even lower block filling degrees (< 70%), but factors such as homogenisation and compressibility has to be investigated further.

For Friedland clay backfill (with ~ 30% swelling clay mineral content), the situation concerning the proportion and geometry of the pellet fill is similar to that encountered for all backfill materials considered, (i.e. the buffer-backfill interaction requires further evaluation with updated backfill geometry before it can be judged to be a suitable material). However, based on self-sealing tests, as a first estimate, it is recommended that the block filling degree should not be very much less than 70% for this material.

For a 30% bentonite/70% aggregate mixture, it was determined that the block filling degree should be > 80–90%. This is based on theoretical calculations of average backfilled tunnel densities achieved as compared to the density criteria needed to exhibit adequate hydraulic and mechanical performance. However, even at this degree of backfilling, the material does not seem to have sufficient self-sealing capacity and is at risk for development of permanent hydraulic piping features. Therefore, it remains to be determined what bentonite/aggregate ratio would be able to provided adequate performance as a backfill.

Based on experiences from the ½-scale tests, the composition, saturation state, installation method and geometry of the pellet fill seemed to affect the saturation behaviour of the system. Further studies are needed to clarify these processes and to optimize backfill design and installation specifications.

In future, the quality control and acceptance criteria of the backfill components will need to be clearly defined. In addition, cost optimisation is needed to choose between potential material alternatives since this may affect the compositions ultimately selected for use.

Operational issues

Three different installation methods were investigated. The one tested with full-scale installation tests showed that a block-filling degree of 60% could be achieved at the specified rate of 6–8 m per 24 hours. This method represented the "static" type, i.e. with straight, continuous joints between the blocks without adaptation to the actual rock contour.

The installation methods described in Section 7 based on installing one block at a time (block method and robot method) or an assembly of blocks at a time (module method) can probably be successfully used to install the backfill, but the robot method and module method need testing. Results show that the modules are fairly stable, but it remains to be shown that the large bottom blocks can be pressed in practice.

Further work is needed to select the best method for backfill installation. In addition, there is a need for ongoing re-evaluation of what effects changes in materials, geometries or backfilling approaches will have on the operations of the repository. This is a topic that will require ongoing optimization as the repository concept moves towards implementation.

Input to design basis

The input of the studied processes (considered as potentially critical ones on the performance of the backfill) and technical issues on the design basis of the backfill are summarized in Table 8-1.

8.2 Basis for selection of backfill concepts for SKB and Posiva

The main objectives of this report were to provide a brief summation of the work done in Baclo Phase III as part of developing a workable backfilling concept for a KBS-3V-type repository. Specifically work focussed on backfill materials, emplacement concepts and their importance to the clay-block and pellet backfilling concept. Baclo Phase III was primarily intended to address the items listed below and the way in which they were accomplished is briefly summarized in this section:

1. evaluate options for design of block and pellet/granule materials for use in backfilling and in so doing provide a basis for selecting backfill materials,
2. provide a basis for recommending reference design(s) for backfilling though evaluation of materials, environmental processes and technical constraints likely to be encountered in a repository,
3. analyze how the potentially critical processes taking place during the installation and saturation phase affect the performance of the backfill and consequently the design basis for the backfill,
4. evaluate how water will move through backfilled volumes and generally identify under what conditions water management will become an operational issue, and identify needs for further investigations and technical development.

Table 8-1. Input of critical processes and technical issues on the design basis of deposition tunnel backfill.

Critical process/ Technical issue	Main activities/output/conclusions from Baclo Phase II and III studies	Input needed in order to resolve question and express it as a design basis
Mechanical interaction between backfill and buffer, i.e. swelling of the buffer to the deposition tunnel	Modelling methods were developed to analyse the process. Taking into account the swelling of the backfill materials, the deformation of backfill seems not to compromise the performance of the buffer (evaluated assuming 78% block filling degree). Following issues were found to affect the mechanical interaction: – Saturation state of the backfill (swelling). – Materials and density state (stiffness) of the materials. – Backfill geometry (block and pellet layout) and block filling degree.	The effect of updated backfill geometry needs to be re-evaluated as well as the influence of materials placed in the upper part of the deposition hole. This may lead to more detailed requirements on thickness of bottom bed and pellet filling at the roof and requirements on block/pellet layout in vicinity of the deposition hole.
Wetting, formation of piping channels and erosion	An extensive amount of information on all three processes was gained in laboratory, ¼ and ½ scale mock-ups. These processes were found to be partly scale and time-dependent. The risk of erosion apparently increases when the single-point inflow is > 0.5 l/min.	Sufficient pellet thickness at the roof/walls has yet to be firmly defined (current estimate ~ 15 cm). The properties of the pellet filling should be optimised considering this issue. The total inflow to a tunnel as well as the maximum point inflow needs to be further investigated and defined. Backfill sequence requires optimisation to improve efficiency. Technical measures to control water inflow need to be developed and tested.
Homogenisation	It was found that sufficient homogenisation was gained with the studied pellet-block combinations for block filling degrees of 70, 80 and 90%.	In practice, the lower the block filling degree, the higher the smectite content of the backfill block should be to provide sufficient swelling and homogenisation. Remains to be studied for lower block filling degrees to study the robustness of the system.
Self-sealing of piping channels	Self-sealing of piping channels was tested for all materials considered for backfilling. Based on the results mixture of bentonite and ballast (30:70) is not recommended as backfill material. In addition, bentonite pellets do not have sufficient self-sealing capacity in their initial dry density after installation (need to be compressed ~ 20% by the blocks).	This process determines material selection for blocks. Sufficient smectite content needs to be defined for density states resulting from block installation efficiencies lower than 70%.
Average dry density/ degree of backfilling	Analysis was made on the achievable average dry densities and the resulting material properties assuming different material alternatives. Tools to design the backfill in terms of material quality and average density have been developed. The achievable block filling degree is affected greatly by the variations in the tunnel geometry and installation method. The current estimation is that 73% of block filling degree can be achieved if the excavation overbreakage is at maximum 20%.	The lower the block filling degree the higher the smectite content of the backfill materials should be.
Installation of backfill components	Installation of backfill blocks and pellets were tested. Sufficient backfilling rate can be achieved with the static installation method under reasonably good conditions.	Static method is recommended if the required backfill rate is high but other options may be suitable under different installation rate requirements. Optimisation of the installation methods for blocks and pellets is still needed and testing under actual repository conditions is required.
Water management	The understanding of the behaviour of wetting, formation of piping channels and erosion comprises a good bases for optimising the backfill design and develop methods for handling water during backfilling.	Development and testing are still needed in order to optimise the backfill design Methods for handling water inflow during backfilling also need to be developed and demonstrated.

Evaluation of backfill materials

A range of backfill materials and emplacement options were examined within this project and the findings presented. The results can be summarized as follows:

- All of the backfill block materials studied, excluding the mixture of bentonite and ballast (30:70), are suitable candidates for backfilling using the block-pellet concept. The 30/70 mixture was excluded mainly due to its apparently limited self-sealing capacity but also due to low safety margin compared to other material alternatives.
- The quantity of swelling minerals required in the backfill depends on the backfill design (achived block filling degree, density) and homogenisation achievable. Studies in Baclo Phase III indicate that the swelling clay component should be ≥ 30% to ensure sufficient self-sealing ability but a range of materials could be used.
- All the bentonite pellets and granules (with high montmorillonite content) examined in Baclo Phase III were found to be suitable candidates for use in backfilling.

Basis for recommending reference design

As noted above, one of the main objectives of this report was to provide information for developing reference designs for backfilling. This was accomplished through defining a design basis for backfill development (Section 4 Design premises and criteria). The major criteria that were taken into account in this process included establishing the requirements of the backfill with respect to hydraulic conductivity, swelling pressure, self-sealing, homogenisation and its deformation as a consequence of buffer swelling. Building on these design premises and criteria, a series of recommendations related to backfill materials, block and pellet design, installation methods and water management were made based on the information developed. This is summarized in Section 8.1. With regards to the Block and Pellet design concept, it can be concluded that:

- The blocks and pellets should be placed in such manner that the minimum density required for fulfilling the requirements hydraulic conductivity and swelling pressure after saturation of the backfill is reached with a sufficient safety margin.
- A block filling degree of > 70% is recommended as testing done at and above this value indicate that they will perform as desired. Homogenisation studies were not performed assuming lower block filling degrees than 70% so experience at values below 70% are lacking. However, use of block filling degrees less than 70% may be possible if materials with relatively high smectite content are considered. In this case it must also be shown that the system's properties after saturation and homogenisation fulfil the requirements set for the compressibility of the backfill.
- The pellet geometry (especially the thickness of the pellet layers placed above the buffer) should be optimized so that the buffer density would always remain at acceptable level, also if the backfill would be in dry state.
- The installation methods should be chosen based on site-specific tunnel geometry (over breakage-%) and the block/pellet geometry needed to provide suitable compression, homogenisation, hydraulic and swelling properties for the backfill.

Analysis of potentially critical processes

Evaluation of several potentially critical processes has occurred. Specifically, determining how those taking place during the installation and saturation phase could affect the performance of the backfill and consequently the design basis for the backfill have been assessed.

- The rate of water inflow into the tunnel can be of critical importance in determining the viability of the block-pellet backfilling concept. Very high point inflow rates can result in substantial localized erosion and weakening of the backfill installed. Baclo Phase III has begun the process of defining the boundary between inflow rates where low and high erosion conditions will develop.
- Substantial removal (or internal redistribution) of backfill due to water movement can result in local conditions where the swelling and hydraulic properties of the backfill could drop below the specified limits. This is largely associated with point inflow rate and the degree of saturation that is present within the backfilled volume.

- Water movement through the backfill is likely to develop as discrete flow channels along the rock-pellet interface, resulting in rapid transfer of water from the backfilled tunnel to the downstream face of the backfill. This can have potentially disruptive effects on operations as the water (and eroded clay) must be dealt with such that they do not interfere with ongoing backfilling operations.

Evaluation of water movement through backfill

A major aspect of Baclo Phase III involved evaluation of how water moves into and through a backfilled tunnel volume. Section 6 provided a detailed summary of the results obtained in these studies and some of the key findings are as follows:

- The potential for piping in candidate backfill materials has been assessed, piping can develop in backfill and under high point inflow rates erosion of backfill can be substantial.
- The backfill cannot be counted on to act as a substantial sink for inflowing water. In particular the pellet materials do not initially saturate uniformly and water can move rapidly from the point of inflow to the working face, particularly under high inflow conditions.
- Under conditions where the volume of pellet fill is limited water can move into the block-filled volume and generate preferential flow paths along the block boundaries potentially resulting in development of erosive features.
- Piping through backfilled volumes tends to occur along existing interfaces, with preference to flow along the pellet-rock boundary. Under moderate point inflow conditions, the piping features do not result in extensive erosion of the backfill. Water tends to move rapidly along the piping feature to the downstream face of the backfill, meaning that it will be necessary to deal with the inflow almost as rapidly as it enters the tunnel.
- Due to the rapid movement of the water through the backfill it will be necessary to ensure that backfill operations do not cease for longer than a few days or up to one week in order to avoid problems with the installation process.

Identification topics in need of further investigation and technical development

Section 8.1 provides an outline of some of the key topics that will need further investigation as part of the ongoing process of developing a workable and robust concept. These items for further evaluation include a number of technical topics. At the time of completing Baclo Phase III the results indicate that the block and pellet backfilling concept is a workable approach that still has some unanswered questions but none of which appear to be unsolvable with ongoing focussed work.

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Appendix 1

List of Baclo reports

Report names	Authors	Organisations	Publication
Finite element modelling of the deformation of the backfill due to swelling of the buffer	Korkiala-Tanttu L	VTT Technical Research Centre of Finland	Posiva Oy, Working report
Mechanical interaction buffer/backfill – Finite element calculations of the upward swelling of the buffer against both dry and saturated backfill	Börgesson L[1] and Hernelind J[2]	[1]Clay Technology AB [2]5T Engineering AB	SKB R-report
Wetting and homogenisation processes in backfill materials	Johannesson L-E, Sandén T and Dueck A	Clay Technology AB	SKB R-08-136
Tests to determine water uptake behaviour of tunnel backfill	Dixon D[1], Anttila S[2], Viitanen M[2] and Keto P[3]	[1]Atomic Energy of Canada Limited, AECL [2]Pöyry Infra Oy [3]Saanio & Riekkola Oy	SKB R-report
Tests to determine water uptake behaviour of tunnel backfill (Baclo Tests at Äspö)	David D[1], Lundin E[2], Hedin M[2] and Rammqvist G[2]	[1]Atomic Energy of Canada Limited, AECL [2]SKB	SKB R-08-132
Backfilling and closure of the deep repository. Phase III – pilot tets to verify engineering feasibility. Geotechnical investigations made on unsaturated backfill materials	Johannesson L-E	Clay Technology AB	SKB R-08-131
Deep repository – Engineered barrier system. Erosion and sealing processes in tunnel backfill materials investigated in laboratory	Sandén T, Börgesson L, Dueck A, Goudarzi R and Lönnqvist M	Clay Technology AB	SKB R-08-135
Backfilling of KBS-3V deposition tunnels – Possibilities and Limitations	Wimelius H[1] and Pusch R[2]	[1]SKB [2]Geodevelopment AB	SKB R-08-59
Investigation of Mechanical properties and saturation of block backfill	Kuula-Väisänen P, Leppänen M and Kolisoja P	Tampere University of Technology, TUT	Posiva Oy, Working report
Hydraulic behaviour of backfill materials	Kuula-Väisänen P	Tampere University of Technology, TUT	Posiva Oy, Working report