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Abstract

The state of knowledge related to use of bentonite pellets as part of backfill or other gap filling components in repository applications is reviewed. How the pellets interact with adjacent sealing materials and the surrounding rock mass is a critical aspect in determining backfill behaviour. The key features and processes that determine how the pellet component of the KBS-3V deposition tunnel backfill will behave are discussed and recommendations related to what additional information needs to be developed are provided.

Experiences related to pellet material composition, size, shape, placement options and more importantly, the density to which they can be placed all indicate that there are significant limitations to the achievable as-placed density of bentonite pellet fill. Low as-placed density of the pellet fill component of the backfill is potentially problematic as the outermost regions of tunnel backfill will be the first region of the backfill to be contacted by water entering the tunnels. It is also through this region that initial water movement along the length of the deposition tunnels will occur. This will greatly influence the operations in a tunnel, especially with respect to situations where water is exiting the downstream face of still open deposition tunnels. Pellet-filled regions are also sensitive to groundwater salinity, susceptible to development of piping features and subsequent mechanical erosion by throughflowing water, particularly in the period preceding deposition tunnel closure.

A review of the experiences of various organisations considering use of bentonite-pellet materials as part of buffer or backfill barriers is provided in this document. From this information, potential options and limitations to use of pellets or pellet-granule mixtures in backfill are identified. Of particular importance is identification of the apparent upper-limits of dry density to which such materials can to be placed in the field. These bounds will determine what properties must be exhibited by adjacent swelling materials (Highly Compacted Bentonite or other densely compacted clay-based backfill blocks) in order that the backfill component meets its performance requirements once system equilibration has occurred.

Although there is some information available from literature related to pellets, there is still a need to evaluate what optimization can be achieved with respect to density, shape, composition, gradation and as-placed properties. Studies completed to date show a typical as-placed dry density range of ~1,000 kg/m^3 for narrow gaps associated with the block and air-entrained pellet backfill to ~1,400 kg/m^3 for pellet-granule mixtures installed in a horizontal tunnel where equipment access is less problematic. The KBS-3V concept presently utilises pellets placed to ~1,000 kg/m^3 which makes qualification of adjacent sealing materials (HCB or other clay-based blocks) of high importance (ensuring system performance goals are met). These pellet materials also require that means of minimizing erosion caused by water flow along the pellet-rock interface be identified and technological means to protect the backfill from erosion be kept ready for use.

Summary

Experiences related to manufacturing and installation of bentonite-based pellet materials for use in repositories for spent nuclear fuel have been reviewed. A considerable body of information related to placement of dense bentonite pellets is available from a variety of sources and has been collected to allow for evaluation of what bounds currently exist with respect to as-placed density of pellet materials in repository applications.

It has been demonstrated that a number of installation options exist that have potential application in placing pellet materials within underground excavations of the type proposed in a KBS-3V repository. The experiences to date with regards to material placement and more importantly, the density to which it can be placed indicate that there are clear limits to the achievable as-placed density of the pellet fill. It should be noted that these limitations are based on use of a fairly limited range of materials that are relevant to backfill block – rock gap filling for a KBS-3V geometry. Much work has been done on materials for use in filling the gaps in the deposition borehole or filling of larger voids (e.g. entire tunnels or shafts). Both of those geometries have different constraints with respect to placement and densification than for tunnel backfilling.

Much of the work done to date shows that the density to which currently available materials and methods can be placed are potentially problematic with respect to the groundwater conditions (flow and salinity) anticipated to be present at either the Forsmark or Olkiluoto sites at the time of backfilling. Pellets used as part of tunnel backfill are susceptible to erosion by water entering the deposition tunnels and susceptibility increases as groundwater salinity and rate of water flow increases. Water uptake and movement into and past pellet fill materials are also affected by groundwater salinity, inflow rate, as-placed density and potentially the shape of the pellet materials.

Field-related factors such as degree of tunnel over-excavation need to be quantified so that more accurate estimation of the quantity of pellet materials that will need to be installed and what the equilibrated density of the tunnel backfill will be. Associated with this is the need to determine if pellet optimization with respect to density, shape, composition, gradation will substantively alter the as-placed properties of the backfill. Ultimately, the materials and methods showing most promise for use in a repository will need to be tested in field trial(s) where repository – type conditions are present.

Contents

1 Background

1.1 SKB and Posiva Repository Concepts

SKB and Posiva are in the process of evaluating options for backfilling in their repository concepts for used nuclear fuel. In both cases the repository is proposed to be located deep underground in crystalline rock. Over a period of nearly 4 decades, a range of repository concepts have been developed and examined. All of them include the use of corrosion-resistant copper canisters to hold the used fuel and adjacent to the canister, clay-based sealing materials (buffer) will be installed to isolate them from the surrounding rock mass as shown in Figure 1-1. Clay-based materials are also proposed for use in backfilling the excavations associated with the repository (e.g. deposition tunnels, access tunnels, ramps and shafts). The clay material proposed for use in the buffer and backfill is a montmorillonite-rich product sold under the generic product name of bentonite by various commercial suppliers.

In order to have confidence in the long-term performance of the sealing system associated with these repository concepts it is important to have demonstrated both an ability to predict the behaviour of the individual components as well as an understanding of how they will interact with their surroundings. This document reviews the state of knowledge related to bentonite pellets proposed for use in the deposition tunnel backfill and how they will interact with adjacent sealing materials and the surrounding rock mass.

Two generic concepts for canister installation were developed as part of repository concept development. In very basic terms these options can be described as follows:

The vertical in-floor concept (KBS-3V) has been selected by SKB and Posiva as their reference for use in a repository for spent nuclear fuel (SKB 2007, Posiva 2010). This involves installation of long copper canisters in boreholes drilled in the floor of deposition tunnels (Figure 1-1). The majority of annular gap between the canister and the surrounding rock mass is occupied by highly compacted bentonite clay (and potentially also bentonite granules or pellets to fill annular gaps remaining

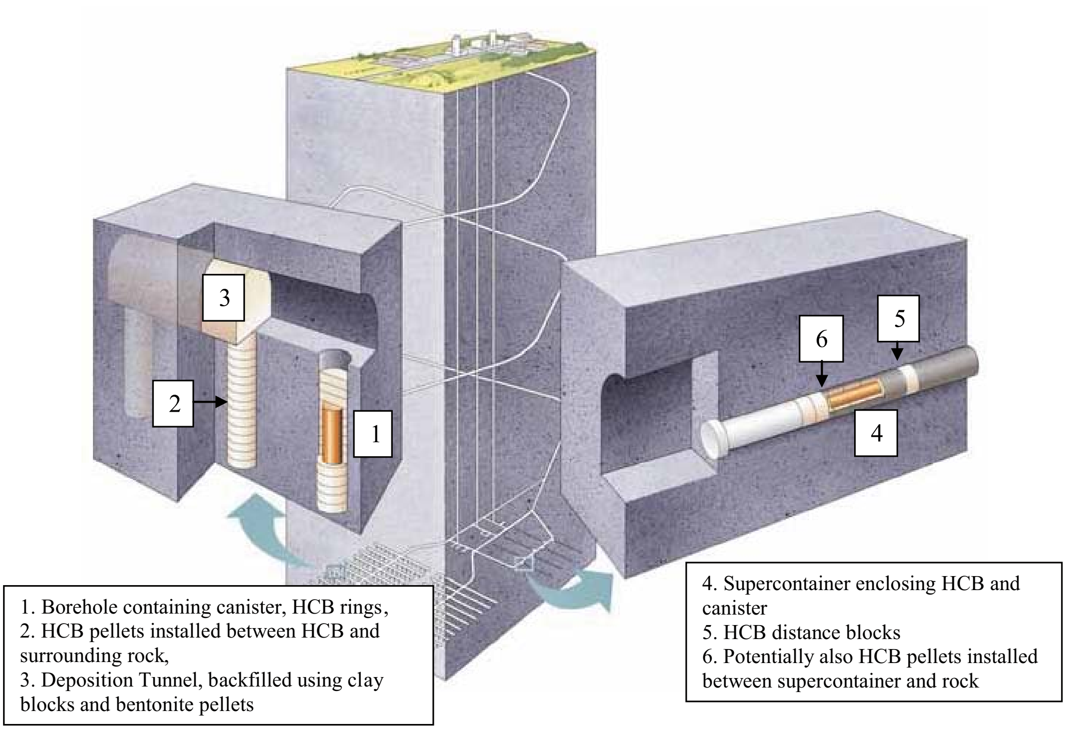


Figure 1-1. *Generic KBS-3V and KBS-3H emplacement concepts.*

following buffer and canister installation). Following canister installation the deposition tunnels are backfilled. At present the reference concept for deposition tunnel backfilling involves use of pre-compacted clay blocks to fill the majority of the tunnel volume and then use of pellets composed of highly compacted bentonite (HCB) clay to fill the remaining volume (Figure 1-2).

The horizontal borehole concept (KBS-3H) is described by Autio et al. (2008), Anttila et al. (2008) and Smith et al. (2007). This concept involves horizontal installation of supercontainer packages consisting of copper canisters and a pre-assembled surrounding of HCB that is essentially identical in composition and density to the buffer component proposed in the KBS-3V concept. Each super-container assembly is kept together through use of a perforated mesh and is installed horizontally in long (up to 300 m-long) boreholes. The geometry of this emplacement concept does not require the presence of a deposition tunnel backfill. It is possible that in order to backfill the access tunnels associated with the horizontal boreholes that pellet materials (HCB pellets) similar to those proposed for the KBS-3Vemplacement tunnels may be needed. If this is the case, then the information developed as part of the KBS-3V deposition tunnel backfill development could be transferred to a KBS-3H backfill.

While both the KBS-3V and KBS-3H concepts are potentially suitable for development, the vertical emplacement concept has been selected as the primary reference geometry (SKB 2007, Posiva 2010). With the 3V concept comes the need to install backfill materials in the deposition tunnels running immediately above the buffer and canister – filled boreholes. It is important to ensure that the back-fill materials installed in these tunnels is capable of effectively isolating the boreholes and can effectively resist any swelling pressure applied to it by the buffer in the underlying boreholes. As part of develop-ing and evaluating canister emplacement options a wide range of backfill materials and construction options have been studied. This work has been summarized by Gunnarsson et al. (2006) who recom-mended that the block and pellet backfilling concept for deposition tunnel backfilling be selected as the reference technique for a KBS-3V repository. Further work on involving materials option evaluation and development of backfill placement approaches is summarized by Keto et al. (2009a).

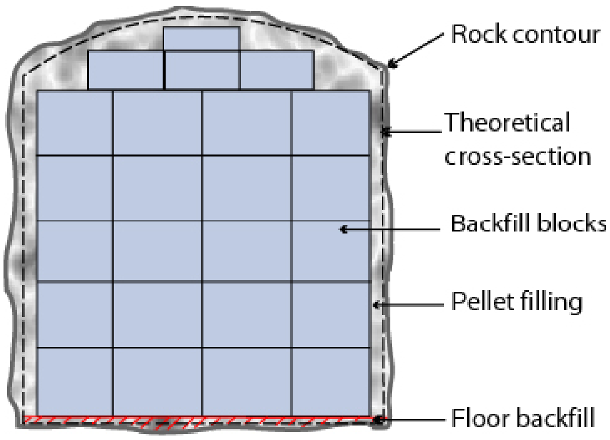


***Figure 1-2.** Cross section of a backfilled KBS-3V deposition tunnel showing the three main components of the backfill. 1) precompacted blocks, 2) pellet fill and 3) material placed under the blocks to provide stable foundation for the blocks (Keto et al. 2009a).*

1.2 Use of clay pellets in KBS-3V concept

1.2.1 Deposition Tunnel Backfilling

It is important to ensure that the backfill materials installed in these tunnels are capable of isolating the boreholes and can effectively resist any swelling pressure applied to it by the buffer in the underlying boreholes. As part of developing and evaluating canister emplacement options a wide range of backfill materials and construction options have been studied. This work has been summarized by Gunnarsson et al. (2006) who recommended that the block and pellet backfilling concept for deposition tunnel backfilling be selected as the reference technique for a KBS-3V repository. Further work on involving materials option evaluation and development of backfill placement approaches is summarized by Keto et al. (2009a).

From the work summarized by Keto et al. (2009a), the process of improving, optimizing and ultimately specifying backfill component materials and their means of manufacture/installation has been initiated. This includes preparation of a state of knowledge summary (this document), identifying how backfill pellet fill might be improved and developing suggestions of how pellet fill materials can be optimised such that the performance of the deposition tunnel backfill can be predicted. Additionally, development of improved materials and methods for their installation will be important in operational planning for a repository.

Gap filling as part of backfill operations has been examined by Sweden, Finland and Canada, with conduct of several laboratory and field studies related to material options and their placement (Gunnarsson et al. 2004, Johannesson et al. 2008, 2010, Sandén et al. 2008, Dixon et al. 2008a, b, 2011, Keto et al. 2009a, Riikonen 2009, Kjartanson et al. 2003a, b, 2005, Martino and Dixon 2007). The pellets to be used in completing the deposition tunnel backfilling process must be such that the backfill barrier can be relied on to exhibit the swelling and hydraulic properties required of it.

1.2.2 Performance required of deposition tunnel backfill

Several basic functional requirements associated with the backfill as a whole have been identified for the SKB and Posiva repository concepts. In both concepts, the use of clay-pellet materials is included in order to ensure that suitable isolation of the excavations is achieved once canister deposition has occurred. Several material options and generic backfilling approaches have been evaluated by Gunnarsson et al. (2006), and how well they met the established performance requirements were discussed in that document.

SKB has developed long-term performance targets for the overall sealing system. This aids in the design and assessment of the performance of the sealing system (including backfill). The subsystem requirements developed are matched to quantitative values derived from the safety indicator criteria defined in the safety assessment SR-Can (SKB 2004). Subsequently the safety functions related to containment were outlined in the SR-Site document (SKB 2010). The SR-Site document summarised some of the key properties required of the backfill component as a whole and identified the following items as being needed for this component in SKB's repository:

- A need to counteract buffer swelling out of the borehole, thereby maintaining buffer density within desired limits (SR-Can Section 8.3.3).
- The backfill should not be a preferred pathway for radionuclide transport and so the following properties are identified as being required:
  - Swelling pressure of > 0.1 MPa.
  - Hydraulic conductivity of < 10^{-10} m/s.
- Temperature of backfill in deposition tunnels must be > –2C.

In Posiva's TKS-2009 report, the safety functions, preliminary system performance targets and target values for various components of a repository were defined. Table 1-1 summarises those associated with backfill and briefly describes the rationale for these requirements. While the information in Table 1-1 is defined for use in Posiva's program, it is consistent with the general goals identified by SKB.

It should be noted that SKB's and Posiva's performance requirements are for the backfill as a whole, there are no clearly defined specifications for the pellet component beyond a need to ensure that the entire backfill remains functional over the long-term. The main roles of the pellet component are to provide lateral support to the blocks, protect them from inflowing/dripping water during the initial stages of system evolution and limit the potential for unacceptable redistribution of the backfill from one region of the deposition tunnel to another by water entering the tunnel. The pellet materials also provide for a greater margin in the functional definitions for the block materials as the pellets occupy volume that the blocks would otherwise have to swell into (especially important in areas with large over-excavated volume).

In addition to the performance requirements for the backfill as a whole there are factors associated with effectiveness and flexibility of the process. The backfilling rate required for the deposition tunnels for the KBS-3V concept is 6–8 m and 5 m per day for the SKB and Posiva repositories respectively (Gunnarsson et al. 2006, Keto and Rönnqvist 2007). Any materials and emplacement options considered or developed must therefore be able to be placed at a rate that meets the production requirements established and the installed materials must be physically stable throughout the operational activities.

Keto et al. (2009b) summarized the deposition tunnel backfill design for a KBS-3V repository, based on identification of critical processes and technical issues. This summary includes much of the information discussed by Keto et al. (2009a) but also identifies inputs needed to resolve some of the outstanding questions and allow for establishment of clearer design bases for backfill and backfilling. Some of the critical processes and technical issues identified by Keto et al. (2009b) as related to backfill wetting, formation of piping features and their evolution, erosion of material following installation and related aspects of system evolution were examined in the ½-scale tests described by Dixon et al. (2011).

Table 1-1. Performance targets for the backfill with possible target values, applicable timeframe and associated rationale as expressed in Posiva's TKS-2009 document (after Hansen et al. 2010).

Performance target	Applicable time window	Rationale
Backfill shall limit the water flow so that transport is diffusion dominated. Hydraulic conductivity < 10^{-10} m/s.	After the target state has been reached, up to one hundred thousand years at least.	Backfill should contribute to favourable conditions for the buffer and canister and limit and retard radionuclide transport in case of canister failure. A sufficiently low hydraulic conductivity is required to avoid significant advective transport along the tunnel and any essential change in bedrock hydrology due to the presence of the tunnels (over the long-term).
Backfill shall ensure a tight contact with the rock wall. Swelling pressure > 200 kPa.	After the target state has been reached, up to one hundred thousand years at least.	Backfill should contribute to favourable conditions for the buffer and canister and to the mechanical stability of the deposition tunnels and near-field rock. It should also limit and retard radionuclide transport in case of canister failure.
Backfill materials should have a sufficiently low compressibility.	After the target state has been reached, up to one hundred thousand years at least.	Backfill should contribute to favourable conditions for the buffer and canister and limit and retard radionuclide transport in case of canister failure. The backfill should be able to limit the expansion of the buffer. It should keep the buffer in place so that the density requirements of the buffer are met.

1.3 Design specifications for a KBS-3V deposition tunnel backfill

The backfill performance requirements presented above can be used as a guide in identifying feasible solutions to selection of material(s), installation design(s), methodologies and quality assurance/control processes that will provide a sufficient safety margin to long-term safety. A list of general design specifications needed for deposition tunnel backfill consisting of pre-compacted clay blocks and bentonite pellets was presented by Keto et al. (2009a) and design factors of particular relevance to the use of pellets in backfilling are summarized in Table 1-2.

From Table 1-2 some general guidelines/constraints can be developed with respect to the pellet component of the tunnel backfill. The density specification for the backfill resulting from the guidelines in SR-Can (SKB 2004) means that the pellet component of the backfill must be able to interface effectively with both the rock and the backfill clay blocks and on saturation not leave any potential for this region to provide a preferential pathway for radionuclide migration away from the deposition holes. In order to accomplish this, the pellet materials must be selected, designed and installed in a manner that will result in effective placement and performance, efficiency in placement operations and long-term stability of the system.

In order to accomplish the performance goals set for the backfill component it is necessary to evaluate both the environmental and operational constraints related to the pellet fill. These constraints are Features, Events and Processes (FEPs) that have an influence on the design and constrain the solutions that can be applied. The key site specific constraints so far identified include:

- 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.

Table 1-2. Design specifications related to pellet materials for backfilling of deposition tunnels (after Keto et al. 2009a).

Design specifications required that affect installation of the backfill	
Density	– Average dry density of the backfill must be able 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 and resulting degree of block filling.
	– Geometry of pellet filled volume.
Backfilling rate	– Installation rate of blocks.
	– Installation rate of pellets.
Design specifications concerning materials and manufacturing of pellets	
Pellets	– Material: required amount of swelling minerals/smecite content, smectite composition, other minerals intentionally added, stray materials.
	– Dry density and water content of individual pellets.
	– Granule size or range of sizes (gradation).

The major constraints related to backfilling and pellet materials in particular identified from the repository design are associated with:

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

How many of these FEPs and constraints will addressed is dependent on the pellet materials that are used in backfilling. In order to effectively address them it is necessary to more clearly define the options available for pellet fill. An important step in this process is to pull together a summary of knowledge related to use of pellet materials in similar geometries and applications. This document provides a brief summary of the work done by various organisations as it relates to use of pellet materials and relates them to the deposition tunnel backfill proposed for a generic KBS-3V repository. From this, consideration is given to the site-specific features known for the proposed repositories at Forsmark and Olkiluoto and how they may affect the design of pellet materials. Additionally, a discussion of what is needed in order to address some of these outstanding issues and ultimately develop a design specification for the pellet component is provided in Section 5 of this document.

1.4 Other Repository concepts that include use of bentonite pellets

1.4.1 Background

Many repository concepts being investigated internationally include use of bentonite pellet materials, either in association with backfill or to fill gaps between the canister and highly compacted bentonite (HCB) clay blocks. In many cases, these fill materials serve the function of both buffer and backfill (e.g. Nagra pedestal concept).

The KBS-3V, KBS-3H concepts and variations on them, are being considered for use by several national programs including Sweden, Finland, Canada, Japan, China, India, Korea and Ukraine. As shown in Figure 1-1 and described in Section 1.1, bentonite pellets are proposed for use as part of both the buffer and the backfill system in most of these concepts. Much of the published work associated with HCB pellets as they relate to repository sealing in Sweden, Finland, Canada and Switzerland has focused on gap filling in the vicinity of the buffer. While often not intended for application in deposition tunnel backfilling, the information related to clay pellet utilisation as a buffer component has application to SKB and Posiva backfill development work.

The evaluation of pellet properties and installation studies undertaken in association with backfill development have generally examined materials options that used commercially available materials. This resulted in limited ability to assess variables such as shape, density and materials as they affect the as-placed characteristics of pellet fill and how this might be engineered.

1.4.2 Horizontal Tunnel Placement (HTP) concept

An emplacement concept being considered by NAGRA and NWMO for use in a sedimentary rock environment involves use of a pedestal composed of HCB blocks to support a canister horizontally installed in a tunnel. Figure 1-3 shows the generic emplacement geometry proposed by Canada's NWMO, other programs such as NAGRA have similar geometries, varying in canister size and tunnel diameter as required by the canister dimensions, mass and heat output as well as the specifics of the geological medium considered. The volume not occupied by the canister and the HCB blocks will be filled with a material containing densely compacted bentonite pellets and a bentonite fines component. (Plötze and Weber 2007, De Bock et al. 2008). In a sedimentary host environment where water influx into the excavations is minimal the pellets still provide a long-term sealing function but more importantly, over the near- and intermediate-term they must be able to effectively conduct heat away from the canister to the surrounding rock mass. This is a challenge for a system where achieving substantive fill density is potentially problematic. Work has been ongoing to quantify the achievable density of the pellet fill and to develop potential material options that might aid in heat transfer and optimize material placement. Although the HTP geometry is much different than that of the KBS concepts, much of the information developed is of use in assessing the options available for the pellet backfill materials that could be used in a KBS-3V repository.

1.4.3 Other applications where HCB pellets are proposed for use

The use of pellets to provide a gap sealing or backfilling function has been investigated by ANDRA and SCK/CEN for use both in sealing the annular gap between a canister and the surrounding geosphere in their horizontal tunnel placement concepts. These concepts vary slightly from those of NWMO and NAGRA in that they have a much smaller volume of initially empty tunnel around them and do not call for a pedestal of highly compacted blocks below them. Examples of these geometries are presented in Section 2.3.4. Pellet materials have also been examined as a component for use in sealing vertical shafts through a sedimentary (clay) host medium. Work was done to characterise and select potentially suitable clay pellet and clay powder mixtures that could be used in sealing a vertical borehole. The results of these studies are presented and discussed in Section 2.3.2.

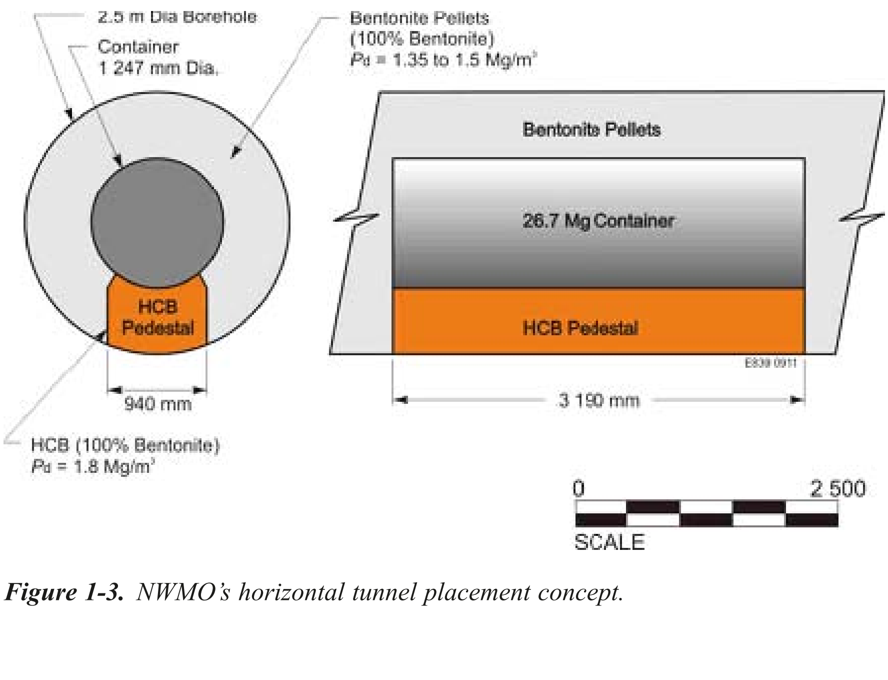


Figure 1-3. NWMO's horizontal tunnel placement concept.

2 Pellet materials options and their use in a repository

As briefly outlined in Section 1, the use of bentonite-based pellet materials has been examined by several national programs considering deep geological disposal of nuclear fuel waste. This section briefly summarizes some of the work done and the results obtained and then discusses how this information can be used to provide a basis for focusing work on materials and installation approaches for pellet materials as it relates to deposition tunnel backfilling. These results also have application to the development of HCB and other pellet materials for use in association with HCB buffer materials in a variety of emplacement geometries.

2.1 Methods to produce clay pellets

Pellets can be produced using two basic techniques; firstly by squeezing through a mould (Extrusion) and secondly by roller pressing. These two techniques are commonly used in industry to produce compacted pellets of various materials and have been demonstrated to be viable for production of bentonite materials.

2.1.1 Pelletizing using extrusion technique

This technique is used in the agricultural industry for manufacture of animal feed pellets, making pellets from wood or bentonite. The aim of this pelletizing technique is normally not to achieve high density materials or consistent sized product (length varies) but to produce physically stable "rods" as a means of packaging the product in an easily handled and utilized form. This technique basically pushes the raw material though a "matrix", normally a roll with holes, which results in a degree of compaction and formation of the cylindrical product, the diameter of these rods can be varied by changing the size of the opening but there are minimum and maximum values that can be practically achieved. Figure 2-1 shows an example of the product produced by this technique.

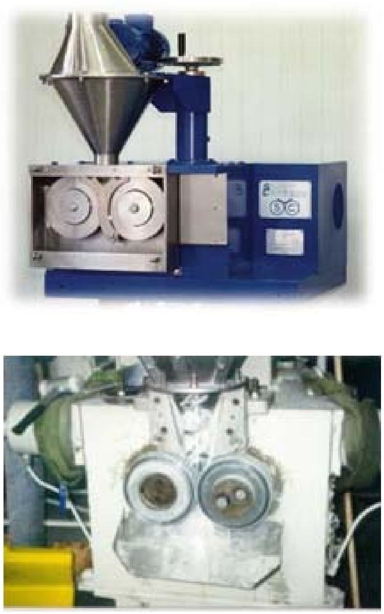
The bentonite rods produced by extrusion have limitations regarding the density to which the individual rods can be produced and can vary considerably in their durability. Examples of some of the density measurements made for bentonite rods are provided in Table 2-1. As well, the non-uniform dimensions and general shape of these materials make achieving high as-placed density somewhat problematic and they tend to bridge during placement. They have been demonstrated to be durable enough to allow them to be "blown" into place using shotcreting equipment (Dixon et al. 2008a, b, Keto et al. 2009a, Riikonen 2009), and so have potential for use in backfilling, especially if some means of installing them in association with materials of differing size can be developed.

2.1.2 Pellet-making by roller compression

This technique was used for making pellets used in numerous studies undertaken over the past 20 years. This is the same basic technology used to produce pharmaceutical tablets as well as a variety of industrial products (examples are coal pellets to provide ease of handling and more uniform burning characteristics and also charcoal briquettes). Using this type of machine, the bentonite is fed by a screw into a small void above to counter-rotating rolls, each containing matching hemispherical voids. The bentonite is compressed into pellets or briquettes between these rolls and exit by gravity from the bottom of the rollers. It is possible to vary the roller speed and the pressure from the screw to change the density of the pellets although beyond a certain rate of material supply and roller speed the improvement in pellet density is minimal and the pellets may actually become more friable. Conduct of trials to determine the optimal settings for the machine and water content for the feed material allows for a consistent product to be produced. Figure 2-2 shows examples of machines used for laboratory-scale pellet-making trials as well as an industrial-scale machine used to mass produce pellet materials.

Roller compression is a well developed technology used to manufacture bentonite pellets used for sealing water wells and has been used to manufacture high density pellets for repository sealing studies. This compaction technique has been demonstrated to be extremely flexible with respect to the range of pellet sizes and densities that can be achieved, see for example Figure 2-1. The bentonite pellets produced have few limitations regarding the density to which they can be produced. Examples of some of the density measurements made are provided in Table 2-1. As well, their highly uniform dimensions allow for blending with other sized materials to improve their as-placed density. They have been demonstrated to be durable enough to allow them to be poured, augered, blown, or compacted into place (De Bock et al. 2008, Nold 2006, Plötze and Weber 2007, Mayor et al. 2005) and so have high potential for use in repository backfilling.

Figure 2-1. *Examples of bentonite pellets used in repository sealing studies. (Upper row are pellets produced using roller compression (briquettes); Lower Left is example of typical extruded bentonite pellet; Lower Right are crushed HCB granules).*



Examples of roller-compression machines for use in laboratory-scale investigations

Industrial-scale roller compression machine (Hosokawa Bepex GmbH)

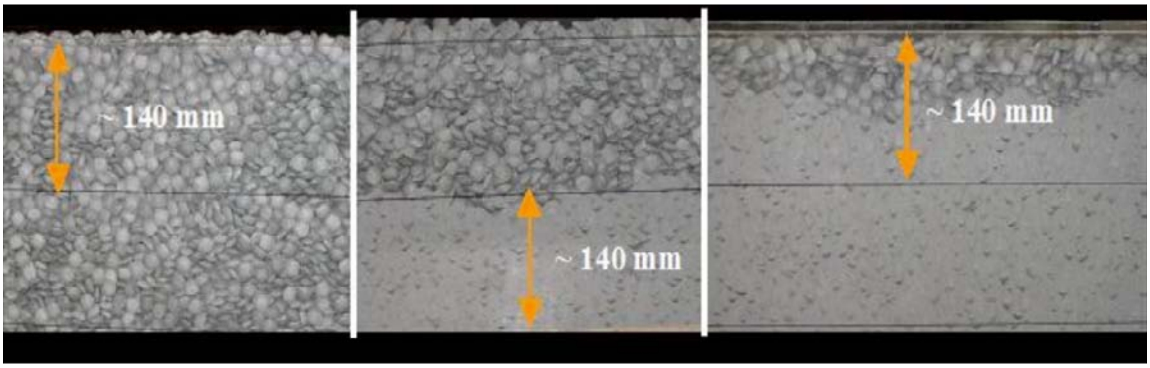
Figure 2-2. *Pellet making using roller compression technique.*

2.1.3 Granulated bentonite

Although not by definition pellets, granulated bentonite or other clay-based materials of preselected size can also be produced by crushing of either raw clay or pre-compacted materials of high density. Crushed materials can be sized and screened to provide graded products that can be used to fill the voids between pellet materials or else on their own as backfilling material. An example of the type of material produced by this crushing process is shown in Figure 2-1.

Granulated bentonite has been demonstrated as being viable for installation either as in situ compacted flooring material for deposition tunnels or for blowing into gaps between backfill and rock (Wimelius and Pusch 2008, Dixon et al. 2005, 2008b, Martino and Dixon 2007).

Although a usable material, there are some difficulties in using granular materials in backfilling of the non-floor regions. Problems are usually associated with maintaining desired particle size gradation, segregation of material sizes during transport and generation of excessive dust during placement. Granular materials also have limited potential for densification during installation and tend to clog installation equipment where water is added to the material during placement. Some success has been achieved in using fine granulated materials as a filler between larger pellets for gap filling in a dry environment (Figure 2-3). Installation of granulated materials will also prove more problematic in a moist environment where water could contact the particles before it reached its desired location within a pellet mass.



a. As-placed Pellets | b. Fines and New Layer of Pellets added | c. Following Vibratory Compaction

Figure 2-3. *Fine-grained (30 mesh) Wyoming bentonite granules used as space-filler in a gap fill installation trial using HCB pellets produced from MX-80 bentonite (Martino and Dixon 2007).*

2.2 Pellet manufacturing trials and material characterisation

In the course of SKB's repository sealing studies and materials evaluations there have been numerous materials production trials and studies related to the ability to place bentonite pellet materials as buffer and backfill components.

Several tests were commissioned by SKB in the late 1990's with regards to manufacture of densely compacted bentonite pellets using the roller compression technique. The same type of laboratory-scale roller compactor as shown in Figure 2-2 was used to evaluate several materials and identify compaction parameters that might be important in determining the quality of pellets produced. The test objectives were:

- to determine if this compaction method was suitable for manufacturing bentonite pellets,
- to determine how the compression force affects the density,
- to determine the influence of water content in the bentonite on the pellets produced, and
- to investigate what pellet density can be achieved.

Several compaction trials were performed as part of this initial screening study and the results are provided Table 3-1.

Using the results of these initial pellet manufacturing trials materials were produced using roller compression that were used in several of the large-scale tests conducted at SKB's Äspö facility. As part of each of these applications, the basic physical properties of the pellet materials were measured and these are also listed in Table 3-1.

A set of scoping tests were undertaken by AECL as part of a review of pellet materials screening to determine options for gap fill between the HCB buffer and the surrounding rock in the IFB concept being considered by NWMO (Martino and Dixon 2007). In these tests materials obtained from a variety of sources were evaluated to determine the density of the individual pellets/granules as well as determining the bulk density of material installed in simulated gaps. Some of the results obtained in the pellet manufacturing trials are provided in Table 2-1.

The Effective Montmorillonite Dry Density (EMDD) values provided in Table 2-1 provide a means of normalizing the behaviour of swelling clay materials (or clay-aggregate mixtures), of various smectite contents based on their swelling clay content. Its significance to the pellet backfill is discussed in detail in Section 3.3.1.

The compaction trials completed in Canada found very similar results to those reported by SKB, the pellets produced are much more sensitive to the water content of the feed material than to the compactive force used to manufacture them. Additionally based on comparison to the results reported by SKB and others, application of very high compressive loads during compaction actually has only a marginal effect on the density achieved. This may be attributed to increasing resistance to closer particle packing as the pellet materials approach saturation. This is a combination of increasing inter-particle repulsive forces as density increases (surface charge on clay particles), increasing degree of water saturation of the pellets resulting in more resistance to further compression and non-linear increase in mechanical resistance to particle realignment as the system density increases (more and more force is required to force individual particles into closer arrangement as density increases).

Pellet manufacturing has also been reported in association with the work at Nagra's Horizontal Tunnel Placement concept as well as sealing studies related to work done at the Hades URL in Belgium. These studies have examined pellets manufactured using Serrata and FoCa (Ca-bentonites) and Boom Clay. The data listed in Table 2-1 shows that these materials typically compacted to a higher dry density than were observed for Na-bentonite materials but that is not unexpected given their lower swelling capacity (Ca, Mg dominated exchange sites in smectite clay component) and in the case of Boom clay, much lower swelling clay content (~48% versus > 75%). It is commonly observed that clays containing low/no swelling clay content or calcium-smectite are able to be compacted to higher dry density for a given compactive effort than are materials prepared using a material rich in sodium – smectite.

Table 2-1. Clay pellet manufacturing experiences.

Material Tested	Force on Rollers	Pellet Size (mm)	Water Content (%)	Pellet Dry Density (kg/m^3)	Pellet EMDD (kg/m^3)	Notes
MX-80	16.4 kN/cm	13×13×6	10	1,910	1,749	Unpublished data; Clay Technology
MX-80	16.4 kN/cm 7.8 kN/cm	“ “ “ “	18 18	Nil* 1,740	1,562	“ “
MX-80	7.8 kN/cm	“ “	10	1,850	1,682	“ “
MX-80	16.4 kN/cm	13×13×6	14	Nil*	–	“ “
MX-80	16.4 kN/cm	30×20×12	10	NM*	–	“ “
MX-80	16.4 kN/cm	30×20×12	14	1,750	1,573	“ “
MX-80	16.4 kN/cm	16×16×8	12	1,700	1,520	Martino and Dixon 2007
MX-80	16.4 kN/cm	13×13×6	10	1,900	1,738	Gunnarsson et al. 2001; Buffer gap fill BaPT
MX-80	16.4 kN/cm	13×13×6	13	1,760	1,584	“ “ CRT: Dh1
MX-80	16.4 kN/cm	13×13×6	13.5	1,750	1,573	“ “ CRT: Dh2
MX-80	16.4 kN/cm	13×13×6	13.1	1,740	1,562	“ “ CRT: Dh3
MX-80	16.4 kN/cm	13×13×6	12.8	1,770	1,593	“ “ CRT: Dh4
MX-80	150–200 MPa		5	2,000–2,100	1,850–1,966	Karnland et al. 2008
MX-80			1.9 4.4	2,320 2,170	2,230 2,048	Pellets subsequently crushed, sized and blended Blümling and Adams 2008
70% MX-80 30% sand	150–200 MPa		5	2,000–2,100	1,850–2,100	Karnland et al. 2008
MX-80	150–200 MPa		2	2,060–2,160	1,919–2,037	Pusch et al. 2002
MX-80		18×18×8	11.3	1,780	1,606	Sandén et al. 2008
Wyom.	10.3–17.2 MPa	25×10×5	10.7–11.4	1,840–1,860	1,671–1,693	#16 and #30 mesh clay; Martino and Dixon 2007
Wyom.	10.3–17.2 MPa	25×10×5	11.6–11.9	1,860–1,880	1,963–1,715	Martino and Dixon 2007
Wyom.	10.3–17.2 MPa	25×10×5	13.2	1,900	1,738	10% crushed pellets; Martino and Dixon 2007
Wyom.	Commercial Products	¼” tablets ½” tablets 3/8” tablts		1,420–1,620 1,490 1,550	1,230–1,435 1,301 1,363	Martino and Dixon 2007
Serrata	Roller	0.4–2	3.3	2,130	2,000	Mayor et al. 2005
Serrata	Roller	> 7	3.3	2,130	2,000	Mayor et al. 2005
Friedland	Roller		14.4	1,810	1,638	
Friedland	Granules/flakes	~8×8×4	7.1	1,995–2,075	1,521–1,627	Sandén et al. 2008/Unpublished data; Clay Technology
Cebogel	Extruded	Rods, d=6.5, L=5-20	18.9	1,720	1,541	Sandén et al. 2008/Unpublished data; Clay Technology
Cebogel:	Extruded			2,100	1,966	Keto et al. 2009a
Cebogel:	Extruded		16	1,810	1,638	Dixon et al. 2008a, b
Kunigel VI	Isostatic 200–600 MPa	1-11		2,000–2,250	1,850–2,144	Spheroids from blocks (Wada et al. 2002)
Minelco	Crushed		19.1	1,670	1,488	Sandén et al. 2008
FoCa	Roller			2,100		Volckaert 2000
FoCa	Roller	25×25×15		1,890		Imbert and Villar 2006
Boom Clay	Roller			2,100	?	Volckaert 2000

* Pellets could not be produced, raw material was too wet or tended to split along axis.

NM Property not measured; BaPT Backfill and Plug Test; CRT – Canister Retrieval Test; PR – Prototype Repository Test; Dh – Deposition hole.

? Mineralogy uncertain or smectite content too low for EMDD parameter to be useful.

The main conclusions that can be drawn from the data provided in Table 2-1 are:

1. A range of pellet sizes can be produced without altering the compactive effort needed to make them.
2. Sodium bentonites having high smectite content (> 75%) show similar compactive properties.
3. Pellet dry density of 1,700 to 1,900 kg/m^3 can be readily manufactured from sodium bentonite clay using available technology.
4. Pellet strength and density can be optimized through water content control and type of raw material fed into compactor.
5. Pellet density achieved for a particular material using roller compaction technology is not especially sensitive to compressive force once approximately 10 MPa is exceeded. In order to substantially increase the density achieved it is necessary to increase the compressive force by more than an order of magnitude (to > 100 MPa).
6. Clays having exchange sites dominated by Ca, Mg can be compacted into pellets having higher dry density than for Na-dominated clays.
7. Clays having a lower swelling clay content can be compacted into denser pellets.
8. Use of extrusion technology to produce densified bentonite rods is more susceptible to variation in the product produced, and the rods are not of uniform size. This may make development of a material that can be placed consistently problematic but does not eliminate this product from consideration.

Only one reference could be found that related to production of pellet materials through blending with non-clay material (Karnland et al. 2008). That paper did not provide any details regarding pellet size, mechanical or other properties but that pellets could be produced is encouraging regarding the potential for developing specialty pellets for improving thermal, mechanical or erosion-resistance of gap fill materials for repository use.

2.3 Laboratory and field demonstrations of bentonite pellet Placement

2.3.1 Pellet placement studies in Sweden and Finland

A number of joint and independent studies examining use of bentonite pellets in association with both the buffer and the backfill have been completed by SKB and Posiva. These studies have examined HCB pellets for potential use in filling the buffer-related gaps in both the in-floor and horizontal emplacement geometries described in Section 1.1 as well as the spaces in the deposition tunnel perimeter which cannot be filled with precompacted backfill blocks.

Buffer Gapfill

The use of HCB pellets as a fill material between the buffer and the surrounding rock in the KBS-3H geometry has received considerable attention within SKB's program. HCB pellets have been installed in a variety of laboratory-scale mock-ups as well as in a number of full-scale experiments conducted at SKB's Äspö laboratory (e.g. the Temperature Buffer Test, Prototype Repository; Canister Retrieval Test). In these tests only a limited range of sizes could be examined due to limited options available from suppliers of these materials. Work related to filling the space between the buffer and the canister or rock has focused on roller-compacted pellets due to their higher initial density, uniform size and generally more robust nature. Studies also examined the key behavioural issues associated with the way in which water entering a pellet filled gap would move in the period prior to completion of deposition tunnel backfilling (water distribution, potential for erosion by inflowing water) (Sandén et al. 2008, Johannesson et al. 2010).

All of the studies done on gap fill found that there were limitations with respect to the density to which they could be placed in a deposition borehole. This means that there are limitations regarding the ability for heat to be transferred from the canister to the surrounding rock mass, which affects (increases) the temperature developed at the canister surface. A listing of some of the typical as-placed density values obtained is included in Table 3-2. Based on the results currently available the only effective ways to improve the as-placed density of a pellet GF would be to: increase the density of the pellets; find a means of installing graded materials that avoids tendency for such materials to segregate during handling and installation; improve technological means to improve the density to which the pellet fill can be installed; or look at options that would allow for improvement of the thermal characteristics of these pellets.

Pellets associated with deposition tunnel backfilling

Pellets for use as a component in deposition tunnel backfilling have been examined in a number of SKB and joint SKB-Posiva studies and experiments (e.g. Gunnarsson et al. 2001, Börgesson et al. 2002, Dixon et al. 2008a, b), as well as similar studies undertaken in Finland by Posiva (Hansen et al. 2010, Riikonen 2009).

Field and field-scale studies undertaken using mock-ups at 1/12th and ½-scale were completed in the joint SKB-Posiva Baclo and Base projects. These studies included focussed work on the use of pellets to fill the gaps between the backfill and the surrounding rock and have been summarised in the report by Keto et al. (2009a).

Posiva also undertook a series of mockup tests as part of their BACEKO project where backfill blocks composed of 60% aggregate and 40% Milos bentonite were used in association with Cebogel extruded bentonite pellets. These BACEKO tests were undertaken to examine materials options that were more Olkiluoto-specific (e.g. using a 3.5% percolating solution rather than the 1% used in the large-scale mock-ups of SKB and use of different materials for backfill block construction). The results of the Posiva study are reported by Riikonen (2009) and Hansen et al. (2010).

Laboratory studies focussed on more generic behavioural evaluation of the backfill system undertaken in the joint Baclo project are summarised by Keto et al. (2009a). These examined some of the basic material characteristics of available materials (density, durability (mechanical and hydraulic), water uptake and movement). Only a limited range of pellet sizes were examined in the course of this backfill development work due to limited options for their acquisition from existing manufacturers, but materials produced by roller-compaction, extrusion and crushing techniques were examined in laboratory-scale studies.

Laboratory tests on pellet materials considered for use as part of deposition tunnel backfilling have been reported on by Sandén and Börgesson (2008), Sandén et al. (2008) and Johannesson et al. (2008). Two important properties investigated regarding bentonite pellet when used in the slot between high compacted bentonite blocks and a tunnel wall were the wetting behaviour i.e. the ability of the pellet filling to store water and the sensitivity for piping and erosion. Other properties investigated are e.g. the healing ability after a piping scenario and the homogenization of backfill blocks and bentonite pellets. The materials investigated in these laboratory tests were both roller compacted pellet (MX-80 bentonite), extruded pellet (Cebogel QSE) and granules (Minelco and Friedland).

The test equipment for the piping/erosion measurements consists of Plexiglas tubes with an inner diameter of 0.1 meter and a length of 0.5 meter, see Figure 2-4. The tubes can be connected to each other in order to vary the test length. The tubes were filled with the pellets material. In one end a steel lid was mounted from which different water flow could be applied. The other end was covered with a perforated plate. The discharged water was collected and the amount of eroded material determined.

The wetting behaviour was tested in a simulated gap, 2×1×0.1 m (Figure 2-5). The artificial slot, simulating a part of the slot between backfill blocks and tunnel surface, had walls made of Plexiglas which made it possible to follow the wetting development from outside. The slot was filled with pellets and water with constant flow rate was applied in a point flow as shown in the picture. Besides studying of the wetting development also erosion measurements were made in this test setup. An additional aim with this test was to check the stability of a pellets slope when exposed to a water inflow. In the course of these tests it was observed that water uptake and transmission characteristics changed with the nature of the pellet materials which indicates that the texture (mode of manufacturing) and shape will affect the hydration behaviour of dry, pellet-only systems.

Figure 2-4. *Photo of the test equipment used for piping/erosion measurements.*

Figure 2-5. *Photo of the test equipment used for studying the wetting behaviour.*

Despite some of the limitations related to gap dimensions and uniformity, intermediate to field-scale tests have provided valuable information related to materials selection, placement and subsequent interaction with inflowing groundwater. Trials have included installation of materials using dry-pouring and blowing using shotcrete technologies, as shown in Figure 2-6 and Figure 2-7. Some typical results from these trials are provided in Table 2-3. The as-placed density of the pellets is still lower than would be necessary for long-term performance of the backfill but the subsequent swelling of the adjacent, much denser clay blocks will result in compression and densification of the pellets. On equilibration, the pellet-block system is expected to meet or exceed the requirements set for the hydraulic and swelling properties of the deposition tunnel backfill.

These ½-scale simulations confirmed that installation of any type of dry pellets in a KBS-3V deposition tunnel geometry will be problematic as pellet fill has a very low angle of repose and so very long distances are required before fill can be placed to tunnel roof elevations (Figure 2-6). Dry pellets placed by blowing rather than pouring have the same low angle of repose and blowing dry materials results in increased pellet damage during placement and increased dust generation (which is detrimental both operationally and with respect to worker safety). Associated with this is a lower as-placed density than can be achieved when water is added during installation and a much lower density of material in the uppermost regions of the tunnel.

***Figure 2-6.** Placing dry Cebogel QSE pellet materials into space between backfill blocks and chamber wall in ½-Scale Experiment at Äspö. (Note slumping of pellets and need to install temporary wooden wall to keep dry pellets in place).*

If pellets are installed by blowing (shotcrete technology) there is the ability to add water to the material as it is being placed. The result of this is the ability to install pellets as near-vertical volumes and achieve a denser and more consistent material into the gap (Figure 2-7). Some of the typical results obtained in mock-ups done at SKB's Äspö laboratory are provided in Table 2-3. Pellets produced using both roller compression and extrusion have been used in the trials conducted by SKB. It has been noted that the extrusion-generated rods tend to be more variable in terms of their size, density and durability than were the roller-compressed materials. This may have importance with respect to as-placed densities and other hydro-mechanical properties of this component but as-yet there is insufficient information available to make a definitive judgement regarding this. Dense, single size pellets also have potential issues related with them, they have less fines and so can be more difficult to place in near-vertical orientation, they also are harder and more likely to bounce back from the installation face (rebounding), resulting in a more problematic installation process and the need to deal with the rebound materials. Finally, a single-sized fill material will tend to have a lower packing efficiency than materials that contain a range of sizes, resulting in a lower as-placed density for the single-size materials.

***Figure 2-7.** Tests to evaluate ability to place Cebogel QSE backfill pellets in ½-Scale tunnel simulator. (Moisture added to pellets during blowing resulting in ability to place pellets easily and in near-vertical manner.)*

2.3.2 Pellet development and placement studies in Belgium

Work associated with clay pellets for use in backfilling was done in Belgium as part of two major studies related to sealing of vertical excavations. These sealing studies focussed on large-diameter vertical boreholes and so the results must be evaluated carefully when comparisons to what could be achieved in backfilling of deposition tunnels. This is largely associated with the geometric differences, the installation and compaction of materials in a vertical orientation is less problematic that in a horizontal application. In the vertical orientation, fill materials remain in the location they are installed and so compaction is possible without issues of pellet fill slumping that occurs when a horizontal opening is being filled. The pellet development work done as part of the Bacchus 2 and Reseal projects at the Hades URL at Mol is however of particular relevance to backfilling of the gap between HCB buffer and the surrounding rock in the deposition borehole. It also has application in potential for use of this type of materials in shaft sealing. Material production and behaviour-related issues identified and discussed as part of these projects also provide background information for use in guiding additional work.

The Bacchus 2 project

The Bacchus 2 Project was sponsored by European Commission in co-operation with ENRESA and ANDRA with CEA as the main subcontractor (Volckaert and Bernier 1996). This experiment was intended to optimize and demonstrate the installation of a clay-based backfill for use in sealing a large-diameter vertical borehole. The backfill material installed consisted of a mixture of high density clay pellets and powder and work done in support of this project included:

- **Study and optimisation of potential backfill materials**
  The sealing material installed in the borehole consisted of a mixture of clay pellets and clay powder. The preparatory studies examined the ratio of clay powder to pellets and the density, size and water content of the pellets were examined as part of the optimisation process. Laboratory experiments were done as part of this evaluation process in order to determine the hydraulic conductivity and the swelling pressure.
- **In situ demonstration of backfill Installation and behaviour**
  The field demonstration done as part of BACCHUS 2 involved the sealing of the large borehole (50 cm diameter) left after the retrieval of the BACCHUS 1 mock-up at the HADES URL (Mol, Belgium). In the backfilling process, granular backfill material was installed around a central filter tube that was used as support and access tube for the instrumentation.

The production of the granular backfill material consisted of the following four steps:

1. Drying of the unprocessed, excavated clay.
2. Grinding of the dried clay.
3. Compaction of the clay powder to pellets.
4. Mixing the pellets with clay powder.

Compaction trials were completed using the roller compression technique described in Section 3.1 and produced pellets of Boom clay (from the Mol site) and the French FoCa and Spanish S2 calcium bentonites and densities of about 2,100 kg/m^3 could easily be produced using these materials . The Boom Clay pellets were used in the field application and were mixed in equal mass ratios with dry powdered Boom clay and compacted by vibration, achieving an as-placed dry density of about 1,700 kg/m^3. A swelling pressure of 0.6 MPa and a hydraulic conductivity as low as $1 \cdot 10^{-11}$ m/s were measured for this material.

The Reseal project

The RESEAL project started in 1996 within the framework of the EC specific RTD programme on "Nuclear Fission Safety" (Volckaert 2000). The stated objective of the project was to demonstrate the sealing of a borehole and a shaft in plastic clay using bentonite-based materials.

Reseal activities included selection of the clay to be used and then at the HADES URL (Mol, Belgium) to:

- demonstrate installation technique(s) for the backfilling and sealing of a 1.4 m diameter shaft,
- demonstrate that a low permeability bentonite seal can avoid preferential migration of water, gas, and radio nuclides along or through the seal or even through the excavation disturbed zone around the seal,
- validate models for the transfer of gas and water through the sealing system including geomechanical aspects,
- demonstrate sealing of boreholes.

Two materials were initially studied for potential use in the field test, a French bentonite (FoCa clay), and a Spanish bentonite (Serrata clay). Both clays were studied in laboratory tests and the FoCa clay was used in the in situ shaft sealing test. Testing of these candidate materials included:

- production of pellets and optimisation of the powder/pellets mixture,
- laboratory experiments to determine their swelling and hydraulic properties, and
- shaft sealing demonstration test.

Screening and characterisation tests related to the production of pellets determined that:

- the pellet production is most efficient (high density and physically robust pellets) when the granules are fine, (< 3 mm diameter),
- the settings of the compaction parameters of the compaction process, rotation speed, powder flow, etc., are important to obtain good quality and high density of the pellets,
- the water content of the clay fed into the compactor has a large influence on the quality of the pellets; but each material had different water-densification characteristics, and
- the highest dry density for the FoCa clay was obtained at a gravimetric water content of 7%.

Powder/pellet mixture compaction trials using the FoCa clay found that a ratio of 65% pellets and 35% powder gave the best dry density under carefully controlled conditions but this ratio tended to segregate during handling and compaction and long hydration time. A 50/50 mixture was less prone to pellet-powder segregation and so was chosen for field installation. A dry density between 1,400 and 1,600 kg/m^3 was achieved in compaction trials and when the shaft was sealed a compacted dry density of 1,550 kg/m^3 was measured. Figure 2-8 shows the shaft sealing materials installed in the Reseal Project's field demonstration. The gravimetric water content of the clay powder was 7 +/– 1.5% and the grain size 0–2 mm. The compaction was made in 15 cm thick layers with a vibro-compactor designed for the test. The vibrocompactor is essentially a rod that is attached to a vibratory energy source (e.g. concrete vibrator used to deair and settle wet mix), the vibrations are transmitted via the rod to the surrounding pellets, resulting in an improved particle packing geometry. At the end of the vibratory process the rod is withdrawn from the clay mass. This technique has also been successfully utilized in several experiments undertaken by AECL (Section 3.3.3). The dry density of loosely poured material in the Reseal test was measured to be 1,400 kg/m^3.

Figure 2-8. *Pellet – clay material installed in Reseal Project's field demonstration (Gens et al. 2009).*

2.3.3 Pellet development work in Canada

Pelletized and granular materials for use in filling the spaces between a canister/buffer installation and the surrounding rock mass (Gapfill) as well as using densely compacted pellets as a backfilling component in deposition tunnels are both relevant to NWMO's repository sealing concepts and have been the topic of ongoing studies in Canada.

Gapfill (GF)

For the repository concepts currently under consideration by NWMO, the GF, despite its small volume relative to the other sealing materials is recognized as being important with regards to determining the performance of the system. It is assumed that as the HCB buffer hydrates, swells and generates high-swelling pressures, the adjacent gap-fill materials will compress and any other remaining gaps or voids will be filled. The amount of HCB expansion into adjacent regions is directly related to the volumes and densities of the HCB and adjacent GF. In time and following water saturation, compositionally-similar HCB and GF portions will evolve towards a system that is more homogeneous with respect to density than was present at the time of installation. The degree to which such homogenisation will progress is still a topic of investigation.

In order to provide the region surrounding the canister with adequately low permeability, sufficiently high swelling pressure and adequate thermal conductivity the density of the material occupying this volume needs to be maximized. Additionally, microbial activity at the surface of containers may lead to microbially induced corrosion (MIC) and to discourage such microbial activity, a high buffer density is needed (Stroes-Gascoyne et al. 2005, Kjartanson et al. 2003a). The only way to effectively accomplish these requirements is to find a material that can effectively fill these gaps without compromising the hydro-thermal-mechanical-chemical-microbial properties of the buffer, or adjacent sealing materials.

Bench-scale studies of GF placement technologies and achievable densities were performed at AECL's Underground Research Laboratory (URL) with the intention of determining the EMDDs that could be achieved using simple and practical placement technologies. The results of these tests were then evaluated to determine what an equilibrated GF and HCB system would have in the way of thermal, hydraulic and swelling characteristics (Dixon et al. 2005). Based on these assessments and comparison to the requirements of the sealing system, it was possible to make a preliminary evaluation as to the suitability of potential GF materials options.

A variety of filler materials were investigated including high-density precompacted pellets, crushed bentonite granules and blends of pellets and aggregate materials (Martino and Dixon 2007, Baumgartner and Snider 2002). GF placement trials were done at bench-scale using a range of granule/pellet sizes and gaps of 10 to 50-mm wide. These trials were conducted under dry conditions and made no attempt to simulate a borehole into which water was actively flowing. Into these dry gaps, particulate materials were poured either with or without subsequent mechanical vibration or tamping. GF materials consisting of densely compacted bentonite pellets and granular fines could be readily placed at EMDDs ranging from ~800 kg/m^3 for 10-mm gaps to ~900 kg/m^3 for 50-mm gaps (Kjartanson et al. 2005). Later studies by Martino and Dixon (2007) were able to improve the as-placed EMDD of the gap fill to 1,100–1,250 kg/m^3 for gaps of 50 mm dimension through use of pellet-fines mixtures and low-energy vibration (Figure 2-9). A summary of these results is included in Table 2-2.

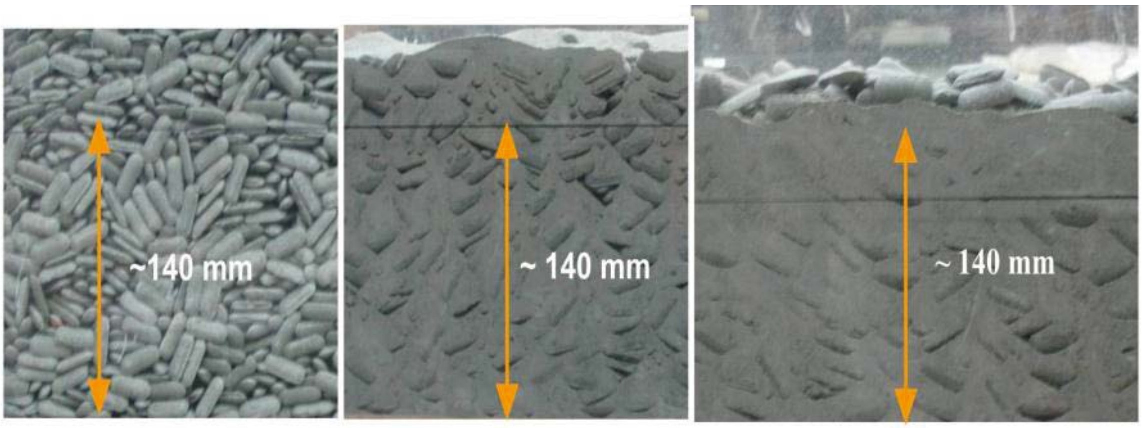
The results of GF placement studies undertaken in Canada are included in Table 3-2 and are very comparable to those obtain by studies undertaken by other organisations. These studies did not attempt to optimize the GF materials with respect to density or composition, factors recognized as being important to determining both the short-term thermal and longer-term T-H-M properties of the canister-buffer-gapfill system. Work is ongoing and planned that will focus on development of pellets composed of HCB or densely compacted bentonite-admixture blends. This will include consideration of pellet shapes, size gradation and non montmorillonite materials that could improve the as-placed characteristics of the GF materials.

Deposition tunnel backfilling

The work undertaken by AECL in developing bentonite-based backfill materials that could be used to fill crown and perimeter regions of a generic repository tunnel has direct application to the installation of materials into the perimeter and crown regions of the deposition tunnel in the KBS-3V concept.

As outlined previously, the various repository concepts considered by in the Canadian program (excepting the HTP concept) all include a backfill component that filled volumes in the deposition tunnels that could not be dealt with using block or in situ compaction approaches. This backfill component is referred to as Light Backfill (LBF) in the Canadian concepts and the composition considered for this backfill component ranges from 30% clay–70% aggregate blends to 100% HCB pellets, depending on the particular deposition concept considered and the purpose of the fill at that location.

In the course of developing these LBF materials AECL has undertaken several backfill development and installation exercises, ranging from small bench-scale tests through to field placement trials as shown in Figure 2-10. Typical results obtained in the course of these trials are provided in Table 2-3. The densities attained in these trials were low relative to the HCB and buffer components of the sealing system but were sufficiently dense to provide constraint to the other sealing components. It should be noted that the results of these tests are comparable to those obtained by the various studies undertaken by SKB (see Table 2-3). Like the SKB results, the EMDD values of the LBF materials developed by AECL are not by themselves adequate to ensure that the system can provide the long-term swelling and hydraulic requirements of the backfill unless they are compressed by the adjacent backfill components. Further work to refine placement technologies and to improve densities for



a. As-placed HCBPellets b. Fines Poured c. Following Vibratory Compaction

Figure 2-9. *Installation of pellet and fines materials (Dixon et al. 2005).*

Figure 2-10. Installation of bentonite-based LBF materials to fill rough-surfaced mock-up and real excavation at 420 m level at AECL URL. Upper: backfilling of a simulated deposition tunnel roof section (Martino and Dixon 2007); Lower: installation of bentonite-aggregate filler materials to provide a continuous contact between rock and clay blocks in AECL's Tunnel Sealing Experiment (Chandler et al. 2002, Martino et al. 2008).

LBF were continued as surface and laboratory studies at AECL's Underground Research Laboratory (Baumgartner and Snider 2002, Dixon et al. 2005, Martino and Dixon 2007) and are the subject of ongoing studies.

2.3.4 Pellet development in Switzerland, France and Belgium

Installation of pellet-type backfill for the NAGRA Pedestal concept was done in 2002 at Mont Terri as part of the Engineered Barriers Emplacement Experiment shown in Figure 2-11 (Mayor et al. 2005). In this study, an auger technique was used to install a graded mixture of bentonite pellets produced from the Spanish Serrata clay (Ca-bentonite) that had a low (3.3%) water content using a commercial briquetting machine (Mayor et al. 2005). The size of the materials produced for use was either > 7 mm or else fell in the range of 0.4 to 2 mm. The coarse material had an average bulk density of 2,180 kg/m^3 with a gravimetric water content of 3.3% (dry density of 2.11 Mg/m^3). The fine materials had a pellet bulk density of 2,210 kg/m^3 with a water content of 3–7% (dry density of 2,130 kg/m^3) (Mayor et al. 2005). Despite the very high granule densities the field placement only achieved an overall dry density of 1,360 kg/m^3. This was less than the 1,400 to 1,500 kg/m^3 expected based on previous smaller-scale tests and was attributed to experimental obstructions that would not have been present in an actual repository situation and the way that the auger was operated during placement (Mayor et al. 2005).

This auger placement method involves use of 2 (or more) auger-fed pipes that are pushed a short distance into the face of the region to be filled with bentonite granulate. The bentonite material exiting the pipes is compressed by their pushing against the passive resistance of the materials surrounding the mouth of the pipe. These pipes are gradually withdrawn resulting in a densified (relative to passive pouring of dry materials), bentonite fill. The less-thn-desired densification obtained in these initial trials indicate that some further material or technology improvements are still needed if higher as-placed densities are to be achieved using this technology.

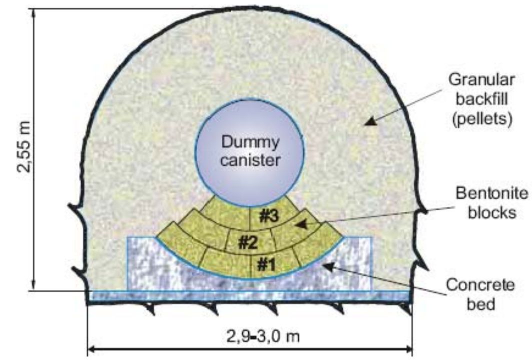


Figure 2-11. *NAGRA Engineered Barriers (EB) Test (Mayor et al. 2005).*

Work has been done in the laboratory and at the Grimsel test site to evaluate bentonite granules produced by crushing pellets manufactured by roller compacting MX-80 bentonite (Blümling and Adams 2008). These tests were largely associated with sealing of boreholes but the application does have relevance to filling larger voids. In these trials dry densities in the order of 1,500–1,600 kg/m^3 were reported for carefully blended materials and substantially lower (1,100–1,300 kg/m^3) for less ideally blended size distributions (Table 2-3). Given the ideal orientation for material placement and compaction (vertical, small diameter boreholes and subsequent in situ compaction) it is unlikely that graded materials of the type installed in these studies could be effectively placed in a horizontal tunnel to the densities reported by Blümling and Adams (2008) but the information does have potential relevance to gap filling in the KBS-3V borehole (provided it is dry).

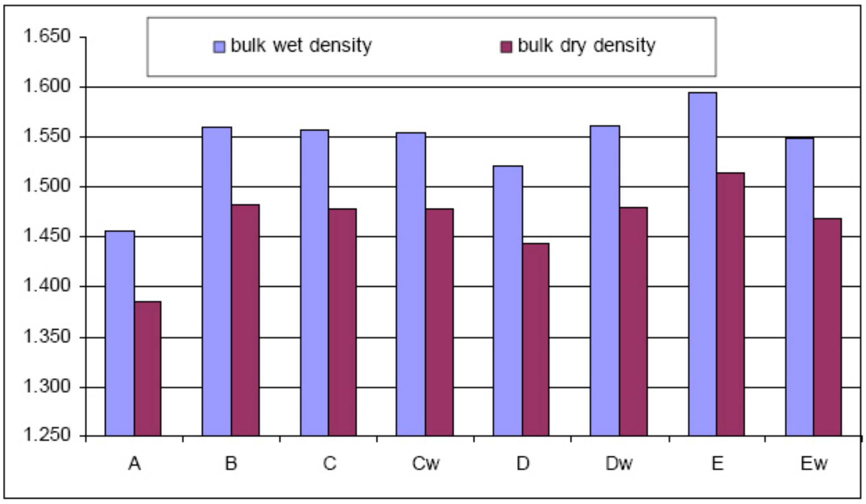
Recent work associated with improving the technologies that may have application to deposition tunnel backfilling has been reported within the ESDRED Project (Plötze and Weber 2007, De Bock et al. 2008). Within ESDRED, NAGRA has extended the work at Mont Terri to include testing and demonstration of granular buffer materials at full-scale to determine if the density specifications required for the buffer can be met in a field environment. These trials used Wyoming bentonite (MX-80) as the base material rather than the Ca-materials used previously. This bentonite was run through the same granulation process as was reported for the 2002 work and the individual granule dry density was raised from 1,170 kg/m^3 of raw bentonite to 2,100 kg/m^3 for compressed material.

Using the same twin auger emplacement and compaction tool used previously (Figure 2-12), granulated, blends of granules of differing size, or blends of granules and pellets were installed at full-scale in Mont Terri. As-placed dry densities obtained for these materials are shown in Figure 2-14. These data indicate that it may be possible to improve the as-placed density of the installed pellets through engineering of the size composition of the installed materials (De Bock et al. 2008).

Figure 2-12. *Placement trials of tunnel fill using twin-auger technique. (De Bock et al. 2008: Note NAGRA canister-sized cylinder placed in tunnel.)*

These pellet studies also included evaluation of the Horizontal Tunnel geometry considered by ONDRAF/NIRAS (Belgium) where pellets could be used to fill the gap between the supercontainer and the surrounding sedimentary medium as shown in a mockup used to evaluate pellet placement options (Figure 2-13). The mixtures examined in placement trials done using air-entrainment (blowing), showed an improvement over the single-sized materials examined previously. The density obtained was still found to be material and technique sensitive. Figure 2-14 shows some of the results obtained using the twin-auger technique shown in Figure 2-12. This technique allowed for an improved as-placed dry density to be achieved (densities of 1,450–1,500 kg/m^3), but still exhibits variability within the as-placed mass of clay.

Figure 2-13. *Emplacement trials for granular materials around supercontainer of type considered by ONDRAF/NIRAS, air-entrainment only (De Bock et al. 2008).*



A 100 % coarse rounded granular material, embedded in two layers
B 92 % coarse, 8 % fine, two layers
C 85 % coarse, 15 % fine, two layers
Cw 85 % coarse, 15 % fine, two layers
D 70 % coarse, 30 % fine, two layers
Dw 70 % coarse, 30 % fine, repeat run, two layers
E 64 % coarse, 28 % fine, 8 % briquettes, two layers
Ew 64 % coarse, 28 % fine, 8 % briquettes, repeat run, only one layer

Figure 2-14. *As-placed densities achieved using HCB pellet – HCB granule mixtures in the Horizontal Tunnel Placement Geometry installed using twin auger technique (Nold 2006, Fries et al. 2008).*

Table 2-2. Properties of bentonite pellets, granules and granule-pellet blends for use as gap fill in deposition boreholes (Typ. 50–70 mm gap width).

Material	Pellet Size (mm)	Pellet Production Method	Pellet Dry Density (kg/m^3)	Dry Density Placed Material (kg/m^3)	EMDD (kg/m^3)	Notes	Reference
MX-80	13×13×6	roller	1,910	1,160	980	Backfill Plug test	Gunnarsson et al 2001
MX-80	30, 12.4	roller	2,400	~1,800	1,627	2-size blend.	Salo and Kukkola 1989
MX-80		roller	2,050–2,150	~1,500	1,310	Reported properties	Pusch et..al 2003
MX-80	16.3×16.3×8.3	roller	1,740–1,870	970–1,150	800–970	Prototype Repository	Sugita et al. 2003
			1,790–1,920	1,000–1,180	830–1,000	Canister Retrieval Test	Börgesson et al. 2002
MX-80	25×10×5	roller	1,860	920 970	756 801	Loose pour Poured then vibrated	Martino and Dixon 2007
MX-80	13×13×6	roller	1,910	920 930–1,010	756 765–829	Dry poured Dry pour then vibrate	Martino and Dixon 2007
Wyoming	Various pellet/ granule ratios	Roller and granules		980–1,340 1,070–1,460	810–1,151 893–1,271	Dry poured Dry pour then vibrate	Martino and Dixon 2007
Wyoming	25×10×5	roller	1,910	990–1,010 1,090–1,140	817–829 912–959	Dry poured Dry pour then vibrate	Martino and Dixon 2007
Wyoming	13×13×6 #30 mesh	Pellets 80% Granules 20%		1,260 1,450	1,073 1,261	Dry poured Dry pour then vibrate	Martino and Dixon 2007
Wyoming	¼" tablets ½" tablets 3/8" tablets		1,420–1,620 1,490 1,550	1,060 1,360	880 1,170	Dry poured Dry pour then vibrated	Martino and Dixon 2007
Wyoming	Granular	crushing	1,480 1,660	880 1,090	720 910	Dry poured Poured then vibrated	Martino and Dixon 2007
Kunigel VI	1–11 spheroids	isostatic	2,000–2,250	1,600	1,123	Crush, round then dry pour and vibrate	Wada et. al 2004

Table 2-3. Properties and as-placed densities of bentonite pellets, granules and granule-pellet blends examined in deposition tunnel backfill and as tunnel floor materials (openings > 100 mm width).

Material	Pellet Size (mm)	Pellet Production Method	Pellet Dry Density (kg/m^3)	Installed Dry Density (kg/m^3)	EMDD (kg/m^3)	Notes and Compaction Method	Reference
MX-80	13×13×6	Roller	1,910–2,010	1,050–1,135	828–1,015	Backfill and Plug test.	Gunnarsson et. al 2001
MX-80	30×20×12	Roller		920	755	Backfill and Plug Test.	Gunnarsson et .al 2001
MX-80	13×13×6 50:50 mix	Roller and crushed	1,910	1,310	1,120	Dry poured	Gunnarsson et al. 2001
MX-80				1,040	865		De Bock et. al 2008
MX-80		Roller then crushed and screened	2,170 2,320	1,440–1,590	1,250–1,400	Lab tests using < 16 mm Fuller-graded crushed pellets and vibration compaction.	Blümling and Adams 2007
				1,620	1,435	Lab tests using < 20 mm Fuller-graded crushed pellets and vibration compaction.	
				1,090–1,330	910–1,140	Lab tests, not vibrated.	
MX-80	18×18×8	Roller	1,780	932	767	Laboratory determination.	Sandén et. al 2008
Friedland	Granules/ flakes	~8×8×4	1,995–2,075	1,010	573	Laboratory determination.	Sandén et. al 2008
Cebogel QSE	6.5 dia 5–20 long	Extruded cylinders	1,720	943	777	Laboratory determination.	Sandén et. al 2008
Cebogel QSE	6.5 dia 5–20 long	Extruded cylinders	1,810	950–1,080	783–902	Block-rock gap fill in ½ scale tests.	Dixon et al. 2008a, b
				990–1,180	819–996	Block-rock gap fill in small-scale tests.	Dixon et al. 2008a
Cebogel QSE	6.5 dia 5–20 long	Extruded cylinders		473 – 971	371–802	Installed in bench-scale tests.	Riikonen 2009
Milos	< 10	Crushed		1,100	921	Used to fill block-rock gap in backfilling trials.	Dixon et. al 2008a,b
Milos	< 10	Crushed		1,360	1,171	Crushed raw bentonite, tunnel flooring.	Wimelius and Pusch 2008
70% Kunigel 30% Sand	< 5	Crushed blocks	<1,900	1,300	649	Shotclay used in Tunnel Sealing Experiment.	Martino et. al 2008
bentonite-aggregate mix	< 5			950–1,600	500–960	Backfilling mock-ups at URL.	Martino and Dixon 2007
Boom clay		Roller	2,100	1,700	?	50/50 Boom clay pellets and powder Bacchus 2	Volckaert and Bernier 1996
FoCa	25×25×15	Roller	1,890 1,890	1,400 1,600	?	50/50 pellet/powder mix, Reseal Project Mol Loose pour Vibrocompacted	Imbert and Villar 2006
FoCa, Boom Clay		Roller	2,100	1,700	?	Vibratory compaction Bacchus 2 Project	Volckaert and Bernier 1996
Serrata	> 7; 0.4–2	Roller then crushed	2,110–2,130	1,360	1,318	Crushed larger briquettes and 2 size blend, auger installation.	Mayor et. al 2005
Serrata	> 7; 0.4–2	Roller then crushed	2,110	1,450–1,510	1,409–1,469	Crushed larger briquettes and 2 size blend, auger installation.	Nold 2006, Fries 2008
FEBEX		Roller	1,700	1,300–1,400	?	Ca-Mg bentonite installed by conveyor/flinger.	Fuentes-Cantillana and Huertas (2002)
Wyoming	Granule blends	Crushing HCB		1,440–1,510	1,250–1,320	Horizontal tunnel placement trials using crushed HCB blocks as source for granules.	Nold 2006, Fries 2008
Wyoming	Large granules	Crushing HCB		1,390	1,200	Horizontal tunnel placement trials using crushed HCB blocks as source for granules.	Nold 2006, Fries 2008
Tunnel Flooring Material							
Cebogel QSE pellets	6.5 dia 5–20 long	Extrusion		1,150	968	In situ compacted on floor.	Wimelius and Pusch 2008
Minelco granules	< 30 mm and < 10% of < 0.125	Crushed raw bentonite		1,250		In situ compacted on floor, optimal layer thickness ~150 mm.	Wimelius and Pusch 2008

? – mineralogy not defined so EMDD not calculated.

2.4 Summary

From the information available on production of bentonite pellets and their subsequent installation into confined volumes such as the buffer-rock gap and the backfill block-rock gap, several key points can be identified.

1. If high-smectite content source materials are to be used in producing pellets for use in gap filling, there is little available information on use of small (< 10 mm dimension) pellets and their potential for use in confined spaces.
2. There is little information available regarding compaction of low-smectite pellet materials using roller compaction techniques. If the tunnel backfill blocks and the surrounding pellet materials are to be composed of similar clay materials in order to encourage system density homogenization then more work is needed on the topic of material manufacturing.
3. There is very little information available regarding bentonite-admixture pellets that might provide filtering capacity to the materials at the perimeter of the tunnel or deposition borehole.
4. There is a lack of information available regarding what admixture materials might provide improved thermal conduction between the canister and the surrounding rock mass.
5. Unless very high compactive forces are used in roller compression machines for production of bentonite pellets (150–200 MPa to achieve ~2,100 kg/m^3 dry density versus 10–17 MPa to achieve ~1,900 kg/m^3 dry density) there appears to be a practical limit of approximately 1,900 kg/m^3 dry density for materials produced from sodium-smectites.
6. The density to which pellet and granule materials can be placed in a field application are very environment and installation technique sensitive.
7. Use of materials containing two or more sizes of pellets/granules discernibly improves the installed dry density of the fill.
8. Air-entrainment of pellets/granules as a technique for installation is operationally expedient but has limitations regarding the density to which materials so installed can be placed. Work is needed to further develop technologies to install pellets in the gap between the deposition tunnel walls and the backfill blocks installed.

These topics are discussed further in Sections 3 and 4 as part of examining some of the key items that need to be further assessed in the course of developing alternative materials and methods for gap fill installation within the environment anticipated at the Forsmark and Olkiluoto sites.

3 Known or anticipated conditions at repository sites in Sweden and Finland and influence on deposition tunnel backfilling

SKB has identified the area adjacent to the existing radioactive waste management facility at Forsmark Sweden (SFR) as a potential site for a deep geological repository for spent nuclear fuel, while Posiva is considering its Olkiluoto site for the same purpose. From the information already developed for pellet materials under a variety of conditions there are features of the Forsmark and Olkiluoto sites that may influence the design, specification and installation of pellet materials in deposition tunnels. This section provides a brief summary of some of these features and discusses how pellet materials will be affected.

3.1 Site conditions at Forsmark and Olkiluoto that may affect backfill placement and performance

The Forsmark and Olkiluoto sites have been the subject of extensive characterisation as part of the development and licensing of the SFR site and the Olkiluoto test tunnel in Sweden and Finland respectively (SKB 2009, Posiva 2010). As these sites are further characterised as part of the site investigation and repository layout design processes, key chemical, geological and geomechanical features are being determined. Some of these will affect how the sealing system and its individual components will behave and interact with one-another. Some of the key material properties associated with the Forsmark and Olkiluoto site that have potential to affect backfill behaviour and installation are listed in Table 3-1. These data illustrate the substantial similarities of these sites and hence issues related to their backfilling will be similar.

Of great importance to backfilling operations and subsequent potential for backfill disruption or erosion is the rate at which water flows into the tunnel and the distribution of this inflow. Hansen et al. (2010) report on the results of a series of calculations done for the Olkiluoto site and observed in the ONKALO tunnel and the resulting plot of the inflow calculations for deposition tunnels of a generic repository design is provided as Figure 3-1. According to these if no grouting of the tunnels is done to limit water inflow, the amount of inflowing water will exceed the suggested design limit of 5 l/min from 2.5 to 8% of the deposition tunnels. Based on the data provided in Figure 3-1 there are approximately 140 to 150 fractures per 300 m of tunnel at the Olkiluoto site. Using the suggested criterion for maximum allowable inflow of 5 l/min per 300 m of tunnel and assuming uniform distribution of water inflow this would mean each feature would produce an average of 0.035 l/min, a value that is well within the anticipated capacity of the backfill to handle for a considerable period following backfill installation. It is unlikely that inflow will be uniformly distributed amongst these features or that there will be uniform distribution of the features themselves, inflow will more likely be associated with fracture clusters, meaning localized inflow much in excess of 0.04 l/min. The inflow criterion of 5 l/min per 300 m of tunnel also needs to be considered in the context that the entire 300 m will not likely be backfilled in one step (SKB 6–8 m/day; Posiva ~4 m/day (Hansen et al. 2010)), meaning that many of the water-generating features will be draining into open tunnels for much of the period that the deposition tunnel is open.

There is also the likelihood that much of the inflow to a tunnel will be associated with only a few discrete fracture features and that inflow into much of the remaining tunnel will be much lower than the 5 l/hr limit. Remediation of such high-inflow features may be necessary prior to tunnel backfilling in order to simplify operations and reduce risk of disrupting the backfill. Recent work examining the role of fracture features in a backfilled tunnel has shown that such features have the potential to act as perimeter collection rings that can combine the flow from multiple low flow features into a single flow path (Dixon et al. 2011). This may result in high localized flow rates as the length of tunnel backfilled increases and the number of flow features combined increase. This is a feature and process that requires field testing under geological conditions representative of the repository.

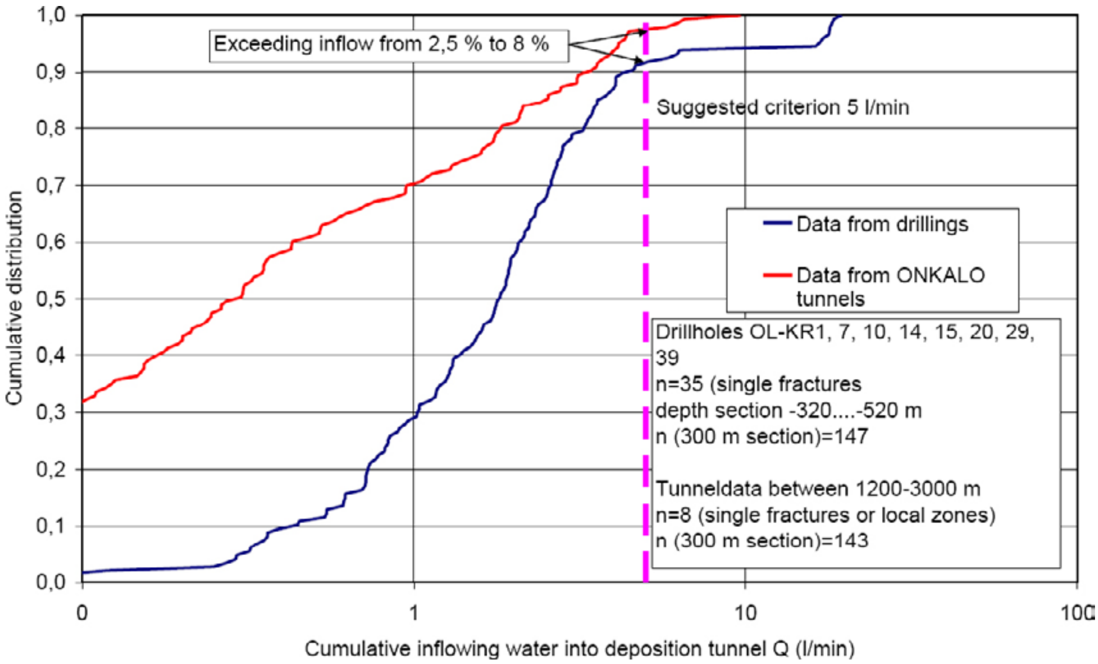


Figure 3-1. *Estimated cumulative distribution of inflowing water in a 300 m-long tunnel based on two sets of assumptions (drill hole data at Olkiluoto site; tunnel excavation data at Olkiluoto site) (Hansen et al. 2010).*

Of great importance to the placement and early performance of the backfill is the salinity of the groundwater entering the newly filled excavations. As can be seen in Figure 3-2 the Forsmark and Olkiluoto sites are different with respect to the anticipated groundwater salinity present at repository depth. The conditions initially present at repository depth in both locations is in the order of 1% TDS (10 g/l). The Forsmark site could see the TDS concentration at the repository depth increase to ~2% should deeper groundwater intrude upwards (Salas et al. 2010). The Olkiluoto site has a more saline deeper groundwater and with deep groundwater upwelling, could have local TDS concentrations in the order of 7% (70 g/L) at repository levels over the longer-term. As can be seen in Figure 3-2, the current conditions show increasing salinity with depth at the Forsmark and Olkiluoto sites.

With changes in salinity with depth (and potentially with time also) there is a need to assess the effects of such changes on longer-term backfill performance. These longer-term changes are not of concern with respect to the initial clay wetting and water inflow into the excavations. As the Forsmark and Olkiluoto sites have similarities in their initial groundwater TDS concentrations (1–2% range), the results of assessments related to backfilling at one site has application at the other site.

Table 3-1. Material and site properties at Forsmark and Olkiluoto that substantively affect backfill pellet placement and backfill performance.

Parameter	Forsmark	Olkiluoto
Nominal repository depth (m).	470	420
Hydraulic head at repository depth (MPa).	4.7 (SKB 2010)	4.2
Rock type.	Granitic	Granitic
Groundwater TDS at repository depth, estimated Design basis (DB) (%).	1.0–1.2 (Gimeno et al. 2008, SKB 2010) 3.5 (Svensson 2006)	1.5–2.5 (Posiva 2010, Hellä et al. 2009) 3.5
Maximum potential groundwater salinity (%)	~3.5	7.0 (Posiva 2010, Hellä et al. 2009)
Tunnel over-excavation volume (%)	< 30	10–20 (Hansen et al. 2010)
Estimated achievable maximum block filling degree (%)	Not defined (> 80%)	71.5–78.0 (Hansen et al. 2010)
Anticipated average water inflow to each 300-m of deposition tunnel (l/min)	~0.3 Limit of 5 l/min (SKB 2010)	Not defined Limit of 5 l/min (Hansen et al. 2010)

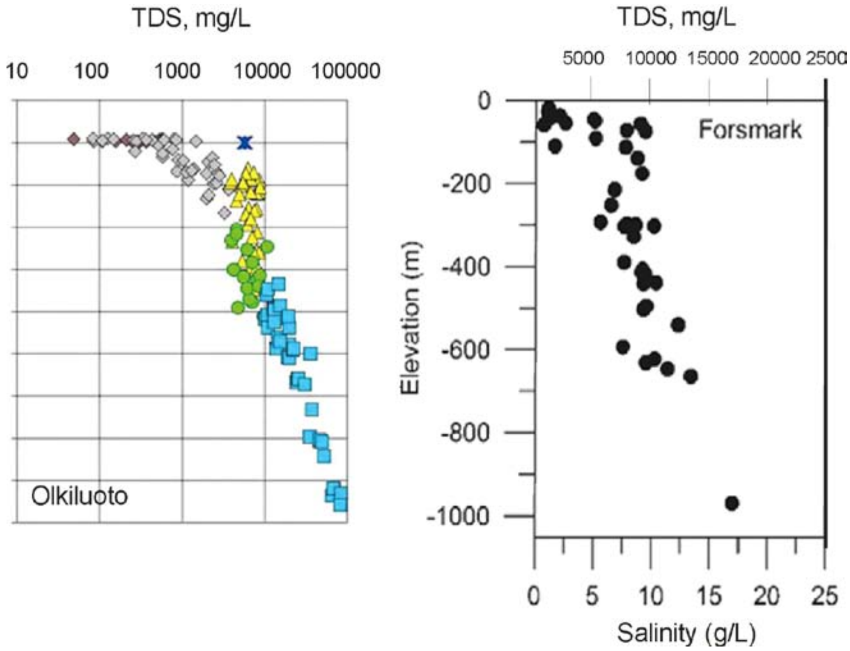


Figure 3-2. *TDS conditions at Olkiluoto and Forsmark site showing vertical distribution of salinity (Repositories both at ~ 400 m depth) (after Tohidi et al. 2010).*

As noted in Table 3-2, both SKB and Posiva are both examining sealing materials under TDS concentrations of 3.5%, which is conservative for both locations at the time of repository construction. That concentration is still conservative for the Forsmark site under any expected hydrochemical evolutions (Salas et al. 2010) but realistic for the Olkiuloto site. Work is also being done to determine material behavior at TDS levels of 7% which is of interest for the Olkiluoto site. These conservative assumptions regarding groundwater evolution ensures that the backfill developed will exhibit suitable swelling, hydraulic and mechanical behavior at the time of its installation and also over the longer term.

3.2 Requirements of pellets in deposition tunnel backfilling

The performance requirements for the deposition tunnel backfill proposed for use in a KBS-3V repository concept were presented in Section 1. In that description there was no definition of specific requirements of the gap fill component of the deposition tunnel backfill. This is because the backfilled tunnel as a whole must meet the overall performance requirements. There are however no specifications for the subcomponents of the backfill.

The pellets proposed for use in filling the space between the backfill blocks and the rock are expected to represent a potentially significant proportion of the tunnel cross-section, especially when the over-excavation volume associated with tunnelling is taken into account (10–30%). It is also assumed that the precompacted backfill blocks that fill the majority of the tunnel volume will swell on access to water and compress the pellet materials sufficiently to provide the backfill block/pellet material in the tunnel with properties that will meet the performance requirements of the backfill.

In many respects the pellet component of the backfill functions as a simple filler of the space between the backfill blocks and the rock. In filling this volume the density loss that would otherwise occur as the blocks swell into an unoccupied volume is reduced. The pellets also provide short-term mechanical and hydraulic protection to the blocks, minimizing the potential for their mechanical disruption due to localized water inflow and providing for a more uniform wetting than would otherwise occur. The pellet materials also provide protection by hampering erosional redistribution of backfill blocks that might otherwise occur during water inflow. These features and processes have been documented in laboratory and field tests related to backfilling conducted by SKB and Posiva (Keto et al. 2009a). However, with identification of a potential repository site there is a need to assess how site-specific conditions may affect backfill evolution and performance. Additionally, opportunities to improve the performance of the backfill and adjacent sealing materials should be investigated.

3.3 Issues associated with use of clay pellets in deposition tunnel backfill under repository conditions

The research work that has been completed and that is continuing on backfill materials and their installation is generically applicable to SKB, Posiva and other organisations considering use of pellets to fill voids within a repository. The local performance of the backfill will be most affected by groundwater chemistry, water inflow rates and patterns as well as the potential effects of the rock stress conditions on the evolution of the repository and the sealing system. The generic and site-specific issues and processes that may affect the effectiveness of the pellet materials proposed for use in a repository can be broken down into those that are critical and those that are not deemed to be potentially important but not necessarily critical to ensuring that the engineered barrier system performs as required.

3.3.1 Site conditions most likely to affect gap fill materials

Of the site conditions outlined in Table 4-1 those that have been identified as having the potential to most affect emplacement room backfill in the KBS-3V geometry are related to the following issues:

Rate of water inflow and mechanical stability of backfill

The rate of water inflow will affect the mechanical stability of the backfill, determine loss of material due to water flowing along the tunnel during backfilling operations and determine the rate at which swelling of the backfill will occur. All of these will affect how backfilling is done and what operational issues/contingencies must be prepared for. Initial hydrogeological investigations at the Forsmark and Olkiluoto sites indicate that they are relatively “dry” locations where only a limited number of water-conductive features will be encountered in the course of repository construction and operation. In such a situation, the potential of major disruption of buffer or backfill systems is much reduced. However in planning for repository operation there is still the need to develop confidence in the materials to be installed and the methods to be used in their installation under conditions where elevated inflow rates are encountered. This is a major reason why material and technology development work needs to be continued under conditions as close as possible to those that might be encountered at the repository site (use of the Äspö or Demonstration facility in ONKALO and conduct of full-scale simulations at these locations).

Groundwater Composition (TDS) on mechanical erosion of backfill

Groundwater composition (especially TDS) has the potential to alter the behaviour of the backfill as a whole and more significantly, the pellet fill installed between the backfill blocks and the rock. The ability of the pellet-filled regions to withstand the mechanical erosive effects of flowing water is considerably reduced by the presence of saline water (Johannesson et al. 2010). Under the groundwater conditions anticipated at the time of repository excavation and operation the backfill will be exposed to a slightly saline groundwater (groundwater at repository depth at Forsmark site at time of backfill placement is expected to have a TDS of 1–1.2% (Tohidi et al. 2010) but in order to include potential increases due to deeper groundwater being drawn into the excavations the assumption is made that the maximum TDS is approximately 3.5% (Svensson 2006). At Olkiluoto the groundwater salinity at the repository level is conservatively assumed to be in the order of 3.5% and at 700 m depth it could locally reach as high as 7% (Posiva 2010, Hellä et al. 2009, Hansen et al. 2010, Tohidi et al. 2010). Salinities of these concentrations can result in increased rate of mechanical erosion if unprotected backfill were exposed to substantial through-flowing water during its installation (Sandén et al. 2008). Once each deposition tunnel is plugged and the contained backfill has saturated, the groundwater chemistry is not generally considered to be an issue regarding backfill erosion although it will affect the hydraulic conductivity and swelling pressure of the backfill.

Groundwater Composition (TDS) on swelling and hydraulic properties of backfill

Groundwater chemistry discernibly alters the hydraulic conductivity (k) and swelling pressure (Ps) exhibited by bentonite-based materials. As the density of a given material increases, Ps increases and k decreases. Additionally, as salinity increases Ps decreases and k increases for the range of environmental conditions considered for a repository. The relationships between density, chemistry and material used has been identified as part of previous work done for buffer and backfill development and means of predicting the water-saturated swelling and hydraulic behaviour have been developed. The Ps and k are controlled by the swelling clay (montmorillonite) content of the bentonite and the density of this component within the material. The parameter known as Effective Montmorillonite Dry Density (EMDD) was developed to allow for ready estimation of the behaviour of bentonite-based materials containing different montmorillonite contents (Dixon et al. 2002), as shown in Figure 3-3 and Figure 3-4. As can be seen in these figures there is scatter in the data but there are clearly quantifiable changes in k and Ps as the result of differing groundwater conditions and EMDD values. From these it is possible to predict the behaviour of backfill (and buffer) materials under a range of groundwater conditions. EMDD is defined as follows:

$$EMDD = M_m/(V_m+V_v) \quad \text{or} \quad EMDD = (M_T \cdot M)/(V_T-((M_{nm}/G_{nm}))$$

Where Mm = dry mass of montmorillonite clay; Vm = volume of the montmorillonite minerals; and Vv = volume of voids, M_T is the total mass of the specimen, M is the montmorillonite content, M_{nm} is the mass of the non-montmorillonite component(s) and G_{nm} is the specific density of the non-montmorillonite component(s). This does require that the montmorillonite content be known. The non-montmorillonite component(s) must also be defined so that their volume can be removed from the calculation.

From EMDD-k and EMDD-Ps relationships it is possible to evaluate what the as-placed density must be achieved in order for backfill installed in Forsmark- or ONKALO- type environments to meet its performance requirements. In an environment where groundwater TDS is conservatively assumed to be 3.5% at time of repository construction and operation (although it may be substantially less depending on the source of inflowing water, see Table 3-1 and Figure 3-2). At the Olkiluoto site, salinity could locally increase to approximately 7% under conditions where deep groundwater upwelling occurs. As a result, the swelling pressure and hydraulic properties of the backfill could alter over the course of repository evolution. Knowing the groundwater salinity conditions as well as the density, composition and proportion of the backfilled volume occupied by pellet fill is important. From this information it is possible to predict both the immediate post-installation and longer-term equilibrated system swelling pressure and hydraulic conductivity of the deposition tunnel backfill. Of importance in such a set of calculations is determining the degree to which the backfill blocks and backfill pellets will homogenize with time. If substantive differences persist in the density of the two components then the potential exists for anisotropic behaviour to persist. System homogenization with time is a topic that has been examined under laboratory conditions and through numerical simulations but is also in need of examination under field conditions that closely simulate those that are anticipated at the repository (through use of Äspö or demonstration facility in ONKALO and conduct of full-scale simulations of backfilling).

Based on the previously established relationships between EMDD, salinity, swelling pressure developed and hydraulic conductivity it is possible to estimate the dry density to which backfill pellets will need to be placed in order that they will exhibit the swelling and hydraulic characteristics defined for the backfill. If it is assumed that the backfill blocks do not develop swelling pressures in excess of the pellet fill (e.g. use of lower swelling capacity clay in manufacture of blocks), the EMDD of the pellet-filled volume must exceed ~500 and ~700 kg/m^3 respectively for conditions of freshwater and deep geosphere groundwater salinity conditions respectively if a swelling pressure of > 100 kPa is desired (values based on lower bounds of data scatter). Similarly, based on the data shown in Figure 3-4 for hydraulic conductivity to remain $< 10^{-10}$ m/s, the EMDD for the pellet fill must exceed ~600 and ~950 kg/m^3 respectively for freshwater and 3.5–7% TDS conditions (lower bounds of 95% confidence limits of data). These bounding EMDD values do not take into account any post-placement compression and densification by the backfill blocks or compression of the backfill by the swelling of the buffer in the underlying deposition boreholes. The pellet density limits listed above are conservative since compression of the pellets by the backfill blocks and buffer are both expected. It should be noted that these values also do not take into account factors such as physical or erosional losses of swelling clay that occurs prior to deposition tunnel saturation or due to long-term material removal processes. The data shown in Figure 3-3 and Figure 3-4, while extensive are not exhaustive and collection of further literature data would likely result in some refinement of the EMDD-k and EMDD-Ps relationships and hence a better definition of the limits for the target density of the pellet fill and blocks.

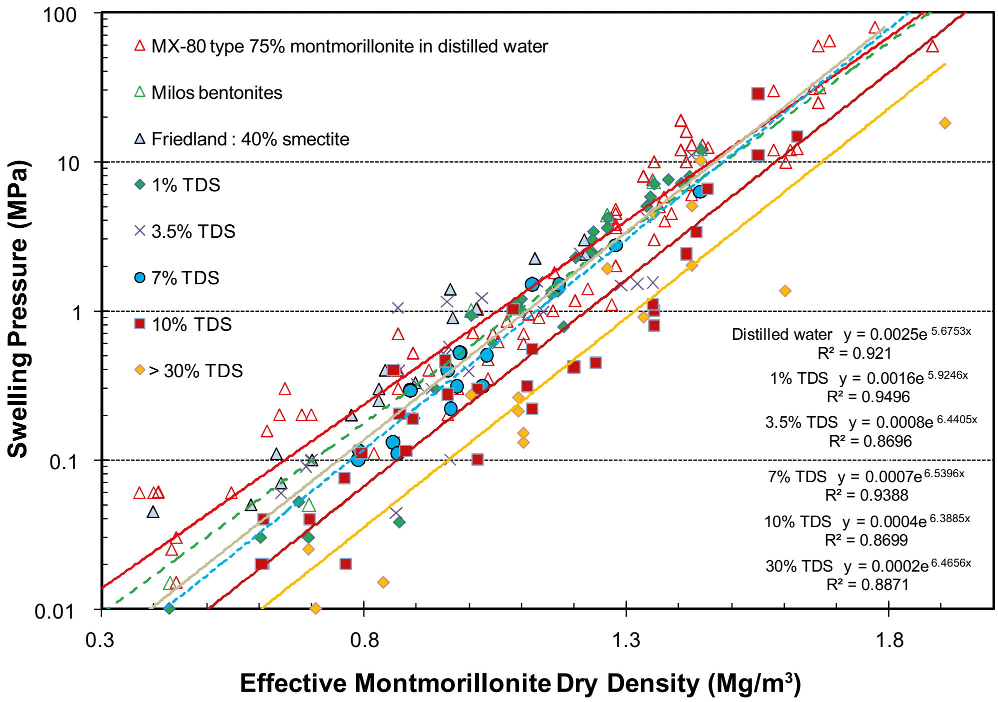


***Figure 3-3**. Relationship between EMDD and swelling pressure for several swelling clays using various groundwater salinities (Data drawn from various laboratories and represent several types of bentonite).*

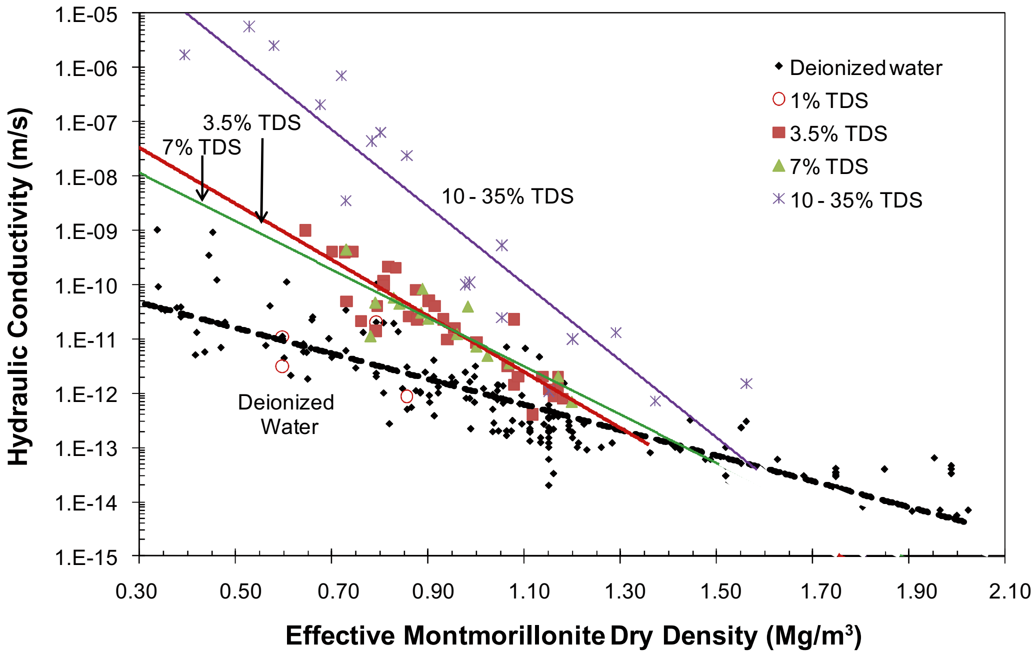


***Figure 3-4**. Relationship between EMDD and hydraulic conductivity at various groundwater salinities. (Data drawn from various laboratories and represent several types of bentonite).*

Based solely on the results of already completed field trials of pellet placement, gap fill of the type(s) already examined (Table 2-3) should be able to provide swelling pressure > 100 kPa and have a k of < 10^{-10} m/s under groundwater TDS concentrations as high as 7%. Beyond 7% TDS, the uncompressed pellet fill material may be marginal or unable to achieve these key properties and a much denser pellet fill will be required. It is therefore necessary to determine to what extent it is possible to improve the as-placed density of the pellet fill and ensure that its as-placed density is not subject to unacceptable levels of density variation. Alternatively, there must be confidence that the block materials will be able to swell sufficiently rapidly to achieve adequate compression of the pellet fill.

Physical loss of bentonite material

Although processes leading to loss of bentonite materials over the long-term are unlikely to be of major concern in a repository located at depth in an environment where low hydraulic gradients and high TDS groundwater conditions persist there are some situations where loss of material have been postulated to occur.

The first of these processes is associated with the preclosure or immediately postclosure period following installation of the buffer and backfill materials. During repository operations there may be considerable groundwater flow from the rock mass towards the openings of the repository. If the incoming water passes adjacent to the deposition borehole or the deposition tunnel and the hydraulic gradient is sufficiently high then advective erosion of fine clay materials in contact with an intersecting hydraulic feature may result in material moving via high-permeability fractures from their as-placed location to nearby, still-open tunnels. Additionally, in the period immediately following the installation of the canister, buffer, gap fill and backfill, inflowing water may result in movement of material along the gap-rock contact towards the as-yet unsealed installation tunnel. In such a situation, if flow rate is sufficiently high, erosion of the material adjacent to the rock might occur.

The basic scenario considered in this situation is that gradual loss of bentonite into the rock mass occurs due to clay movement into discrete cracks and joints that intersect the borehole or tunnel. In the case of a hydraulically – active fracture intersecting an placement borehole or deposition tunnel there is the potential for the bentonite to self-inject into the fracture aperture as well as for this injected material to be further dispersed as colloidal materials by the flow of groundwater. This topic has been discussed by Liu and Neretnieks (2006), who concluded that advectively – driven erosion of materials in a saturated repository system was unlikely. Internal erosion during the operational and pre-saturation phase might result in some erosion due to locally higher hydraulic gradients but this would require an interconnected and high permeability fracture system to intersect the borehole as well as nearby open volumes where the bentonite could be deposited.

Another process identified as potentially being associated with advective or self-injection loss of clay is a mechanism whereby colloidal dispersion occurs. Such long-term loss of material due to chemical and advective erosion processes associated with glaciations continues to be the topic of ongoing investigation in order that confidence in the sealing system performance is maintained.

Physical condition of excavated surfaces of tunnel

The physical condition of the excavations and the rock surfaces could affect the installation and subsequent performance of the pellet component of the deposition tunnel backfill. If the rock surfaces are very uneven (gap between clay blocks and rock varies considerably) there is the potential for the pellet fill to be placed at inconsistent density as the result of regions where pellets cannot be effectively installed.

The presence of an extensive excavation damaged zone in the rock immediately adjacent to the tunnel walls can substantially affect the effectiveness of the backfill as a barrier to contaminant transport.

Rock Stress and Spalling in Tunnels

The rock stress conditions, more specifically the relatively high differential stress condition present at this site. This may affect rock stability and potentially the shape and volume of the tunnel that will need to be filled with pellet materials. A high differential stress condition means that an increased potential for rock breakouts/spalling into excavated volumes exists. This may be an operational and safety consideration during backfilling operations. With spalling comes the potential for regions between the backfill blocks and the rock to be filled or blocked by rubble before the pellets can be installed. This will result in inconsistent pellet placement and inadequately filled regions could become preferred pathways for water and/or water-eroded backfill clay movement along the tunnel. This could compromise the effectiveness of the backfill barrier prior to deposition tunnel closure and completion of the saturation process. This situation is not really something that can be effectively addressed through pellet design or placement technology selection as spalling requires a positive contact pressure and this cannot be assured during the initial stages of backfill evolution or in dry tunnel sections where the pellets will not have access to water and so no swelling occurs. Under some circumstances pellets placed in the gap between the rock and the HCB buffer in the deposition borehole may provide a more effective confining force and limit the potential for thermally-induced spalling in the borehole wall but this has not yet been tested.

Non-Uniformity in Tunnel Excavation

It should also be noted that very few of the backfill gap filling placement trials conducted to date have examined the variable nature of an excavated tunnel. The gaps have generally been uniform (excepting work by Wimelius and Pusch (2008)) where artificial surface irregularities were induced and in the Tunnel Sealing Experiment (Martino et al. 2008) where material was placed against a rough rock surface. Wimelius and Pusch (2008) concluded that an opening of at least 100 mm was necessary in order to get reliable and uniform material installation. This and the initial results of 1/12th-scale tests done at Äspö (Dixon et al. 2008a) contribute to the currently proposed method for filling the 150 mm gap between blocks and rock called for in block-pellet backfilling. Given that there is expected to be a non-uniform excavation in the tunnel, giving rise to substantial (estimated 10–30%) volumetric over-excavation, the ability to adjust backfill geometry and emplacement technologies to field-scale excavations will be necessary. It has generally been observed that over-excavation is the highest in the floor regions of the excavation (Hansen et al. 2010) and this will mean that a greater amount of floor levelling materials will be needed. The development of pellet-based gap fill materials that can be placed to substantial density will help in ensuring that the backfill will meet its performance goals despite local variations in the volume of pellet fill that is required to complete tunnel backfilling.

3.3.2 Operational considerations related to gap fill proposed for installation as part of backfill barrier

The topics of greatest concern related to installation of pellet materials into the gap between pre-compacted backfill blocks and the walls of deposition tunnel are related to the physical stability of these pellets and getting them into place in a consistent manner. The conditions and processes that can substantially affect the stability of the individual pellets and the volume they occupy have been described above in Section 4.3.1. However before these conditions can begin to affect the backfill pellets, blocks or composite system the blocks and pellets must be installed. As outlined in Section 3.3 there have been numerous pellet emplacement trials and demonstrations undertaken. From these trials several recurring issues have been identified, primarily associated with pellet installation and its effectiveness.

The primary material and operational issues associated with the pellet component of the backfill (and to a lesser extent deposition borehole gap fill), can be broken down as follows:

1. What is required to produce pellets of high physical stability and uniformity.
2. How to place material so that it stays in place.
3. What installation method and material is most efficient and reliable, minimising waste and mess during installation.
4. How to optimize density uniformity of placed material.
5. How to maximize as-placed density of pellet fill.
6. Determining the optimal thickness of the pellet fill component in terms of protecting the block materials, ensuring short-term mechanical and hydraulic stability to recently backfilled regions.
7. Identify the type of pellet fill that provides the most resistance to piping and subsequent clay erosion and maximizes delay in water discharge at the downstream face of an open deposition tunnel.
8. Establishing what type of pellet fill provides the greatest physical protection to backfill blocks.
9. Finding how the saturation of the deposition tunnel backfill progresses and how will the type of pellet fill used affect system evolution (e.g. piping features through backfill, channelling of flow along rock-pellet interface, maximizing the initial water retention by the backfill component).
10. Impact of pellet type on the development of isolated unsaturated regions during backfilling and subsequent air movement out of these features.

All of these issues are of potential importance in the backfilling of a deposition tunnel and in particular the type of pellet fill ultimately selected for use. Some suggestions for how some of these might be addressed are provided in Section 5.

4 Addressing potential issues related to use of pellets in backfilling

The state of knowledge related to current bentonite pellet material options and experiences in repository mock-ups were provided in Section 3. Using these available sources of information, the anticipated conditions at the Forsmark site were evaluated and potential conditions and processes that might be disruptive to pellet materials were discussed in Section 4. Additionally, topics of primary concern or requiring additional evaluation were outline in Section 4.3. From this an approach to addressing potential issues related to use of pellets in deposition tunnel backfilling has been developed and is outlined below.

Based on review of the state of knowledge regarding gap fill materials, options and properties requirements associated with the KBS-3 backfilling option, several important conclusions can be drawn and recommendations for ongoing work can be made.

1. Unless the tunnel is almost completely dry, gaps between the backfill blocks and the surrounding rock mass will need to be filled shortly after block placement occurs. Determining what degree of block filling is achievable and evaluating what density of pellet fill is needed in order to ensure the system can meet its performance requirements needs to be clearly defined. For a deposition tunnel where a 150 mm annular gap, plus the volume associated with as much as 30% over-excavation (SKB design assumption), the block component must swell sufficiently to compress the pellet materials to a point where backfill performance requirements are met. In the longer-term where the entire block mass has swelled uniformly, this represents only a few percent volume change. However initially the outer blocks will need to swell more than a few percent in order to compress the pellet materials to their required density. This issue can be addressed through conduct of scoping calculations that consider the range of material options (e.g. degree of block filling, range of block densities available and their volumetric swelling capacity, mineralogical properties of various block and pellet materials and environmental conditions that are anticipated to exist in the deposition tunnel).
2. Materials considered for installation as an SKB-type backfill have been limited to commercially available extruded bentonite materials, crushed raw bentonite and to a limited degree, roller-compacted pellets. With the exception of the crushed raw bentonite, most of the materials installed in tests by SKB and Posiva have been essentially uniformly sized and have not included graded sizes that might improve as-placed density. Trials undertaken in Canada, Switzerland and Belgium using graded materials observed marginal to substantial increase in as-placed density. Field-scale trials to examine the effects of using graded materials of the composition proposed by SKB and Posiva for tunnel backfilling would be useful in evaluating the potential usefulness of further engineering the pellet fill.
3. There appear to be practical limits for the as-placed density of pellet-based gapfill (even when graded materials were used). Increasing the dry density of the individual pellets from nominal values of 1,900 kg/m^3 to approximately 2,200 kg/m^3 (or higher) is possible if high compaction pressures are used during pellet manufacturing. This is only a 10–15% increase.
4. Pellets for use in backfilling have only been produced and tested in a limited range of sizes and shapes. Work in Canada and Belgium indicate that under certain circumstances the as-placed density of dry gap fill materials are improved by altering the shape of the pellets and applying vibratory energy during material placement. A joint study that examines the densification of bentonite pellets under a range of shapes and sizes, together with basic materials parameters examination is being undertaken by SKB, Posiva and NWMO. This study will identify what improvement to the as-placed density of dry pellets can be achieved by modifying the pellet size and composition. This study includes durability and erosion resistance evaluations to determine if improved material performance is achieved by changing pellet size, shape or density and if any improvement observed is substantial enough to warrant the additional effort required to produce specialised pellets.

5. The predicted properties of the backfill block-pellet system are based on assumptions of their reaching density (or EMDD) homogeneity through compression of the pellet fill by the hydrating clay blocks. This end-state condition is not yet demonstrated and estimates need to be made as to how long this equilibration process will take need to be undertaken. Similarly, if different materials are used for the pellets and the clay blocks, the density of the two materials needs to be established. From such equilibrium state determinations it will be possible to determine if they meet the performance requirements set for the backfill as a whole. Studies are ongoing that examine aspects of the homogenization process and these should be evaluate whether they cover the full-range of anticipated field conditions.
6. Mock-ups to examine basic placement technologies and as-placed density and homogeneity conditions for pellet fill materials have provided valuable boundary conditions for evaluation of the initial state of deposition tunnel backfill. There have been no placement trials yet done under field conditions (underground in representative tunnel, with realistic rock conditions and naturally inflowing groundwater) that pay close attention to gap fill materials. Such demonstrations are needed in order to determine what materials are best suited for installation in a repository environment and to identify any conditions that may affect backfill installation or performance. This type of demonstration might be best undertaken at the Äspö facility where repository-scale excavations and naturally-occurring hydraulic features have been mapped and characterised.
7. Extruded bentonite pellets have been the material most-commonly examined filler material associated with tunnel backfilling by SKB and Posiva. Examination of other pellet materials and opportunities for improving both extruded and roller-compacted materials are needed in order to determine if either material option has any intrinsically-superior feature(s) and if the effort to improve densification or other properties is cost-effective both with respect to materials used and any improvements to buffer or backfill performance. If modified roller-compacted pellet materials show substantial improvement to currently available materials, the potential for compositionally-modifying extruded pellets should also be examined. This could be done as a bench-scale study using a small extrusion machine and is being undertaken as part of a joint SKB/Posiva/NWMO pellet optimisation study.
8. While not a backfill pellet –specific issue, examination of potential admixtures to the bentonite should be examined to determine what their effect on colloid generation and colloid filtration may be. This evaluation is being done as part of the joint SKB/Posiva/NWMO pellet optimisation study.

As noted in the text above, many of the items identified as being important to development of a robust backfill are being evaluated as part of the Åskar joint work project being undertaken by SKB and Posiva. As the above-listed items are considered and uncertainties addressed, it will be possible to clearly identify the most suitable materials and methods for the installation of pellet materials as components in the buffer (and perhaps buffer) system within a repository. With identification of materials options will come clearer definitions of materials installation requirements, as well as identification of what installation equipment development is needed.

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