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Backfilling Techniques and Materials in Underground Excavations:
Potential Alternative Backfill Materials in Use in Posiva’s Spent Fuel Repository Concept

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Potential Alternative Backfill Materials in Use in Posiva’s Spent Fuel Repository Concept

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May 2009
ABSTRACT

A variety of geologic media options have been proposed as being suitable for safely and permanently disposing of spent nuclear fuel or fuel reprocessing wastes. In Finland the concept selected is construction of a deep repository in crystalline rock (Posiva 1999, 2006; SKB 1999), likely at the Olkiluoto site (Posiva 2006). Should that site prove suitable, excavation of tunnels and several vertical shafts will be necessary. These excavations will need to be backfilled and sealed as emplacement operations are completed and eventually all of the openings will need to be backfilled and sealed. Clay-based materials were selected after extensive review of materials options and the potential for practical implementation in a repository and work over a 30+ year period has led to the development of a number of workable clay-based backfilling options, although discussion persists as to the most suitable clay materials and placement technologies to use.

As part of the continuous process of re-evaluating backfilling options in order to provide the best options possible, placement methods and materials that have been given less attention have been revisited. Primary among options that were and continue to be evaluated as a potential backfill are cementitious materials. These materials were included in the list of candidate materials initially screened in the late 1970’s for use in repository backfilling. Conventional cement-based materials were quickly identified as having some serious technical limitations with respect their ability to fulfil the identified requirements of backfill. Concerns related to their ability to achieve the performance criteria defined for backfill resulted in their exclusion from large-scale use as backfill in a repository. Development of new, less chemically aggressive cementitious materials and installation technologies has resulted in their re-evaluation. Concrete and cementitious materials have and are being developed that have chemical, durability and mechanical properties that should allow their use in limited quantities in a repository (e.g. grouts, shotcrete or concrete plugs/seals). Widespread use of cemented backfill materials is still not a viable option for backfilling of Posiva’s repository although some of the technologies developed for materials placement in the mining industry have potential for repository application.

Extensive work has been done in order to identify a range of potentially suitable clay-based backfilling materials and technologies that could be used to install them in a repository environment. As a result of these efforts a suite of materials and technologies are available for backfilling of repository openings and although many have not yet been demonstrated at full-scale in an underground environment there is considerable confidence that one, or more of these options will prove suitable.

Keywords: spent nuclear fuel, disposal, backfill, assessment, concept
Täyttötekniikat ja materiaalit maanalaisissa louhituissa tiloissa. Sovelluksena Posivan käytetyn ydinpoltoaineen loppusijoitus.

TIIVISTELMÄ


Loppusijoitussympäristöön soveltuvin savi-pohjaisten täyttöainealan ja asennus teknikoiden kehittämiseksi on viime vuosina tehty laajalti kehitys- ja tutkimustyöitä ja työn tuloksena on syntynyt useita vartenotettavia ratkaisuvahtoetoja. Vaikka osaa ratkaisuista ei ole vielä ehditty testata suurta mittakaavaavassa, voidaan pitää toden näköisenä, että yksi tai useampi näistä ratkaisuista tulee todistetusti täyttämään loppusijoituksele asetetut vaatimukset.

Avainsanat: käytetty ydinpoltoaine, loppusijoitus, täyteaine, arviointi, konsepti
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1 INTRODUCTION

A variety of geologic media options have been proposed by countries involved in developing a safe means of permanently disposing of spent nuclear fuel or fuel reprocessing wastes. Media proposed internationally include hard crystalline rock (e.g. granite), sedimentary rock formations (e.g. continental clays, clay stones, limestone), volcanic rock (e.g. tuff) and massive salt deposits. In Finland and Sweden the concept selected after more than 30 years of investigation and research is construction of deep repositories in crystalline rock (Posiva 1999, 2006; SKB 1999). In Finland it is proposed that a spent fuel repository be constructed at Olkiluoto (Posiva 2006) and at present excavation of an underground characterization facility is occurring. Should the site prove suitable, excavation of additional tunnels and several vertical shafts will be necessary in order to move the canisters into the repository and then emplace them. These excavations will need to be backfilled and sealed as emplacement operations are completed. Complicating the development of backfilling materials and techniques is that complete saturation of the repository backfill may take several hundred to a few thousand years (Hellä & Pastina 2006). Locally in high-water inflow regions, saturation may occur within days (or even hours) after the backfill is placed, potentially causing backfill erosion. As a result of these variations in local conditions the development of backfill and backfilling technologies is a considerable technical challenge.

Work leading up to the selection of appropriate disposal concepts and means of achieving safe disposal of spent nuclear fuel has involved examination of a wide range of emplacement geometries and methodologies. In order to safely close the repository once canister emplacement is accomplished there are many options for sealing and backfilling. Those relevant to the Posiva repository concept have undergone continual re-evaluation as repository design options have been developed.

This report reviews the placement technology options and materials currently being evaluated as potential backfill. Of particular interest in backfilling is re-evaluation of materials and methods that have been given less attention than the clay and aggregate materials generally accepted as being suitable. There have been suggestions since the beginnings of concept development that cementitious materials could be utilized in backfilling of a repository. Concerns related to their ability to achieve the desired performance criteria for backfill has meant that they have largely been discounted for large-scale use as backfill in a repository.

Development of new, less chemically aggressive cementitious materials and installation technologies has resulted in preparation of this document and a re-evaluation of the potential for using these materials. Technologies developed by the mining industry to place tailings and aggregate materials provide some potentially useful applications in backfilling of a repository. Development of cementitious materials that are chemically, mechanically and hydraulically suitable for widespread repository is advancing, particularly with respect to concretes and grouts that have chemical, durability and mechanical properties that would allow for their use in limited quantities in a repository (e.g. grouts, shotcrete or concrete plugs/seals). Development of materials suitable for more widespread use in backfilling is less advanced and is not generally considered as being sufficiently developed to be viable, however they, their advantages and disadvantages are discussed together with other concepts.
2 REPOSITORY CONCEPT AND BACKFILLING

2.1 KBS – 3V and KBS – 3H Repository Concepts

Evaluation of options for disposal of spent nuclear fuel in a deep geological environment began in the late 1970’s in a number of nations as the inventories of spent power reactor fuel began to accumulate. Much of the initial work into developing workable approaches to permanently dispose of spent nuclear fuel was done by SKB who developed the KBS-3 concept (KBS 1983). This generic concept has subsequently been used to develop detailed concepts known as the KBS-3V (vertical emplacement holes in floor of tunnels) and KBS-3H (horizontal emplacement drifts) shown schematically in Figure 2-1. The generic reference concept developed for spent fuel disposal in granitic rock and adopted by Posiva (Posiva 2006) is based on the horizontal emplacement geometry option KBS-3H and is described in detail in the Posiva (2006) report.

The long history of collaborative work between Posiva and SKB has facilitated the development of Posiva’s Olkiluoto-specific repository concept and aided in focussing in on approaches to repository sealing that are most applicable to this candidate repository site. Based on the results of site and economic evaluations of the candidate repository site at Olkiluoto, the KBS-3H with its smaller excavation volume requirements has been selected as the potential option for consideration (Posiva 2006). The 3V option is the reference option for repository design and evaluation purposes. A conceptual layout for the Olkiluoto repository has been developed in Figure 2-2.

Figure 2-1. KBS-3V and KBS-3H Emplacement Geometries (Posiva 2006).
Much of the early work associated with developing concepts for spent fuel occurred in Sweden with utilization of the Stripa Mine facility to examine options for spent fuel isolation and develop tools for use in geologic evaluation of granitic rock for potential suitability for hosting a repository (SKBF/KBS 1980). The Stripa facility provided a location where international research was carried out until 1992 when the facility was closed. Gray (1993) provides an overview of the engineered barriers work carried out at Stripa over the course of its operation. Stripa was succeeded by a number of underground research facilities built in hard crystalline rock (e.g. Äspö-Sweden, Grimsel-Switzerland, URL-Canada) where international collaboration has continued. Much of the work done at these facilities has focussed on development of materials and technologies for sealing of excavations in the deep geologic environment. A component of the sealing system that has been a consistent part of all repository sealing concepts is backfill and its evaluation began in the early stages of the Stripa project.

The KBS-3V – type concept was the first to be evaluated in detail by Sweden, Finland and Canada. It involves larger excavation openings than for a horizontal emplacement since the canisters must be lowered vertically into the emplacement boreholes. As a result of the larger openings there is the possibility to use larger emplacement equipment as well as larger backfill installation equipment. With this comes the challenge of how to effectively backfill these openings and how to accomplish this when in close physical proximity to the containers (Figure 2-1).

The KBS-3H – type emplacement concept involves smaller excavation openings and so canister handling and emplacement equipment must operate under a different set of constraints than in the 3V geometry. One particularly important aspect of the 3H concept is the greater physical separation between the canister-buffer package and the backfill. This is shown in Figure 2-1 but is more clearly shown in Figure 2-3. In the 3H emplacement geometry the buffer and the backfill components are never in contact. The
buffer in the emplacement drifts is restrained by a mechanical plug (concrete) to ensure that the installed materials remain in place. As a result there is no need for the backfill to provide mechanical restraint to the buffer. Similarly, the separation also removes the need to operate backfilling equipment in the vicinity of the waste canisters.

**Figure 2-3.** KBS-3H Concept (note large distance between canister and backfill (after Posiva 2006).

### 2.2 Current Status of Posiva-SKB Backfill Development

#### 2.2.1 Joint Posiva - SKB Activities

While the KBS-3V and -3H emplacement options have some significant differences between them, they are more similar than different. This is especially true when it comes to backfilling in these repository concepts. As noted previously the 3H geometry has the advantage of not having to deal with close proximity to the canisters and buffer and backfilling can be considered to be a totally separate operational activity within the repository. With this separation the stringent density and emplacement requirements (e.g. ability to constrain buffer in its borehole) of the emplacement tunnel backfill is removed from the 3H geometry. In the regions beyond the emplacement tunnel (3V) and emplacement drift (3H) the backfill requirements become much more comparable. There will be the need to backfill the access tunnels, service rooms, ramp and shafts in both the 3H and 3V concepts.

Whether Posiva ultimately selects the KBS-3V or KBS-3H concept for use, Posiva and SKB have a large number of common interests with respect to developing workable backfill materials and technologies for use in a repository. In recognition of this common interest Posiva and SKB have an extensive and ongoing program of cooperative work related to backfill development and demonstrations. Most of this work is being done as part of the BACfilling and CLOsure of the repository (BACLO) project jointly supported by Posiva and SKB (Keto et al 2009). While BACLO focuses on the 3V concept the information developed on materials, installation technology and other aspects are also directly applicable to Posiva’s KBS-3H repository work.
3 HISTORICAL ASPECTS OF MATERIAL SELECTION FOR USE AS REPOSITORY BACKFILL

From the beginning of the process of evaluating geological media and engineered barriers options in the late 1970’s there has been an ongoing process of concept review and improvement. This was reflected in the evolution of the deep geologic repository concept documented in KBS-1 (1977), KBS-2 (1978) and KBS-3 (1983) and the detailed development of the KBS-3H and KBS-3V options (Posiva 2000; 2006; SKB 2001). Associated with much of the early concept and materials selection process was a series of option evaluations, many of which were incompletely documented since the focus was to develop the concepts and materials selected rather than documenting those that were not apparently practical. Most of the national programs examining permanent disposal for spent nuclear fuel in a hard crystalline rock medium used the means of prioritizing backfill materials options that was subsequently documented in a review of backfilling and sealing approaches and options prepared by Mott et al. (1983).

Mott et. al (1983) provide an excellent summary of the initial assessment and screening process undertaken as part of establishing the direction taken by Finland, Sweden, Canada and other national programs in developing backfilling and sealing of repositories. Mott et al. (1983) records many of the reasons that led Finland and other nations to select natural materials (aggregate, clay or mixtures of these materials) as candidate system backfill. It should be noted that in the early stages of concept development there was often no terminology differentiation between the sealing material immediately adjacent to the canister (now referred to as buffer) and that used to fill the rooms, tunnels and shafts (now referred to as backfill) and so there is a need to be careful when examining some of the original documentation related to backfilling.

The candidate “backfilling” materials were expected to provide adequate isolating capability to the repository and different materials were recognized as having advantages for use in different areas. It was established early in the repository concept development process that the fundamental requirements of a repository backfilling and sealing system in any geologic medium are:

“- to provide an effective engineering barrier which will prevent or inhibit the release of radionuclides from ‘active’ parts of the repository,
- to eliminate preferential groundwater migration paths within ‘redundant’ parts of the repository,
- to exhibit a long-term compatibility with other components throughout the repository system”

(Mott et al 1983)

These are the same basic requirements identified in the original KBS-3 concept document (KBS 1982) and have remained throughout the development of the more detailed repository concepts presented by Posiva (2000; 2006) and SKB (2002). A similar set of generic sealing system performance guidelines have been adopted by most repository concepts, regardless of the geologic medium considered.
The basic process used to initially screen backfills and backfilling approaches was similar for most repository concept development efforts internationally and is reproduced in Table 3-1 through Table 3-4. In many cases the process of screening backfilling concepts, leading up to selection of reference materials and techniques was inadequately documented, often leading to later uncertainty as to why particular materials were selected for evaluation. The logic used by Posiva and others to screen and select potentially suitable backfilling materials is presented in Mott et al. (1983).

**Table 3-1. Candidate Buffer and Backfill Materials for Geologic Repositories. (after Mott et al. 1983; Table 16)**

<table>
<thead>
<tr>
<th>Material Group</th>
<th>Principal Attributes</th>
<th>Material Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spoil</td>
<td>A, E</td>
<td>Crystalline rock clay</td>
</tr>
<tr>
<td>Clays</td>
<td>B, C, D, E</td>
<td>Illites, Kandites, Palygorskites, Smectites, Vermiculites, Chlorites</td>
</tr>
<tr>
<td>Zeolites</td>
<td>D</td>
<td>Various</td>
</tr>
<tr>
<td>Pozzolanas</td>
<td>B, E</td>
<td>Various natural pozzolanas, Pulverized fly ash (PFA)</td>
</tr>
<tr>
<td>Hydraulic Cements</td>
<td>B, E</td>
<td>Portland cements, Polymer cements, Hydrothermal cements</td>
</tr>
<tr>
<td>Minerals/Aggregates</td>
<td>A, E</td>
<td>Natural aggregates, Crushed aggregates</td>
</tr>
<tr>
<td>Bitumens</td>
<td>B, E</td>
<td>Natural bitumens, Various industrial bitumens</td>
</tr>
</tbody>
</table>

**Attributes**
- A  Good heat transfer properties
- B  low permeability
- C  favourable chemical buffering properties
- D  favourable retention properties
- E  favourable mechanical properties

From the materials listed in Table 3-1, a ranking of potential suitability of these materials was developed based on state-of-knowledge at that time regarding the longevity (not clearly defined by Mott et al. 1983), design properties heat transfer, hydraulic, chemical buffering properties, radionuclide retention properties and mechanical properties. The resulting ranking is presented in Table 3-4. Work done since the time of initial material screening would alter some of the ratings developed (e.g. longevity, radionuclide retention properties) but would not substantially change the basic results documented in the early 1980s. It should be noted that Mott et al. (1983) also included carbon and polymer/chemical grout materials in their listing of potential buffer/backfill materials. For a variety of reasons they are clearly not suitable for use in backfilling (e.g. chemical compatibility or toxicity, long-term stability, microbial interactions and cost), and so are not discussed in this document or included in the tables. Based on these initial materials screenings the most obviously suitable materials for consideration in backfilling of the repository openings were rock spoil, clay-based materials, cementitious materials (e.g. concrete), or mixtures of these materials.
Table 3-2. Preliminary Backfill screening on the basis of longevity. (after Mott et al. 1983; Table 17)

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>RANKING</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| SPOIL             | 1       | ➢ Geochemically and physically compatible with host environment,  
                           ➢ On-site availability at nominal cost  |
| CLAYS             | 1       | ➢ May exhibit excellent longevity,  
                           ➢ Certain types may undergo alterations (e.g. Na to Ca bentonite),  
                           ➢ Diagenetic changes precluded by temperature-pressure constraints |
| ZEOLITES          | 3       | ➢ Potentially reactive esp. under extreme alkaline conditions,  
                           ➢ Stability under repository conditions unknown,  
                           ➢ Dehydration precluded by temperature-pressure constraints |
| POZZOLANAS        | 2       | ➢ Good geological and archaeological evidence for longevity for naturally-occurring pozzolanas, although influence of ambient repository conditions requires investigation,  
                           ➢ Long-term stability of PFA is likely to be comparable to or better than natural varieties. |
| HYDRAULIC CEMENTS | 2       | ➢ Favourable archaeological evidence exists although further research is required to determine optimum formulation,  
                           ➢ Hydrothermal cements are inherently more stable than Portland cements,  
                           ➢ Longevity of polymer-based cement is doubtful |
| MINERALS/AGGREGATES | 1       | ➢ Geological evidence suggest excellent longevity provided mineralogy is matched with that of the host formation |
| BITUMENS          | 1       | ➢ Geological evidence suggests excellent longevity, mainly due to lack of affinity to water |

Rankings: 1. Documented evidence of geochemical stability over geological time  
2. Documented evidence of stability over significant time-intervals  
3. Some doubt as to long-term stability under certain physico-chemical conditions

Despite having some advantageous aspects, initial concerns associated with the very high pH generated in cement-based materials and its impact on the regional groundwater, canister durability, contaminant mobility and stability of nearby clay-based materials made consideration of use of any cementitious materials in a repository problematic (Mott et al. 1983). Cementitious materials were identified as lacking the self-sealing capability and ability to provide a continuously positive load on the rock adjacent to it. As a result of these concerns many programs concentrated much of their ongoing efforts on non-cementitious backfill options while still working towards the
development of specialized cementitious materials that would not generate adverse pH conditions and that could be relied on to be very durable/stable and of low permeability.

Ongoing work on cementitious materials has primarily been intended to allow for their use as construction expedients (localized grouting for groundwater inflow control, shotcrete for stabilization of excavation walls in regions of poor rock quality), during repository excavation and operation. There has also been a general acceptance that some concrete materials will ultimately be needed in the construction of plugs and seals in repositories in hard crystalline rock for the Finnish (Posiva 2006; Tanskanen 2007); Swedish (SKB 2001) and Canadian (Dixon et al. 2001; Maak and Simmons 2005) concepts. Recent work has also indicated that limited use of specialty concretes and other cementitious materials will not likely be detrimental to backfill performance (Arcos et al. 2006; Luna et al. 2006) although concerns persist regarding extensive use of cementitious materials (Alexander and Neall 2007).

Development of backfill placement techniques and materials containing a cementitious component continues, predominantly by the mining industry. These materials are also routinely reassessed for potentially wider applications such as in repository backfilling. Many of the original reservations regarding the suitability of cementitious materials in backfilling and repository structures have persisted but others have become less of an issue. In order to document the development of this technology over the nearly 25 years since the initial repository backfilling concepts were screened and selected, and its current potential for application, a brief review or the initial concepts and current technology is provided later in this document.

The development of clay, aggregate or mixtures of these materials as backfill has progressed from the initial assumption of general applicability through a still ongoing program of material and technological development. In a number of cases concepts and materials have been tested in large-scale backfilling trials as well as demonstrations of full-scale repository sealing constructions (Gunnarsson et al. 1996; 2001; Börgesson et al. 2002; Chandler et al. 2002b). These tests have led to the development of a number of approaches to backfilling of underground openings using clay-based materials and conduct of an extensive program of work to demonstrate their application (Posiva 2006).
### Table 3-3. Initial classification and ranking of backfill materials (design properties). (after Mott et al. 1983; Table 18)

<table>
<thead>
<tr>
<th>Material Type*</th>
<th>A Heat Transfer</th>
<th>B Hydraulic Properties</th>
<th>C Chemical Properties</th>
<th>D Radio-nuclide Properties</th>
<th>E Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Zeolites</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Pozzolanas</td>
<td>R</td>
<td>2</td>
<td>2</td>
<td>1/2</td>
<td>3</td>
</tr>
<tr>
<td>Hydraulic Cements</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Minerals/Aggregates</td>
<td>1/2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bitumen</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

* Spoil materials not included in original group classification since a variety of host media were considered. Crushed spoil was deemed to generally equivalent to siliceous aggregates.

R - Fundamental uncertainties concerning longevity.

### Table 3-4. Summary of initial materials screening and classification. (after Mott et al 1983; Table 19)

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DEFINITION</th>
<th>SCREENING &amp; CLASSIFICATION CRITERIA</th>
<th>MATERIAL GROUPS/TYPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Materials properties are well known, allowing for quantitative performance evaluation</td>
<td>LONGEVITY RANKINGS (SCREENING) predominantly 1 and 2 PROPERTY RANKINGS (CLASSIFICATION) predominantly 1 and 2. Ranking 3 tolerated if property likely to be improved by mixing with other constituents.</td>
<td>➢ Crystalline rock spoil, ➢ Illite, kandites, smectites, ➢ Portland cements, ➢ Pulverized fly ash, ➢ Natural sands and gravels, ➢ Crushed silicious aggregates, ➢ Industrial bitumens</td>
</tr>
<tr>
<td>2</td>
<td>Material properties are known to an extent that allow them to be tentatively incorporated in backfill, pending the outcome of further research</td>
<td>LONGEVITY RANKINGS (SCREENING) predominantly 1, 2 and R PROPERTY RANKINGS (CLASSIFICATION) predominantly 1, 2 and R. Ranking 3 tolerated if adverse property likely to be improved by mixing with other constituents.</td>
<td>➢ Palygorskites, ➢ Natural zeolites, ➢ Natural pozzolanas, ➢ Polymer/hydrothermal cements</td>
</tr>
<tr>
<td>3</td>
<td>Materials which may possess desirable attributes but properties are poorly understood</td>
<td>LONGEVITY RANKINGS (SCREENING) are 1, 2, 3 and R PROPERTY RANKINGS (CLASSIFICATION) High proportion of R-rankings</td>
<td>➢ Vermiculite, ➢ Synthetic zeolites</td>
</tr>
</tbody>
</table>
4 BACKFILLING OF UNDERGROUND OPENINGS

Backfilling of underground excavations involves installation of filler material(s) into the openings following completion of the activities that initially required the removal of the naturally-occurring geologic materials. Reasons for excavation are numerous but commonly include activities such as: mining, underground facilities construction (e.g. natural gas storage, subways, or utilities installation (e.g. water, gas, electrical conduits…). Once the purpose for which the excavation was made has been accomplished there is commonly a need to backfill the openings in order to: provide mechanical support to the openings; stabilize the surrounding rock mass to facilitate closure or further excavation; reduce groundwater flow into or through the excavation; improve heat transfer characteristics (e.g. electrical power lines) and a variety of other purposes. One of the first steps in determining the backfilling approach is to define the functional requirements of the backfill.

Backfilling of underground openings in a manner that results in filling to a density that will ensure that the tunnel does not exhibit unacceptably high localized water flow or develop gaps between the backfill and the crown of the filled opening is not a simple process. The role and purpose of backfill in underground mine openings is also not the same as in a repository for spent nuclear fuel. It is necessary to clearly define the goals of backfilling in each application and in some cases the purpose of backfilling will vary within the same underground facility. As a result there is a need to evaluate past experience in non-repository applications of backfill and backfilling technologies and determine which have the greatest potential for successful application. The discussion in this section deals with the basic purposes and goals in backfilling in mines, civil construction and nuclear waste repositories. Detailed descriptions of some of the options and materials screened for suitability as backfill are provided below.

4.1 Purposes and goals of backfill in mining

Underground mining is a human activity that has spanned many thousands of years but only in the past 50 to 100 years has there been a substantial application of backfilling as a technological tool. Backfilling is typically considered to result in a permanent closure/abandonment condition and historically was not a requirement. In most cases the rock in which mines are located still contain some ore material that is not economically viable at the time of closure. As a result many mine operators prefer not to backfill and permanently seal workings so as to facilitate reopening at some undetermined time in the future. Mine regulations also historically did not require environmentally stringent closure plans and often mining companies ceased to exist once operations ceased, leaving no resources to properly backfill and seal them. As a result historically most mines were simply abandoned to either collapse or not as the local geologic conditions dictated. As a result there are a large number of major environmentally damaging (typically heavy metal or acid water – generating abandoned metal mine facilities around the world. Much of the environmental damage might have been avoided/limited if current mining practices, including backfilling and sealing of underground excavations were utilized.
The purposes of backfilling operations in modern mining operations is typically associated with one of the following basic needs/requirements:

1. To provide mechanical support to excavations to allow additional removal of ore (pillar removal) or else to limit/prevent surface subsidence as the result of excavation collapse;
2. To provide a location for disposal/isolation of mine tailings;
3. To “prevent” or limit groundwater flow into or through key locations within the mine;
4. To limit contaminated water discharge from underground openings; or
5. To prevent subsequent intrusion into abandoned mine workings.

In terms of providing passive mechanical support to excavations, backfill options are numerous. As part of ongoing mining operations where pillar and room excavation is often done (involving leaving part of ore body to provide roof support (pillar)). During ore extraction it is not uncommon to use some form of backfill to provide a passive support system in the already excavated volumes, thereby allowing later removal of part or all of the pillars (also ore material). This type of backfilling can be done using slurried mine tailings (with or without cementitious component to increase strength and stiffness), fine sand-sized materials (again with or without cementitious component), or may in some cases involve use of expansive foam. The particular type of filler material used depends on the stiffness required of the backfill, the geologic and geochemical environment present and the time over which the backfill is expected to function.

In terms of providing a location for disposal/isolation of mine tailings, old mine workings often provide an ideal environment. Typically the ore bodies disturbed during mining are not chemically stable in the wet, oxidizing conditions induced by mining and removal of the ore to the surface. This is particularly the case where sulphide ores are mined (acid mine drainage). Commonly the result of such disturbances is the initiation of oxidizing processes that can lead to generation of acidic solutions and associated mobilization of heavy metals and other undesirable compounds. Relocating mine tailings back into the geologic environment they originally came from can go a long way towards reducing rates and quantities of contaminants. This action is only a partial solution to the volume of waste rock generated by mining as the volume of tailings will always greatly exceed the volume that the intact rock originally occupied.

The use of backfill as a water control tool is common in operating mines as well as in mines that are being closed. Backfilling in an operating mine provides a means of reducing the volume into which groundwater can enter but also provides resistance to the movement of that water (and contaminants). This is of particular use where sections of a mine are closed off and water inflow control is needed to facilitate ongoing mining operations elsewhere. In such situations installation of large volumes of low permeability material can be used to reduce the rate at which water can move from the abandoned areas to the operating areas during ongoing operation of the mine, after which it serves to long-term function. This backfill normally has a requirement to function as an inflow-reducing material and is not expected to exhibit hydraulic characteristics comparable to the surrounding rock mass since its purpose is typically water control rather than flow prevention. Even so these backfilled volumes need to be installed to a high degree of consistency and uniform performance, especially where
they are expected to resist high inflow conditions and potentially high hydraulic gradients across them. As a result they may include the use of packed in place aggregate materials that are subsequently cement grouted or in situ compacted materials of low permeability (e.g. aggregate-clay mixtures).

Backfilling to control or moderate the movement of water into, through and out of mine workings is of particular importance in mining operations where there is an exit point for the mine drainage at or near ground level or if the site is located in a hydrological discharge location. Movement of water into mine workings typically occurs along pre-existing joints or fractures and so can oxygenate regions where reducing conditions previously existed. The result is often the production of acidic mine drainage and high metals content in the water that exits the mine workings. Where backfill is used to reduce the volume of water that can enter the excavations and reduce the rate at which the water can move there will be a greater tendency for the water entering the system to become anoxic/reducing, reducing the rate at which contaminants are generated and moved. It should be noted that the goal typically set for this type of backfilling operation is to slow the process down to rates that can be handled by the mine dewatering system and not to match the hydraulic character of the surrounding rock or ensure that diffusion-dominated mass transport is established.

Backfilling by its very nature also makes subsequent animal or human intrusion into the old mine workings more difficult and thereby makes the site a safer location with respect to inadvertent intrusion. The use of massive fill components (boulders or cemented materials) in those regions at or near the entrances to an abandoned mine facility provide an effective deterrent to casual intrusion but will not prevent a technologically capable intruder from re-entering the facility if it is unmonitored.

4.2. Purposes and goals of backfill in civil construction

Backfilling of underground excavations made as part of civil construction has a wide range of purposes and goals. In most cases backfilling is associated with the need to provide passive support to excavations once the civil structure/utility is installed or to provide a contiguous contact between the installation and the surrounding rock mass. For example, pipes or cables may have sand, mud, paste or cementitious materials installed into the annular space between them and the surrounding rock. In most respects the application of backfilling in civil construction is comparable to that described for the mining industry.

Another civil-engineering application for backfill-like materials is groundwater protection. Bentonite-based barriers are commonly used as liners or slurry trenches in order to protect the groundwater below and around landfills or sites containing hazardous materials. There is a considerable body of information available in the technical literature that discusses application of backfill-like materials in environmental protection applications. In Finland bentonite membranes and layers are also used to protect groundwater systems from saline runoff from highways (Hämäläinen et al. 2005) by providing an impermeable near-surface barrier to water infiltration and allowing separate collection of salt-impacted runoff. These are examples of applications
that provide increased confidence in the potential suitability of bentonite-based barrier materials in controlling contaminant migration (e.g. under saline groundwater conditions in a repository) and its ability to be installed in large quantities to high degrees of consistency. However near-surface barrier applications allow the use of large equipment and do not suffer the physical constraints (rock walls and confined areas) that are present in a repository environment.

4.3. Purposes and goals of backfill in a repository

While seeming similar in many ways to mine backfilling, there are many fundamental differences in the goals of backfilling in a repository for spent nuclear fuel. In mining the primary goals are to control water flow to manageable rates, provide support to poor quality rock following extraction of large volumes of ore and dispose of potentially chemically reactive tailings materials. A repository for spent nuclear fuel is a unique application in that excavation is solely for the purpose of installing a waste package. A repository will have special care taken during its excavation in order to minimize damage or disturbance to the surrounding rock and the rock extraction ratio is very low relative to most mining operations where backfilling is undertaken. In a repository the excavations are to be backfilled primarily to provide isolating capacity to the system and to make subsequent intrusion into the repository extremely difficult. Depending on the emplacement geometry selected and the local ground conditions, backfill may need to keep the sealing materials (buffer), installed adjacent to the canisters in place. Over the long-term backfill materials may also provide a limited degree of resistance to radionuclide movement through sorption of these materials onto the surface of clay and/or aggregate surfaces.

Backfilling in a repository can also assist in keeping the tunnel and room excavations mechanically stable, a function similar to that in mine backfilling but at a very different scale. In mine backfills, mechanical stabilization is intended either to provide a means of increasing the extraction ratio of the ore body, provide some limited resistance to water movement through the excavation or to prevent subsidence of the ground surface or vertically adjacent excavations. In a repository, excavation stabilization is predominantly associated with minimizing potential for ongoing development of the excavation-disturbed zone immediately adjacent to the excavation, especially if high rock stress conditions exist. Provision of even passive restraint at the rock surface can greatly affect the subsequent extent of the damaged rock zone around excavations (Chandler et al. 2002b). The low extraction ratio and the high strength of the crystalline rock means that surface subsidence is not foreseen to be a concern in a repository.

Associated with the basic mechanical function of backfill in a repository for spent nuclear fuel there is a need for it not to adversely affect the performance of other components of the repository sealing system. This means that it must maintain its chemical, mechanical and hydraulic characteristics over many thousands of years. Some of the evidence collected from field investigations that point towards the long-term stability of bentonites is presented by Smellie (2001). Specifics as to the expected role and performance of backfilling materials in a spent fuel repository are discussed in greater detail later in this document.
5 BACKFILL MATERIALS AND PLACEMENT OPTIONS

5.1. Backfilling of Repository Openings

5.1.1 Purpose of Backfilling

The requirements of a repository sealing system as outlined by Posiva requires that the backfill exhibit certain basic characteristics, presented in Table 5-1 (Posiva 2000, 2006). They include re-establishing of the equivalent of the initial groundwater flow and geochemical/transport conditions present at the repository site. This means that the disposal tunnels must be prevented from being major pathways for groundwater and contaminant transport. There is additionally the need for the backfill to prevent inadvertent (or casual) intrusion into the repository at some time in distant future. In order to accomplish these requirements the backfill must be able to ensure that the swelling clay used as the buffer material in contact with the corrosion-resistant canisters used to hold the spent reactor fuel in the location it is initially placed. There is also a need for the backfill to contribute to maintaining the tunnels as mechanically stable features. In the 2000 and 2006 Posiva program documents the purpose of backfill research and development activities in Finland was outlined. It can be described as focusing on identifying materials and methods (for production and emplacement) for a backfill that is able to tolerate the inflow of saline ground water without significant changes in its effectiveness as a safety barrier. A general conclusion was that the overall function of the backfill (assumed to be clay, aggregate or a mixture of these materials) could be achieved by maximizing the dry density of the backfill material and by minimizing the void spaces in the backfilled tunnels. In order to achieve this, a focus was put on developing improved compaction and other methods for backfill emplacement techniques.

As described in the repository concepts of Posiva (2000; 2006) and SKB (2002) there are a limited number of fundamental requirements of the backfilling material(s) related to ensuring that the requirements of the safety case are achieved. Table 5-1 summarizes the basic safety-case requirements defined for the backfill in the Posiva (2000) and SKB (2002) KBS-3 repository concepts. The wording of the two sets of requirements vary slightly but cover the same basic issues; mechanical suitability; minimizing mass transport; compatibility with other components and; long-term stability. The Posiva requirements for a KBS-3H-type repository do not contain a requirement to withstand compression by the buffer since they are not in contact.

In order to accomplish the established purpose of the backfill, it needs to be chemically and mechanically stable for very long times and should not have or develop any properties that could significantly degrade the function of the other barriers in the repository system. This typically has been interpreted to mean that backfill must therefore be stiff enough to keep the buffer in place in the KBS-3V geometry, have a sufficiently low hydraulic conductivity to prevent contaminant movement. The presence of at least a minimal (~100 kPa) positive contact pressure has been identified as being desirable in a backfilling material (Gunnarsson et al 2007). This pressure was subsequently increased to 200 kPa to provide a greater margin with respect to the ability to support the excavation. This pressure provides support the tunnel perimeter, limiting stress-induced rock degradation and ensuring that no open pathways develop between the backfilling material and the surrounding rock.
Table 5-1. Basic Safety-Case Requirements of Backfill for a KBS-3 repository.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posiva (2000)</td>
<td>Compressibility</td>
<td>Keep the buffer and canister in place in the deposition hole</td>
</tr>
<tr>
<td></td>
<td>Hydraulic</td>
<td>Prevent the tunnels from becoming major conductors of groundwater and transport pathways of radionuclides</td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td>Shall not have any harmful chemical interaction with other barriers</td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>Contribute to the stability of the tunnels.</td>
</tr>
<tr>
<td>SKB (2002)</td>
<td>Compressibility</td>
<td>In order to maintain density of buffer the backfill shall have a compressibility that is low enough to minimize the upward expansion of the buffer.</td>
</tr>
<tr>
<td></td>
<td>Hydraulic</td>
<td>To prevent the tunnels from being conductive pathways that influence water movement in the repository the backfill shall, over the entire length and cross-section of the tunnel, have a hydraulic conductivity in the same order of magnitude as that of the surrounding rock, or so low than the water transport is dominated by diffusion.</td>
</tr>
<tr>
<td></td>
<td>Interaction with other barriers</td>
<td>The backfilled tunnels shall not have any negative influence on the barriers in the repository.</td>
</tr>
<tr>
<td></td>
<td>Durability</td>
<td>The backfill shall be stable in a long-term perspective and its functions be maintained under the expected repository conditions.</td>
</tr>
</tbody>
</table>

The KBS-3H repository concept does not have emplacement tunnels in the same sense as in the 3V concept. In 3H, the canisters are installed horizontally in long, relatively small diameter drifts with the space between the canister and the surrounding rock occupied by highly compacted bentonite buffer. There is also the expectation that a concrete plug will be placed at the end of the emplacement drifts in the KBS-3H concept (Table 3). This eliminates the need for backfill to resist the swelling pressure generated by the buffer component. Backfill will not be needed until the access tunnels and other excavations are ready for final closure. This results in a less important role for backfill in the initial near-field isolation of the canisters as it will not be installed until a considerable distance from the canisters has already been sealed. Beyond the emplacement tunnels of the KBS-3V and the emplacement drifts of the KBS-3H concepts the role of the backfill in isolating a repository will be the same.

These basic differences in the KBS-3H and 3V repository concepts will therefore influence what type(s) of backfilling materials are deemed adequate and what installation approaches can be taken in repository backfilling.

Development and testing of backfilling concepts has been done through co-operative work with SKB within the BACLO (BAckfilling and CLOsure of the repository) project. The overall objective of BACLO is to develop backfill concepts and techniques for sealing and closure of the repository. The aim of the program is twofold: to develop
the technical feasibility of the concepts and to assess the ability of various backfill materials and emplacement concepts to meet the long-term safety requirements of a KBS-3V repository. The results of Phase III (2006-2008) of this project is documented in a report by Keto et al. (2009).

While the focus of Baclo is to develop backfill and backfilling concepts that have application in the KBS-3V geometry, much of the information developed is applicable to backfilling of a KBS-3H repository. In the KBS-3V concept the backfill is needed to fill the emplacement rooms, rendering that region relatively impermeable and it must be capable of resisting any upwards (vertically compressive) force developed by the buffer that surrounds the canisters in the floor of the emplacement tunnel. Beyond the emplacement tunnels of the KBS-3V repository concept, the backfill needs to fill other openings (access tunnels, ramps, service areas and ultimately shafts), ensuring that they do not provide preferential transport pathways for contaminant migration.

Other studies that address some unique aspects of backfilling for the smaller tunnel cross-section and slightly different material being considered are being undertaken by Posiva’s Baceko project.

The main system requirements for the backfill originate from long-term safety considerations and have evolved from those defined in Posiva (2000) to those outlined in Posiva (2006) and Tanskanen (2007). Additional subsystem requirements have developed from operational safety and radiation protection, environmental impact, as well as from programmatic, operational and economical consideration. Gunnarsson et al. (2006) outlined the backfill subsystem requirements related to the KBS-3V concept for the SKB program. They are essentially identical in either the KBS 3-V or 3-H geometries and therefore are to a large extent relevant to Posiva’s repository concept. As of early 2007 the performance requirements for backfill identified by SKB were:

- the backfill shall restrict advective transport in deposition tunnels so that the function of the bedrock is not impaired,
- the backfill in deposition tunnels shall restrict the upward swelling/expansion of the buffer so that the function of the buffer is not impaired (in KBS-3V),
- the backfill in deposition tunnels must not in other ways significantly impair the barriers safety functions.
- the backfill shall be long-term resistant and its functions shall be preserved in the environment expected in the repository,
- the backfill shall be based on well-tried or tested technique,
- the backfill properties shall be controlled against specified acceptance criteria,
- the backfill shall be efficient regarding consumption of raw material and energy,
- backfill installation shall be possible to perform in the specified rate, and
- the backfill shall be cost efficient.

The basic requirements for backfilling outlined in Posiva (2000) have changed slightly as more information has been developed regarding backfilling options and backfill requirements, but no major redirection has been necessary. The focus of work has remained the development of clay and clay-aggregate backfilling materials that have the characteristics required and demonstrating their performance. In order to reflect some of the site-specific concerns related to the geologic conditions likely to be present in
Finland, Keto (2003) expanded on the basic backfill materials properties requirements for a clay-based backfill of the type described in (Posiva 2000). In that report it was noted that the backfill should have the following properties:

1. Sufficiently low hydraulic conductivity in saline solution (TDS 35 g/l),
2. Low effective porosity, high bulk density and high clay and montmorillonite dry density,
3. Optimal gradation curve and optimal moisture content to provide optimal compaction properties to the backfill,
4. The interfaces between the tunnel and the backfill should be tight in order to avoid boundary flow,
5. Presence of swelling capacity (0.1 MPa), in backfill to hinder boundary flow and support the excavation openings,
6. Low compressibility and high value of shear strength.
7. High value of specific surface.

Beyond these points is the need for the backfill to prevent human intrusion and limit impact of glacial events. These points are also being addressed in recent backfill development activities being undertaken by Posiva and SKB.

5.1.2 Backfilling Concepts

Beyond the defining of potentially suitable backfill materials is the need to develop backfilling approaches that will be most appropriate for the different geologic, hydrogeologic and geochemical conditions that will exist within the rock mass where a repository will be constructed. In order to deal with variations at the repository site Posiva is considering an approach that will allow backfilling materials and methods to be varied to deal with local or regional conditions. This would involve turning the repository into a series of isolated compartments. Within each compartment the materials placed would be suitably uniform but materials placed in different compartments may differ in recognition of changing geologic, geomechanical, geochemical and other conditions. Examples of some of the backfilling options under consideration by Posiva are presented in Table 3-4.

Concepts that have/are being evaluated (Keto 2003; Gunnarsson et al. 2004) include:

A. Compaction of a mixture of bentonite and crushed rock in the tunnel.
B. Compaction of a natural clay with swelling ability in the tunnel.
C. Compaction of non-swelling soil type in the tunnel combined with application of pre-compacted bentonite blocks at the roof.
D. Placement of pre-compacted blocks; a number of materials are considered.
E. Installation of high quality plugs to isolate high hydraulic conductivity areas.
F. Combination of sections consisting of a) crushed rock compacted in the tunnel and b) pre-compacted bentonite blocks. The bentonite sections are installed regularly above every disposal hole.

These concepts were initially screened as described by Gunnarsson et al. (2003) based on the need for a backfill that will meet the initial requirements for backfill in the KBS-3 concept and concepts A, B and D have been examined in the joint Posiva/SKB BACLO program. Concept C considers predominantly non-swelling materials and so
was not examined in BACLO because it was not a low-permeability material that met the basic requirements for backfill as laid out in the original KBS-3 concept. Concepts E and F are composed of sections with different types of materials that require separate placement systems. The question of the effectiveness of these approaches where high permeability zones and a heterogeneous backfilling system is present resulted in a recommendation that no further work should be directed specifically at those concepts in phase 2 of the BACLO project (Gunnarsson et al. 2003). However, options E and F form the basis of the compartment concept and so have been examined by Posiva as activities outside of the BACLO project as they would be used outside the deposition tunnels. Additional backfilling approaches for regions outside the deposition tunnels include the use of two different backfill materials installed in different manners as shown in Figure 5-2 (Maak and Simmons 2005) a variation of which has been examined by Korkiala-Tanttu and Ritola (2006) which is described in Section 5.2.3. JAEA (Japan) has developed a similar range of backfill placement concepts (JNC 2000).

![Diagram of backfilling concepts](image)

**Figure 5-1. Options for backfilling and Sealing. (Gunnarsson et al. 2004)**

In the compartment concept for sealing, the various regions within the repository and its access ways would be treated separately, with installation of a series of very high-quality plugs or regions with higher quality backfilling materials and shown in Figure 5-3. These high-quality plugs isolate regions that are filled with backfill materials that are not particularly effective as hydraulic barriers (e.g. crushed rock or lower density aggregate/clay materials). This approach to backfilling would be particularly relevant in regions where the local rock is fractured or of limited quality and so installation of a high-quality backfill would not be particularly effective in controlling groundwater movement. As the purpose of backfilling of these regions would be to maintain an overall hydraulic performance of the system to the equivalent to the original geologic conditions, this approach may be appropriate in some regions of the repository. In regions where rock quality is better plugs or backfilling materials that provide hydraulic disconnects could be installed. This approach is consistent with the hydraulic requirements outlined in Table 5-1 (Posiva 2000).
Figure 5-2. Backfilling in Canadian concepts. (Maak and Simmons 2005)

Figure 5-3. Options for Backfilling of Shafts and Ramps.
Evaluation of a range of materials and technologies that could be used to achieve the backfilling goals in the various backfilling options described above has been the focus of ongoing work by Posiva as well as other organizations interested in the isolation of nuclear fuel waste in a geologic medium (e.g. SKB, NAGRA, NWMO, JAEA). As a result of the consideration of both uniform backfilling and compartment concepts for repository backfilling and plugging re-evaluation of options for backfill materials and approaches is appropriate. In order to document the reasoning for the backfilling approaches selected as being most appropriate for Posiva’s repository concept, a review of backfilling requirements, concepts, materials and experiences associated with underground openings is provided. Based on this review, the options available for backfilling a repository are presented, discussed and a brief summary of the results of studies to determine the appropriateness of the selections is provided.

5.2 Materials Options and Emplacement Technologies for Backfill

5.2.1 Review of Backfilling Options

As described above, the backfilling approaches examined by Posiva, SKB and most other national programs evaluating options for a spent fuel repository in hard crystalline rock (e.g. Canada, Japan), have focussed on development of clay-based materials. These materials and methodologies that can be applied to install them as reasonably uniform volumes in the tunnels, shafts and ramps of a repository have undergone extensive evaluation. Despite this focus on clay-based materials, repository concepts are not inflexibly defined and so a number of other backfill material options have been and continue to be examined.

The general background and history leading to focussing on clay-based and aggregate backfill materials has been described previously. The selection of clay and clay-aggregate materials as the primary focus for backfill development work did not preclude ongoing monitoring of alternative materials and technologies; especially those associated with mine backfill development. This section discusses the initial screening of and subsequent development of these options and assesses their suitability for use in Posiva’s repository (2000, 2006).

The development of the KBS-3 concept included the recognition that there was the need of backfill materials to effectively fill the room and tunnel openings left after canister installation was completed. The backfilling material and the means by which it was to be emplaced was not rigidly defined in order to allow room for system modification and technology development. The basic assumption in the concept development stage was that the backfill would likely be a mixture of a clay mineral-based material and aggregate (either crushed host rock or other suitable material) that would have some capacity to swell to fill any voids or defects that might occur during the backfilling process. By using such materials it was anticipated that the requirements outlined in Table 5-1 could be met but it was necessary to demonstrate the means by which placement could be done and quantify the effectiveness of the backfill. The early selection of clay-based backfill was not arbitrary but was based on careful consideration of the options available.
Based on early evaluation of the functional purposes of backfill and materials that could provide these functions a wide range of materials and technologies are available. For the purposes of this report, clay-based backfilling materials are defined as those containing a clay-mineral fines component. The clay material component(s) can be mixed with aggregate to produce a mixed clay-aggregate backfill. This means that clay-based backfill includes clay-only, artificially blended clays mixed with aggregate, as well as mixtures of natural clay and aggregate. There are also potential backfill materials that do not contain a clay-mineral component although they may contain a clay-sized component. For the purposes of this report these materials are defined as being aggregate backfill. Work towards demonstration of suitable backfill materials and their installation in various regions of a repository has resulted in a number of options being developed.

Most programs focussed their initial efforts on the barrier materials closest to the spent fuel (canister, buffer) and left development of barriers farther from the canister until later. Posiva began its backfill development and evaluation work with Kirkkomäki (1997) where a 15% bentonite clay, 85% crushed rock mixtures was proposed. This concept has since undergone re-evaluation as the result of the 2001 selection of the Olkiluoto site as a potential repository location. Initial site evaluation at Olkiluoto identified groundwater salinity as high as 3.5%. Given the sensitivity of relatively low bentonite-content materials to salinity (Dixon 2000) and the identified need for the emplacement room backfill of the KBS-3V concept to provide some positive pressure on the surrounding rock the backfill materials and installation concepts have been re-evaluated by Posiva. This re-evaluation has included participation in the BACLO project (a joint Posiva-SKB project) as well as studies conducted by Posiva. In many cases testing and demonstrations have been conducted at-or-near full-scale to confirm performance of candidate materials and to evaluate various backfilling options. The range of options and materials that were initially identified or have subsequently been evaluated are briefly discussed below and are listed in Table 5-2.
**Table 5-2. Backfill Materials Examined and Placement Techniques Considered.**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>PLACEMENT TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thrown*</td>
</tr>
<tr>
<td>Bentonite</td>
<td>√^1</td>
</tr>
<tr>
<td>Natural swelling clay</td>
<td>√^1</td>
</tr>
<tr>
<td>Non-swelling clay</td>
<td></td>
</tr>
<tr>
<td>Bentonite &amp; aggregate</td>
<td>√</td>
</tr>
<tr>
<td>Aggregate &amp; natural clay</td>
<td>√</td>
</tr>
<tr>
<td>Non-swelling clay &amp; aggregate</td>
<td>√</td>
</tr>
<tr>
<td>Aggregate – only</td>
<td>√^2</td>
</tr>
<tr>
<td>Aggregate &amp; cement</td>
<td></td>
</tr>
</tbody>
</table>

* Includes placement by high-energy air-blowing and mechanical throwing
** Densification through pile installation
^ For the purposes of discussion this is defined as including paste injection and rocky paste injection technologies.

1 Precompacted pellet and granulated clay material used to fill space between main backfilled volume and roof/perimeter regions
2 Shotcrete, Gunnite materials, well established technology

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5.2.2 Geologic Conditions Affecting Backfill: Groundwater Salinity

A number of factors have been identified that have the potential to adversely affect the performance of clay-based backfilling materials. These include factors induced by the construction and operation of the repository (e.g. oxidation of surrounding rock, introduction of non-native microbes, elevation of pH as the result of grouting activities or introduction of other cementitious materials). These topics have been discussed in a large number of documents developed by various national programs examining repository concepts and are not further discussed in this report (excepting a general discussion on the impact of cementitious backfill materials provided in Section 4.3).

One factor of considerable importance to repository performance and not able to be changed through engineering, materials selection, or remediation is the natural groundwater salinity.

The effects of saline porefluids on clay-based materials has long been recognized both in the natural environment (e.g. Norwegian and Canadian Quick Clays) and engineered barriers to contaminant migration. In the natural environment there is a general tendency for groundwater salinity to increase with depth in crystalline rock (especially granitic plutons). Beyond such general trends it is impossible to predict the magnitude of the increase with depth prior to actually doing site investigations and salinity range will vary dramatically depending on the site and host medium. The basis for choosing salinity of 3.5 % (TDS) as the design value for the Finnish repository located in Olkiluoto is described in Vieno (2000):
“Today the salinity at the depth of 500 metres varies from 15 to 25 g/L. A design basis value of 35 g/L would allow intrusion of groundwaters presently lying 100 to 200 metres below the 500 metre level. As 35 g/L is the salinity of ocean water, it would also take into account the maximum possible salinity of water infiltrating at the surface.”

In contrast the URL site in Canada found TDS concentrations as high as 9% at depth of 400 m (Gascoyne et al. 1987) and the Äspö site in Sweden has only 1 % (SKB 2004).

The basic performance requirements of the backfill are to ensure that its ability to prevent preferential pathways for contaminant migration (3V and 3H) is maintained and that it provides modest support to the emplacement tunnel walls (3V). These basic requirements have resulted in a need to carefully consider a range of materials and potentially disruptive processes as part of the process of identifying suitable backfill materials. Kjartanson et al. (2003) provided a review of the basic backfilling concepts and clay-based materials options and identified issues related to the then current status of backfilling development. Of primary concern at that time and still valid for backfill materials for repository use in Finland, Sweden, Canada and elsewhere where the repository is located below the local water table, is the influence of groundwater composition. Using the information provided by Dixon (2000) it is possible to assess the influence of porefluid salinity on the swelling pressure developed by and the hydraulic conductivity of smectitic clay – based backfills, particularly as they might influence a repository in Finland. The basic density requirements for the emplacement tunnel backfill (KBS-3V) are to achieve the hydraulic properties required (diffusion based mass transport) and minimum swelling pressure (200 kPa positive pressure at rock-clay contact) targets. Both of these parameters are influenced by the specific swelling clay used (smectite content), density achieved as well as the local groundwater salinity. Based on a combination of laboratory performance data and field emplacement data for backfill it can be concluded that many of the initially proposed backfilling options (e.g. in situ compaction of bentonite-aggregate mixtures) would not likely achieve the performance required of an emplacement room backfill in the KBS-3V concept. This is supported by the results of field tests at the Äspö facility in Sweden (Gunnarsson et al. 2001) where densification was highly problematic, especially in the crown regions or where water inflow was occurring during backfill placement. In order to evaluate other materials for suitability an ongoing program of work is being undertaken by Posiva as part of both the buffer development and Baceko programs.

As a result of the established influence of groundwater salinity on the swelling and hydraulic performance of backfill materials there has been a concerted effort to develop materials and technologies that can maximize the degree of densification achievable in repository tunnels. These materials and approaches include development of precompacted backfill block emplacement to fill the majority of the tunnel volume and the use of highly compacted bentonite pellets to fill the remaining volume. These technologies are described below.

5.2.3 Clay - Only Backfill

Posiva, SKB and Nagra have all considered the use of clay-only materials as backfill. Materials considered include clays compacted in situ in the tunnels, rooms and ramps,
precompacted natural clay materials (typically containing a smectite clay component), precompacted natural clays that have their swelling and hydraulic properties improved through blending in smectite clay. Most commonly the smectite considered for addition to natural clay materials is the industrially produced clay known as bentonite. Bentonite is produced by drying and crushing of natural montmorillonite-rich clay-shale materials and has good swelling properties, a low hydraulic conductivity but these properties can be sensitive to groundwater salinity, especially when its density is low (Dixon 2000).

Pneumatic and Throwing-type Installation
Placement of clay-only materials (materials composed of fines-only), as a backfill can be achieved through placement of granulated or pelletized clays using air-emplacement techniques (similar to shotcrete) or mechanical throwing technologies (ie. using conveyor-belt –type equipment).

Air-emplacement techniques are being considered by Posiva, SKB, NAGRA and NWMO to allow for installation of backfilling materials into confined volumes where other emplacement or compaction approaches are not effective. Figure 5-4 shows examples of some of the emplacement trials done in Canada as part of the Canadian NWMO’s contribution to the BACLO project. Finland, Sweden and Canada have actively examined methods to blow or throw pellets or clay-aggregate mixtures in order to achieve the maximum possible densification in backfilled tunnels (Baumgartner and Snider 2002; Martino and Dixon 2006; Gunnarsson and Börgesson 2004). Of particular interest is to develop a means of placing fill materials into confined regions such as the tunnel crown. Granulated or pelletized clay materials have been demonstrated as being placeable using this technology but the density achievable is limited, but still results in a better system than one where a portion of the tunnel volume is initially unfilled. Figure 5-4 shows examples of the type of equipment and materials utilized in placement trials done as part of the BACLO project.

Throwing using conveyor-belts, blowing using shotcrete-type equipment and augering technologies are also being considered by Nagra as potential means of placing backfill for its repository concept in sedimentary rock (Mayor 2005; Nold 2006). It should be noted that the Nagra horizontal emplacement concept does not differentiate between buffer and backfill as the canister is placed horizontally on a bed of precompacted bentonite blocks and then the majority of the openings are filled with pellets of densely compacted bentonite clay. The Nagra concept differs in several key aspects from Posiva’s KBS-3H, primarily in that the Nagra concept involves much larger emplacement drifts which will require and allow for operation of backfilling equipment rather than the narrow clearances present in the KBS-3H geometry. The Nagra repository concept also calls for the facility to be located in dry (no liquid water inflow), sedimentary rock and will operate at an intentionally higher repository temperature (>100 C). All of these features result in a system where backfilling materials must function in a very different environment to that expected in Finland and result in different options for materials and their placement being available. The basic differences in the repository concepts of Nagra and Posiva does not mean that techniques developed by Nagra to manufacture and place bentonite pellets cannot be adopted, if appropriate, to backfilling some regions in Posiva’s repository.
In Situ Compaction
In situ compaction of the clay materials is possible under conditions where essentially no groundwater inflow occurs. This approach is very sensitive to the water ratio of the clay materials and the compaction effort applied and so water influx or variations in tunnel geometry will make effective and consistent densification problematic. Under conditions where there is no water influx, properly blended and water conditioned clay materials can be taken underground and placed using conventional compaction equipment (e.g. rollers, dynamic impact equipment). This approach also has limitations as to the densification achievable and uneven densification will occur, especially adjacent to the perimeter of the openings. Of particular concern would be how to achieve adequate compaction in the uppermost regions of the backfill and to quality-assure their installation. As a result this approach may be more suitable to regions more removed from the emplacement tunnels or drifts of the KBS-3V and KBS-3H concepts.

Use of Dense, Precompacted Blocks of Clay
One solution to compaction inefficiencies in clay-only backfilling materials and sensitivity to local water inflow conditions is the production of large precompacted
blocks of high density. These blocks can be manufactured under controlled conditions a considerable distance away from the volume to be backfilled and then transported to the installation location where they are carefully placed as shown schematically in Figure 5-5.

![Figure 5-6. Moving the blocks to the desired location.](image1)

![Figure 5-7. Placing the blocks.](image2)

**Figure 5-5. Placement of precompacted clay blocks.** (Gunnarsson et al. 2006)

Spaces between the block filled volume and the excavation perimeter can be filled with more clay-based materials using throwing technologies (air or mechanical). This concept is being actively developed and evaluated as it has the potential to simplify quality control and ensure placement of a backfill to a high average density, as well as utilizing already established technologies for manufacturing and materials movement. It also allows backfilling to deal with the uneven surfaces and variability in the cross-sectional area of the openings. Large-scale emplacement trials of block and pellet backfill have been completed at the buffer laboratory at SKB’s Äspö facility (Wimelius and Pusch 2008). This two-component backfilling approach shows promise as a means of backfilling in challenging conditions, especially those regions where water moves into and through the system during backfilling operations. Posiva, SKB and other organizations are addressing questions related to placement technology and the behaviour of the backfill both within the BACLO project as well as independently supported work related to SKB and Posiva repository-specific issues (e.g. different excavation geometries).

In a nearly reverse approach to the current Posiva and SKB backfilling concepts (where precompacted backfill blocks are installed to occupy the majority of the tunnel volume), precompacted blocks of swelling clay can and have been installed in backfilled volumes
where in situ compaction was used to install clay-aggregate materials into the majority of the openings (Gunnarsson et al. 2001a,b). Densely compacted clay blocks (together with highly compacted bentonite clay pellets) were used to fill the crown regions where in situ compaction of clay-aggregate materials was less effective than desired Figure 5-6. The intent of the installation of the blocks and pellets into the crown region was to ensure that this region had adequate density to ensure that a positive pressure was maintained in the tunnel crown and that no gaps were present, even if the porewater salinity was elevated. This approach was utilized in the Backfill and Plug Test as well as the Prototype Repository Test at Åspö. The issue of porefluid salinity was briefly discussed in Section 5.2.2.

![Figure 5-6. Use of precompacted clay blocks near crown of tunnel. (Gunnarsson et al. 2001a)](image)

### 5.2.4 Clay – Aggregate Mixtures

Mixtures of clay (bentonite, natural smectitic or mixture of bentonite and natural clay) and aggregate are under active consideration for use as repository backfill in Finland, Sweden and Canada (Pusch 1998; Pusch and Gunnarsson 2001; Kjartanson et al. 2003; Keto 2003; Gunnarsson et al. 2004). There are numerous advantages to this type of material (improved compaction characteristics (higher dry density), higher strength, lower compressibility, reduced use of imported clay materials, lower cost for clay material component….). This type of material was the focus of much of the early work in Canada related to backfilling of repository openings (Yong et al. 1986) and a wide range of potentially suitable clay-aggregate materials and emplacement techniques have been developed and demonstrated. Much of the information related to bentonite-sand material developed as part of Canada’s buffer development program as well as demonstration of tunnel sealing technologies (Chandler et al. 2002b).

**Pneumatic and Throwing-type Installation**

As with the clay-only backfills described above, it is possible to pre-manufacture clay-aggregate pellets for installation into confined spaces. Similarly, blends of clay, sand and gravel materials have been produced and placed using air-entrainment and throwing equipment of the type described previously. A range of materials have been mixed and
successfully tested in field or simulated field conditions (Baumgartner and Snider 2002; Chandler et al. 2002a; Martino and Dixon 2006; Gunnarsson and Börgesson 2004 (clay pellets only)). The same types of equipment and installation techniques presented in Figure 5-4 have also been used in field trials to place aggregate-clay mixtures using conventional shotcrete technology. With careful application these materials can be placed relatively quickly (4 to 10 m$^3$/h) to a reasonably high degree of uniformity but the achievable dry density is somewhat limited (1.4 to 1.5 Mg/m$^3$ for an aggregate-clay mixtures of 50 to 70% clay content), Baumgartner and Snider (2002), Martino et al. (2003), making this approach potentially problematic as a solution for overall tunnel backfilling (the density of the bentonite component is quite low and so the system is sensitive to changes in porewater chemistry). These materials and this placement technique do however have application in filling gaps between precompacted blocks or in situ compacted materials and the surrounding rock mass. Tests done using highly compacted bentonite pellets and pneumatic emplacement achieved dry densities in the order of 1.1 to 1.2 Mg/m$^3$, which is sufficient to maintain a limited positive swelling pressure within the backfilled volume (Martino et al. 2003).

Backfill blowing and throwing technology has been adapted to and is commonly utilized in the mining industry, where backfilling of mine opening are often undertaken. In mine applications the materials installed are typically mine tailings or spoil materials, often with some cementitious component rather than clay. This technology is discussed in greater detail as part of discussion of aggregate-only and aggregate-cement backfilling materials and placement systems.

**Manufacture of Precompacted Blocks of Aggregate-Clay**

As with the manufacture of precompacted blocks of clay, the ability to manufacture and place blocks of aggregate-clay material in repository-like environments has been demonstrated (Gunnarsson et al. 2006; Chandler et al. 2002).

Aggregate-clay mixtures have a number of attractive features, including:

- need for lower compactive effort during manufacture,
- improved dry density,
- higher stiffness,
- greater physical durability (important during handling and placement), and
- a lower unit cost as aggregate replaces more expensive clay materials.

Many of these trials involved relatively small sized blocks (largest so far produced is 0.8 x 0.6 x 0.5 m) and shown in Figure 5-7 but manufacture of larger blocks is technologically possible (Gunnarsson et al. 2006). Development of equipment to lift and place these blocks is also under development (Gunnarsson et al. 2006).
Figure 5-7. Large Precompacted blocks of backfill. (Gunnarsson et al. 2006)

In situ Compaction of Aggregate-Clay Materials

In situ compaction of aggregate-clay mixtures has been the focus of considerable work within Posiva, SKB and other national programs looking at technologies to install densely compacted aggregate-clay materials in a repository. Clay-aggregate mixtures have been prepared and compacted in situ in a variety of studies (Gunnarsson and Börgesson (2002); Gunnarsson et al. (2004); Korkiala-Tanttu et al. (2007); Gunnarsson et al. (2006) and Dixon et al. (2002).

In situ compaction is a viable means of installing backfill in large openings in a repository, especially vertical or near-vertical openings such as shafts and ramps. Horizontal openings such as tunnels and rooms are somewhat more problematic and there are difficulties in achieving uniform densification, especially in the regions close to the crown of the tunnels and rooms. Another issue related to in situ compaction, as well as most other options for backfill placement is inflow water from the surrounding rock. The presence of inflowing water in tunnels, rooms, ramps or other openings that are to be backfilled makes densification problematic, particularly if in situ compaction is desired. In situ, as well as most means of backfill compaction is water ratio sensitive and compactability is typically degraded with the presence of water ratio beyond a fairly narrow range (range is dependent on the particular material used and the density desired).

Studies at the Äspö facility in Sweden and elsewhere have demonstrated the ability to install large volumes as inclined layers in repository-like conditions using in situ compaction (Gunnarsson et al. 2001). Recent studies have also identified areas where improvements to the compaction process can be made (Adam 2006 in Korkiala-Tanttu et al. 2007). Examples of the approaches proposed for compaction of inclined layers of backfill and equipment developed to test their effectiveness are presented in Figure 5-8 through Figure 5-10.

As an alternative to full-face compaction of inclined layers, high degrees of densification can be achieved in the lower portions of tunnels using conventional
horizontal roller or impact compactors as shown in Figure 5-10. The use of horizontal compaction in tunnels and rooms is not a complete solution to backfilling, as it cannot be used to fill the entire volume, eventually there is insufficient headroom to operate the compaction equipment. Once that point is reached in the backfilling process other compaction equipment or techniques must be used. Examples of these options are placement of materials using blowing or throwing technology or placement of precompacted blocks Figure 5-4, or other backfilling approaches e.g. Figure 5-6 and Figure 5-11. These approaches are also discussed below as part of enhanced in situ compaction options.

**Figure 5-8.** In situ compaction of inclined layers of backfill. (after Gunnarsson et al. 2001)

**Figure 5-9.** Machine-Mounted Compactor. (photo by P.Keto)
Challenges to achieving adequate densification in the crown regions of the tunnels and rooms has been recognized in most backfilling approaches including KBS-3 and that proposed by Canada. In the KBS-3V and 3H concepts, a variety of options have been examined including development of specialized compaction equipment and use of different materials in different parts of the backfilled volume (Korkiala-Tanttu and Ritola 2006). In Canada two distinctly different backfill materials were identified as being needed to effectively close the tunnels and other underground openings. They were defined as Dense Backfill and Light Backfill in reference to their relative density. The manner in which they would be placed would also differ; dense backfill could be in situ compacted or installed as precompacted blocks while the light backfill is generally assumed to be blown into place and would occupy the crown and perimeter regions where dense compaction was not achievable (Dixon et al. 2001).

**Figure 5-10.** In situ compaction of horizontal or inclined layers of backfill using roller and vibratory plate technologies. (Korkiala-Tanttu et al. 2007).

**Figure 5-11.** Composite backfill using precompacted blocks. (Gunnarsson et al. 2004)
The use of a swelling clay component in more densely compacted (lower) aggregate-clay backfill regions provides it with the ability to expand, autonomously-densifying the lower-density materials close to the roof and walls of the openings. While an attractive feature in the backfill there are still concerns regarding the degree to which equilibration process can be relied on to ensure that adequate density is achieved. As a result studies are ongoing to determine the rate and degree to which adjacent dissimilar materials will deform and homogenize.

In situ compaction of aggregate-clay mixtures provides an ability to vary the proportion of clay used in the backfill without major technological impact on the backfilling process, thereby allowing modification of the backfill to reflect regional hydraulic performance needs. The variation of material composition can be done without the need to undertake major equipment changes, only the procedure used to achieve compaction (time and effort to be applied to compact backfill).

**Enhanced In Situ Compaction**

Enhanced in situ compaction involves the densification of the backfill beyond that initially obtained during placement. In most situations this is associated with post-placement densification of clay-aggregate, or in some situations aggregate-only backfills. There are a number of techniques that could potentially be used to improve the as-placed density and Korkiala-Tanttu and Ritola (2006) review a number of options having the potential in achieving post-placement densification of backfill in a repository. To aid in assessing some of these options, they were assessing based on their Strengths, Weaknesses, Opportunities and Threats to their functionality (SWOT) (Korkiala-Tanttu and Ritola 2006). The basic results of these assessments of these approaches to enhanced in situ compaction are reproduced below (with some modifications resulting from more recent considerations):

1. **Horizontal in situ compaction with shotcrete technology**: Used to install “shotclay” material in crown regions (technologies examined by AECL of Canada (Baumgartner and Snider 2002; Chandler et al. 2002b, Martino et al. 2003) as part of the engineered barriers development work supported by NWMO (Canada) and more recently as NWMO’s contribution to the BACLO project (Figure 5-4). Aggregate-clay backfill materials can be placed using shotcreting technology at dry densities in the order of 1.4 to 1.5 Mg/m³ (for bentonite-aggregate mixtures containing from 50 to 70 % by mass of bentonite) (density achieved depends on composition of material placed). Within the BACLO project Posiva and SKB have done additional work to evaluate this technology for installing highly compacted bentonite pellets (discussed previously in this document).

   - **Strength**: - basic techniques known,
     - tunnel shape not critical,
     - basic technology exists,
     - filling can be done in steep(near vertical) layers.

   - **Weaknesses**: - potentially too low a density attained,
     - may require post-placement compaction,
     - need for compressed air,
     - unevenness of roof may be a problem.

   - **Opportunities**: - placement can be made in long lengths.

   - **Threats**: - is compaction adequate,
- can machine operate in low headroom and long lengths,
- Interaction between backfill and equipment,
- Material rebound,
- Mixing between layers and removal of joints between layers

2. **Displacement method:** Involves horizontal in situ compaction in lower tunnel, shotclay in crown and then installation of displacement piles into crown region to densify that material (Figure 5-12).

In many ways this concept parallels technologies applied to improve the density and strength of soft soils prior to construction of buildings or other infrastructure. In those applications the soil (often a very soft clay), has a large number of displacement piles installed. These piles act to provide higher soil bearing capacity to the foundation but if placed close enough together, actually act to densify the soil contained within the piled region to achieve further strengthening of the soil.

While the primary purpose in a repository would not be to increase the strength of the backfill, displacement piling does have the potential to densify the upper backfill. This would result in a lower hydraulic conductivity and a higher stiffness upper backfill region that would be less susceptible to compression by the underlying higher–density materials thereby improving overall backfill performance.

**Strengths**
- can be used to increase densification,
- shape of tunnel does not affect results.

**Weaknesses**
- only short sections of backfill (8-10m) densified at one time,
- need to develop machinery, methods and materials,
- horizontal piling is not a well-developed technique.

**Opportunities**
- can be used to increase compaction.

**Threats**
- ability to achieve compaction goals is not known,
- non-uniform compaction,
- reinforcement needed for face of underlying layered fill materials (base collapse),
- durability of pile materials,
- generation of corrosion gases in long-term (steel piles).
3. **Mechanical compression:** Involving full-face mechanical compression (with or without vibratory component). This technique would use pressing plates; vibratory compaction and a backfill material feed system to place material into the tunnel along its entire face. This placement process would involve a series of thin layers and machine, like a TBM that uses the rock walls as reaction backing to apply a mechanical pressure against the entire vertical face of the backfilled excavation as shown in Figure 5-13. There are a considerable number of potential difficulties in both construction of such equipment and then determining its effectiveness.

- **Strengths**
  - Efficient compaction,
  - One piece of equipment used.

- **Weaknesses**
  - Machinery not developed yet (cost and time).

- **Opportunities**
  - One technique for full tunnel, one working stage.

- **Threats**
  - Can one machine’s pressing plates be constructed to effectively cover entire tunnel cross-section,
  - Can a workable machine be developed?

Figure 5-13. Full-Face mechanical compression of backfill. *(Korkiala-Tanttu & Ritola 2006)*
5. **Vertical seal walls** involving installation of regions of high-density bentonite, cementitious grout or bentonite-aggregate added to already installed backfill using high-pressure injection via pre-installed tubes (Figure 5-14). In this approach the lower regions of the tunnel would be compacted using in-situ technique to achieve target density to as high an elevation as possible. Once maximum in situ compacted depth is achieved a series of injection pipes are installed and the remaining volume is filled with backfill using shotcrete or other placement technique. The injection tubes are then used to pump dense, paste-like bentonite, bentonite-sand or cementitious materials to compress backfill and also essentially clay grouts perimeter. This means formation of series of cut-offs that will improve density and reduce hydraulic conductivity of backfill near roof and perimeter. Will also require installation of concrete support walls every 30-40m to provide support to BF during injection process.

**Strengths**
- simple and efficient
- not much equipment needed,
- length can be varied,
- improves contact between roof, walls and filler,
- time before injection can be varied.

**Weaknesses**
- need for concrete wall (curing time),
- composition of injection material ?,
- quality of compaction hard to ensure,
- long-term safety and functionality?

**Opportunities**
- flexible approach,
- potential for using different materials in different areas.

**Threats**
- can the required bentonite density be attained?
- chemical compatibility with other system components.

![Figure 5-14. Vertical seal walls and injection densification. (Korkiala-Tanttu and Ritola 2006)](image-url)
5.2.5 Aggregate - Based Backfills

Experiences in mines and other openings
Installation of backfill into underground openings is a technology that has been developed by the mining industry. Literature from this source provides useful insight into what materials and technologies may be useful in a repository environment and which are not.

Tunnels and ramps constructed to gain access to regions having suitable geologic conditions for canister installation will likely pass through regions of lower quality rock. Based on the compartment concept for repository sealing described previously (Figure 5-1 and Figure 5-3) there may not be the need for very low permeability backfill within such regions of low quality rock. In such regions installation of aggregate-only materials may prove to be as effective as clay-aggregate or other fill materials. In such regions there is also a greater potential for loss of fine-grained or colloidal clay materials into the fractures in the surrounding rock as the result of hydraulic and geochemical processes. Aggregate fill would not be as susceptible to such processes. There may also be regions where a very low permeability backfill is not what is needed to prevent subsequent intrusion into the tunnels or to resist glacial action. As a result of these factors, evaluation of aggregate materials is a topic that has received ongoing consideration as part of Posiva’s backfill development program.

Use of aggregate-only or aggregate with some cementitious component has been evaluated on an ongoing basis since the initiation of backfill development work and was included in the discussions by Mott et al. (1983). Since that time, options for use of these materials have been part of the regular evaluation of technology process in repository development work. With the introduction of the compartment-concept for deposition tunnels, access routes and other cavities (Autio et al. 2001), a wider range of aggregate-based backfill materials and options for their placement have been examined.

Aggregate materials are often used in conjunction with cementitious materials in backfilling of underground openings for mining applications. For the purposes of this document and in recognition of the potential role of aggregate-based backfilling materials, cementitious and non-cementitious backfilling materials and technologies are discussed separately in this report. Materials that do not contain cementitious materials are discussed in this section while those containing cementitious materials are discussed in Section 5.3.

Aggregate produced from excavated host rock are perhaps the most mineralogically and geochemically compatible materials that can be used in a repository, depending on the location of the source material and the grain size distribution of the materials proposed for use. Siliceous materials also provide a high degree of durability and stability. These materials can be placed in tunnels and ramps using a variety of technologies, blowing, throwing, dumping and depending on the nature of the materials used can be compacted using a variety of means. The primary limitations to use of these materials are that they:

- are not particularly cohesive (tend to be somewhat difficult to compact in any geometry other than as horizontal layers or shallow slopes),
- provide no active support to the overlying rock,
may settle, leaving a gap at the crown of the tunnel,
provide limited sorption capacity for most contaminants.
Surface storage of aggregate before re-introduction into the repository may result in introduction of undesirable materials (contaminants).

As a result of these limitations aggregate-only systems are generally not suitable for backfill in regions where they would provide a preferential transport pathway for contaminants or where active roof support is desired. In other regions where these properties are not critical, aggregate materials may have potential for use.

**Installation by In Situ Compaction, Throwing, Blowing and Placing**

The installation of aggregate material in the lower regions of tunnels can be achieved using conventional roller or plate compaction technologies. These materials can be compacted to reasonably high density and depending on the particle gradation of the aggregate reasonably low hydraulic conductivities can be achieved (e.g. $10^{-10}$ m/s), (Yong et al. 1986). Materials such as tunnel boring machine cuttings are particularly attractive if a relatively low hydraulic conductivity is desired. The low hydraulic conductivity exhibited by these materials is the result of the size, shape and relatively high fines content of these cuttings. The uppermost portion of the backfilled openings will still be problematic since it will be difficult to achieve adequate densification.

A properly graded aggregate material can be installed to a high compacted density in the lower regions of the tunnels, it will be very stiff and have a low potential for self-settlement, both features that are desirable in a rock fill. As is the case for clay-based backfilling materials, in situ compaction of aggregate materials in the upper regions of the tunnels is problematic. It is not likely that aggregate materials can be installed at adequate density to provide active support (positive pressure at contact), to the surrounding rock. These materials can be placed dry and thereby avoid water drainage issues and will permit some water movement through them during operations without adversely affecting placement operations.

In most mining applications where backfilling is undertaken to provide a means of raising the floor of working excavations and facilitate ongoing removal of overhead ore, crushed mine rock and tailings are often used as filler, often with a cementitious component but not always. Backfill materials are also installed to provide roof support in areas where the rock is or is at risk of yielding (either creeping or failing). In such regions the concern with backfilling is not to limit water movement but to provide passive mechanical support to the surrounding rock. These backfill materials are often designed so as to allow gravity drainage of water through them to their base where water can be drained off. In this way the fill will self-consolidate and there will not be a build-up of hydraulic pressure within the fill. Such hydraulic pressures are potentially dangerous in underground operations, especially where work is ongoing at levels below that of the filled regions.

The technologies used to place aggregate in underground locations are much the same as used for any aggregate placement application, with some minor complications since working space is limited. In most mines where dry rock fill is used is moved by gravity from a higher elevation via special chutes, trucking or conveyor belts. In limited space
conditions shotcrete / gunnite placement techniques can be used but they have limitations regarding the maximum aggregate size, shape and particle size distribution. Use of throwing or blowing techniques will generally encounter problems with material segregation during the placement process. This will result in poor placement efficiency and potentially hydraulically and mechanically heterogeneous backfill. Fine to medium – grained aggregate materials can be readily deposited using these techniques and are commonly used in handling of mine tailings and placement of aggregate materials as backfill in mines. These technologies are described in Section 5.3.2.

Figure 5-15 shows an example of the type of opening into which aggregate fill is typically installed in mine backfilling applications. It is clear that the size of openings portrayed in this figure are much larger than would be present in a repository and the depth of fill placed can reach tens of metres (or more) depending on the ore body. The fill placed in this type of application is placed for operational purposes to allow ease of access to the ore bodies and do not serve the same purposes as would be needed in a repository (roof support to prevent EDZ expansion, limit water/contaminant transmission).

Beyond placement of aggregate within hydraulically contained regions, there is an additional aspect of repository closure where use of rock material can play a role. This is in the upper-most regions of the repository excavations, close to the surface. In these regions, the host rock is likely to be highly disturbed and installation of highly impermeably materials would not provide any resistance to water movement in the vicinity of the openings. In such locations the role of backfill is largely to provide a physical barrier to repository intrusion, either by man or else to resist removal of backfilling materials by ice or water action at some time in the distant future.

To provide a barrier to tunnel and repository intrusion, a combination of very large stone blocks has been proposed for installation in the regions closest to the surface (Korkiala-Tanttu and Ritola 2008). They would be installed to minimize any voids within the excavated volume but would not be a particularly effective hydraulic barrier, water could freely move within the rock-filled volume. These massive rocks would resist removal by ice or flowing surface water. There would also be no fines component to erode and water movement in the fill would allow for natural circulation of near-surface water within this region without providing a particularly preferential vertical flow path. A tendency for local groundwater to enter the upper portions of the backfilled excavations would also provide an additional complication should intrusion be attempted (depending of local groundwater conditions and fracture patterns, openings would tend to flood as rock was removed). Below the depth of anticipated near-surface erosive activity, the backfill materials can be changed to those that provide a more effective hydraulic barrier. This could include regions of massive concrete fill although given the uncertainties regarding very long-term durability of concrete in glacial melt water conditions concrete should not be relied on by itself. Ultimately, using a compartment concept, the backfill at depth would be tailored to be comparable to that of the surrounding rock.
Hydraulic / Slurry Fill
A very popular mining industry technique to install backfill materials into large openings where support is desired is the installation of hydraulic or slurry fill (Souza and Degagne 2001). These materials are fluid mixtures of water and fine-grained mine tailings that are pumped into openings. They have the advantages of being quite quick to install, quite effective in filling the opening and relatively inexpensive to install. They are also an excellent means of dealing with some of the fines (potentially chemically undesirable in the surface environment), generated during mining operations. These materials often have a cementitious component added to them to provide physical stability and strength, but not always. They also have problems in the mining environment of tending to consolidate leaving free-water volume above them, this water then needs to be drained and more slurry installed. They are also of low strength and high fluidity and so care must be taken to ensure that they to not fail and flow into regions where they are not desired. Additionally, they require a considerable cement/binder content in order to achieve relative stability, and moderate strength.

Paste Backfill
Paste-backfill is used by the mining industry and is installed by pumping mixtures of water and crushed rock fines (sometimes with a non-swelling clay and a cementitious component) into openings. This backfill material is not properly clay as it is largely composed of silt- to sand-sized crushed rock and does not contain the layer silicates normally associated with clay minerals. Paste materials will be discussed later in this paper as part of the evaluation of cementitious and aggregate materials. Paste fill is a material that has been extensively developed over the past 3 decades. Composition is adjustable to allow for differing performance requirements. It is typically a mixture of fines (rock), binder (cement) and water that can reach 72-88% solids by weight. It needs to have between 15 and 40% of <20-µm fines component in order to make it pumpable. The hydraulic conductivity has been reported to be adjustable to be as low as $10^{-9}$ to $10^{-10}$ m/s, which is of interest in a repository environment. Density can be improved by addition of larger sized aggregate and ensuring the correct size gradation is defined and maintained. Stiff paste fill can achieve ~2.3 wet density (O’Hearn 2001) but this is using high-density mine tailings. The properties described above are for materials that
use a cementitious component to provide the paste with volumetric stability and strength as well as fluidizing (e.g. organic superplasticizers) agents.

Some of the advantages and disadvantages of this technique for backfilling are as follows:

**Advantages:**
- Can potentially provide a greater and more predictable strength with less cement than slurry or hydraulic backfills,
- It could provide a homogeneous high density (low porosity) backfill but could be pumped into place,
- The nature of this material should mean that no decant water is generated meaning no alkaline outflow,
- Generally all types of tailings can be used, including fines, meaning excavation rock could be used.

**Disadvantages:**
- Typically it is a more expensive process than other mine backfilling options involving cementitious materials (slurry, hydraulic backfill),
- It is a process that requires a high degree of materials preparation and placement design, process control and quality checking required for other cementitious backfilling materials.
- Materials are not demonstrated as being durable over the longterm needed for a repository.

In summary, it has yet to be established if this technique is able to reliably function without cement and/or fluidizing components or if such a material would provide the type of filling materials needed for a repository. The properties of paste backfill with a cementitious component are discussed in Section 5.3.2.

### 5.3 Use of Cementitious Materials in Backfill

#### 5.3.1 Use of Cement and Concrete as Repository Backfill

The obvious operational advantages of installing concrete-type backfilling materials were recognized during the initial options screening process for repository backfilling. However they were overshadowed by concerns related to the stability and chemical compatibility of these materials with the other sealing system components and the surrounding geosphere. Much of the initial evaluation process and issues identification associated with cementitious backfilling materials were documented by Mott et al. (1983) in their review of repository sealing options.

In the initial screening process, concrete was proposed for use as bulk backfill, intended to provide excavation support and high-integrity plugs and seals. In early materials evaluations conventional cementitious materials were reviewed and deemed to be strong but brittle, with low tensile strength and had potential issues related to segregation, shrinkage, brittleness and thermal cracking. Cement-stabilized backfills such as those used in mining applications were also considered. The initial apparent advantages associated with such materials were however offset by the limited capability of concrete to provide substantial buffering or sorption capacity to the system. Their thermal properties are dependent on other mix components, porous aggregate fill needed to be
used in order to facilitate cement/grout permeation and their buffering properties would be determined by the bulk fill material (Mott et al. 1983). It was suggested that mixing cementitious materials with other components such as zeolites, clays or metals might result in a better backfill but the interactions between these materials was not known (Mott et al. 1983).

Another major concern at the time of initial screening of options for backfilling was that of material longevity and functionality. The longevity of cementitious materials in the environment was evaluated on the basis of information available at the time of initial materials screening (~1980). Ordinary and low-heat Portland cements were concluded to be of low stability in sulphate-rich environments but sulphate resistant Portland cements were more durable. Based on available archaeological evidence, conventional Portland cements were estimated to have excellent longevity in low-sulphate environments, but that there was little archaeological evidence available for concrete in chemical conditions similar to those anticipated in the repository environment (Mott et al. 1983).

Based on a review of the state of knowledge at the time of initial repository concept development Mott et al. (1983) capture the conclusion reached by most programs evaluating repository backfilling concepts, - that clay-based materials had a greater potential for successful application in repository backfilling.

“For repositories constructed in hard crystalline rocks, the presence of natural and induced discontinuities present the greatest threat to containment. The specific use of a swelling backfill at potential points of water entry (fissures, joints) could deal with “radial” entries. Disimprovement in the integrity of the host rock peripheral to the repository chambers would be more difficult to deal with on the basis of existing ground treatment capability.” Mott et al. (1983)

From this initial assessment of a wide range of potential backfilling approaches it was decided to focus the majority of work related to buffer and backfill development on clay-based materials. A very extensive program of work has been undertaken in order to qualify materials in terms of their short- and long-term performance as well as the practicalities of installing them. The result has been the development of a range of materials and placement options that are intended to provide workable options and alternatives that can be used in a repository.

Despite the focus of backfilling work on clay-aggregate materials considerable effort has and continues to be expended on development of cementitious materials for use in specialized repository applications. Of particular interest has been the development of specialized materials and designs for tunnel, room, drift and shaft seals and plugs, as well as grouting and shotcreting materials. These materials are typically low pH, low shrinkage, high-strength and low-heat of hydration concrete and cementitious compounds that would have minimal impact on adjacent materials or the regional groundwater. Much less effort has been spent on bulk backfilling materials based on cement technology, although as described in Section 5.3.3, a watch has been kept on development of that type of filler.
5.3.2 Backfills Containing Cementitious Component

Issues related to cement-clay interaction, the impact of hyper alkaline (high pH), solutions or limited use of cementitious materials have not been conclusively settled with regards to repository application (a very brief overview of the state of knowledge is provided in Section 5.3.3). It would appear that for conservative design purposes extensive use of cementitious materials in backfilling is not likely to be acceptable based on the current level of knowledge and uncertainty regarding their performance. However, in order to be kept aware of the advances in the mining industry, Posiva and other national programs have ongoing watch and assessment processes in place so as to maximize technology transfer.

The primary issues with the use of mining technologies and practices for backfilling to stabilize openings and underground disposal of mill tailings and waste rock, are related to the very different purpose of backfilling. A mine looks to backfilling as a tool to dispose of unwanted (and chemically reactive) mine tailings and to help maximize ore recovery. A spent-fuel repository looks to retarding contaminant transport, support excavations to prevent development of EDZ, isolate hydraulic features, prevent human intrusion and limit impact of glacial events. Despite these fundamental differences there are some areas where the experiences of the mining industry can provide guidance. Of particular interest is development of placement technologies and equipment. Examples of these watches and assessments can be found in the documents produced for Posiva by Kukkola (2001).

The mining industry uses four basic approaches to backfilling of large underground openings. These are:

1. Dry filling using rock, dry mill tailings, sand and gravel,
2. Cemented rock or aggregate fill,
3. Hydraulic fill or slurry fill (using water as transport medium),
4. Paste filling (with optimized psd, high fines content, minimum water content and non-segregating during handling).
5. Shotcrete/Gunnite filling where concrete materials are blown into place.

Aspects of these backfilling approaches as they can be applied to backfilling without the presence of cementitious materials have been discussed in Section 5.2.5. Most of the applications for these materials (excepting dry filling) require the utilization of cementitious materials. For the purposes of completeness the features and limitations of using cementitious backfill materials are provided below.

*Cemented Rock or Aggregate Fill*

Cemented rock or aggregate fill is perhaps the simplest application of backfill installation in the mining industry. It typically involves cemented rock fill and is used where higher strength backfill is needed. Waste rock from excavation and crushed/screened fill are used to provide a fill material with a good particle size distribution. Cement slurry is added to the fill material either prior to placement or else is sprayed onto the mixture as it is placed. This is typically done on large-scale using heavy equipment where headroom is not an issue. This material typically contains 3-7%
Portland cement or blast furnace slag (if low water ratio is present). Porosity and hydraulic conductivity of concrete rock fill is typically quite high as mine drainage is typically desirable and so this material can also be expected to segregate during placement. Such techniques will therefore not tend to provide a particularly low permeability backfill but it will remain in place.

Higher quality applications of this approach are used in the mining industry and elsewhere when installing pre-compacted aggregate plugs for water control purposes. In those situations a high permeability, clean aggregate is used and cement paste is pressure injected into the aggregate to generate a strong, very low permeability plug and has been considered for potential use in a repository. Similar materials and approaches have been suggested for general backfilling of tunnels in a repository (Kukkola 2001). Aggregate would be pre-placed and then injected with low viscosity cementitious material via pre-installed pipes. Preplaced aggregate and subsequent grouting to install underground plugs is a technology that has been used by the mining industry as well as in hydroelectric water control structures to install hydraulic plugs in critical locations and normally requires considerable post-placement grouting to seal areas that are not initially plugged. It should also be noted that such plugs for mine applications are also designed to control water seepage rather than provide a diffusive barrier and so seepage past / through or around such plugs is normally acceptable, so long as it is not erosive or excessive. It is unlikely that this would be acceptable in a backfilled repository tunnel. As with any use of cementitious materials there are potential problems. These include pH issues with respect to groundwater chemistry, solubility of contaminants, chemical and mineralogical stability of buffer, shrinkage of cement during curing causing openings and preferential flow paths to develop. It is also likely that cement will degrade with time and at a rate that is not clearly established.

It is therefore unlikely that installation of high-quality plug-like backfill will be a practical solution for large portions of a repository as this approach is typically time intensive and has a limited length that can be installed and grouted at one time. There are also issues related to ensuring that the aggregate is fully grouted and pathways for preferential water movement do not persist. This approach does however have potential for use in installation of plugs or backfilling or regions where water influx is an issue.

**Hydraulic / Slurry Backfill**

Hydraulic backfilling uses mill tailings, water and often a binding (cementitious) component and installed by pumping through pipes. This material will contain a relatively small (<5 %) cement or ground slag component to provide the binding component to the slurry materials. Hydraulic backfilling is a very popular method for mine backfilling as it is easy to place, effective in filling entire void volume and relatively inexpensive while allowing for underground disposal of waste materials from mining and processing activities. It also has a number of disadvantages including the need to drain decant (water left after fines begin to settle), and tends to require a large cement content in order to be stabilized. The tendency for the material to settle and dewater, while tolerable in a mining environment where backfilling is an ongoing process would not be feasible in a repository where small volumes need to be filled in a timely manner. This fill could also not be relied on to remain volumetrically stable or
provide even passive support to the roof of the tunnels and ramps (resulting from ongoing self-consolidation).

**Paste and Rocky Paste Backfill**

In most mine backfills the particle size distribution of backfill is designed to allow water percolation through backfill, preventing hydraulic pressure build up while providing enough strength to support operations on its upper surface. Paste backfill is different; it has a high fines content and low hydraulic conductivity. A high fines content and careful particle-size gradation minimizes the water used to pump the mixture by pipe to its installation location. In order to keep it in place a cement content of 2-5% is added to the paste. As a result of the need to keep the water ratio as low as possible there is a considerable material and process control aspect to this placement technology.

Rocky Paste Filling (PF) is similar to paste backfill excepting that it includes a much coarser aggregate component. RPF consists of a well-graded aggregate with lots of fines, ground rock or clay, binding agent and minimal water. This material has been reported to be able to reach a density target of 2300 \( \text{kg/m}^3 \), will not segregate and can be pumped. It should be noted that this density involved use of particles of high specific gravity and may not be representative of what can be achieved using granitic rock. There is also the issue of the large quantity of external water introduced in the process of paste installation.

![Figure 5-16. Slinger-type RPF placement equipment and resulting tunnel filling. (Yanske et al. 2001)](image-url)
One approach to backfilling of ramps and tunnels would have material installed in two stages. The first would involve compaction of the RPF material in the lower portions of the tunnel. Conventional road-type equipment (plate, roller) technology would be used for placement and the material placed would have a small cementitious content. This RPF could provide a low deformability and low permeability in the base layer and in the in-floor emplacement concept (KBS-3V), it would be stiff enough to prevent buffer clay swelling, even before the upper region was backfilled. The upper portion of the rooms and tunnels would be filled later using a slinger-belt, shotcreting techniques or pumping of RPF. Figure 5-16 shows the type of equipment used to throw RPF and an example of the type of placement that can be accomplished using such a technique. This approach was recognized as being potentially usable in JAEA’s H12 report (JNC 2000), shown in Figure 5-17.

<table>
<thead>
<tr>
<th>Fluid (cement type)</th>
<th>Material transporter</th>
<th>- Transfer vehicle transports the mixed material.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driven pump</td>
<td>- The mixed material is delivered to driven pump to be piped out.</td>
</tr>
<tr>
<td></td>
<td>Distributor</td>
<td>- A nozzle of the pump moves for the uniform spreading.</td>
</tr>
</tbody>
</table>

*Figure 5-17. Cement Backfill Concept for JAEA. (JNC 2000)*
5.3.3. pH – related issues and development of low-pH cements

Discussion in Section 5.3.2 is largely related to the technical aspects of installing and designing of backfilling materials that contain a cementitious component. In addition to the technology of placing backfill there needs to be a careful consideration given to the chemical and geochemical aspects of backfill and its interaction with the surrounding geosphere and adjacent sealing system components. Of particular concern are those aspects related to a fundamental feature of almost all cementitious materials, the generation of high pH. This was a major concern during the initial screening of materials for potential use in repository backfilling as summarized by Mott et al. (1983) and continues to be a concern. Although it is recognized that some cementitious materials would be necessary during excavation and repository operations (IAEA 2003; OECD 2003), there is a reluctance to consider its extensive use. The primary concerns are related to its longevity and pH impacts on the repository environment. In order to better quantify the extent to which these materials can be used most national programs examining deep geologic disposal have ongoing work on cementitious materials.

The discussion below briefly reviews the key issues, concerns and activities related to developing a better understanding of the role of pH (alkalinity) on the behaviour of the repository sealing system. Most of this discussion draws from the recent work of Alexander and Neall (2007) who provide a detailed discussion on potential sources of perturbation on a spent fuel repository at the Olkiluoto site. The information provided is then used to provide guidance as to the likely impacts of using cementitious backfill materials in substantial areas of Posiva’s repository.

High pH OPC Materials
The most pressing issue identified in initial screening of potential backfilling materials was related to their tendency to drive local pH conditions to extremely high levels, potentially resulting in mineralogical alteration in other sealing system components (bentonite) and dissolution/precipitation processes in the repository (Mott et al. 1983). Evaluation and addressing of this issue has been the focus of considerable effort over the past 25 years. Firstly, the chemical, geochemical and mineralogical effects of cementitious materials on other repository materials have been examined and a measure of the rates at which negative processes would progress has been investigated. The second activity associated with cementitious materials has been development and evaluation of cementitious materials other than conventional, ordinary Portland cement (OPC), usually for specialized applications within the repository (e.g. tunnel or shaft bulkheads, shotcrete, grout). These alternative cementitious materials need to be less chemically aggressive (lower alkalinity or lower pH), and yet provide the hydraulic and mechanical characteristics desired of a sealing system component.

Of particular concern regarding the ability of cementitious materials to provide the long-term sealing function deemed necessary in a backfill there are ongoing issues related to cement-generated high pH conditions in the surrounding groundwater and the resultant degradation of the clay-based buffer. It is not uncommon for long-term pH conditions in excess of 11 to be generated as the result of cement curing. This is not in equilibrium with the surrounding geosphere or nearby buffer materials where pH in the order of 7 to 9 (depending on local groundwater conditions and rock-type), is likely to exist. High pH
conditions are known to substantially alter the solubility state of adjacent materials (e.g. quartz, clay, metals, contaminants) and can result in loss of many of the properties deemed attractive in other sealing system components. There is an abundance of literature that discusses the potential impact of alkaline solutions on bentonite behaviour (e.g. Ahokas et al. 2006; Lehikoinen, 2004; Vuorinen et al., 2006; Karnland et al., 2006; Karnland, 2004 and Nakayama et al. 2004). Beyond the impact of alkaline leachate on buffer and backfill materials, there are also concerns that such pH conditions could alter the corrosion characteristics of the canister holding the spent reactor fuel (Alexander and Neall 2007).

Alexander and Neall (2007) do an excellent job of highlighting the lack of consensus regarding the processes and comparability of tests done in batch and flow-through cell experiments and dense clay materials such as would exist in a repository. They identify the shortage of tests of alkali-clay interactions conducted under realistic density and groundwater conditions, something that is needed in order to have confidence in the results of models predicting system evolution.

Alexander and Neall (2007) also provide a brief summary of the state of knowledge related to potential perturbation effects of OPC alkaline leachates from grout materials on the Olkiluoto repository. In this assessment it was assumed that OPC generates an initial pH in the order of 13.4 that decreases to 12.5. If leachates are pushed from the cement due to flow of groundwater through them, then high pH conditions may result in a hyper alkaline plume. If subsequent mass transport of the leachate through adjacent buffer or backfill material is governed by diffusive processes, only a few decimetres of alteration would occur and that the tunnel backfill (clay-based) would have considerable buffering capacity for pH (ability to consume OH-). They conclude that given the distance between the tunnels and the emplacement drifts in the KBS-3H geometry as well as the mass of HCB that is adjacent to the canisters, it is unlikely that grouting could result in a substantial alteration of the buffer. This same conclusion was reached by modelling the effects of low pH shotcrete and grout material located on the walls of an emplacement room backfilled using a bentonite-aggregate mixture (Luna et al. 2006). In these simulations pH in the backfill never exceeded 10 and only a small (<1%) decrease in porosity due to precipitation of calcite was predicted. It should be noted that these analyses did not consider the widespread use of cementitious backfill.

It was also noted by Alexander and Neall (2007) that: “…hyper alkaline leachate/bentonite interaction is a young science and “cutting edge” geochemistry so models and certainty in assessments could not be expected until the work became more mature.” Based on this state of knowledge, it is difficult to put reliance on widespread use high-alkalinity OPC-based sealing materials (e.g. as backfill).

Low alkalinity (low pH) cementitious materials
Alexander and Neall (2007) provide a very complete summary of the status of development of low alkalinity cementitious materials and the state of knowledge with regards to their durability and potential issues associated with their use in a repository environment. For the sake of simplicity a number of paragraphs that clearly and concisely describe the state of understanding related to these materials have been extracted directly from Alexander and Neall (2007). For ease of reader reference, the
sources cited by Alexander and Neall (2007) and reproduced in paragraphs taken directly from that source are provided in the reference section of this paper. In several cases the references cited in Alexander and Neall (2007) were not available to this author and are provided for reference purposes only.

“Low pH porewater cement can be produced in a range of ways such as using a low alkali source rock (e.g. Schäfer and Meng, 2001) or reducing the amount of cement clinker used (e.g. Grey and Shenton, 1998) or using >50% blast-furnace slag in the cement (e.g. Smolczyk, 1974) and it is even possible to produce cements with acidic pH levels (e.g. Bohner et al., 1997). Although much of the cement grout used by the Romans over two millennia ago was effectively low alkali cement (see, for example, the discussions in McKinley and Alexander, 1992; Miller et al., 2000), little interest was shown in the development of modern low alkali cements in the radwaste industry until about two decades ago when AECL began further developing existing cements for use as high performance plugs, seals and grouts.”

The use of low alkali cement grouts was initially contemplated due to better handling and fracture penetration properties (e.g. Mukherjee, 1982) and lower heat generation (e.g. Gray and Shenton, 1998). While these properties remain of interest, much work is currently focused on the greater chemical compatibility (or, more precisely, less serious incompatibility) with bentonite (e.g. JAEA 2007) and the repository host rocks (e.g. Nakayama et al. 2006). However, areas where some doubt remains as to the relevance of low alkali cement are long-term durability (e.g. Philipose et al., 1991) and organic content (e.g. Kronlöf, 2004).

It is important to note that Posiva, or any other implementer worldwide has a designated low alkali cement and has been heavily involved (unilaterally, in collaboration with SKB and NUMO and, more recently, the EU) in testing a wide variety of ‘recipes’ to find the most appropriate range of characteristics, including a leachate with pH less than 11. …Vuorinen et al. (2005), Bodén and Sievänen (2006), Sievänen et al. (2005, 2007) and Arenius et al. (2008). All of these studies show that, despite initial leachates of up to pH 13, the leachates of most formulations tested to date in Posiva’s programme, rapidly drop to around pH 11 or less. Those that do not do so, have been dropped from the development programme. To date, there are little data available on the likely behaviour of the low-alkali cements in saline waters, but Vuorinen et al. (2005) noted that leaching of low-alkali grouts with saline water generated leachates with lower pH (by 0.5 to 1 units) than when the same grout was leached by fresh water.”

Alexander and Neall (2007) reported that Posiva currently plans to use MX-80 bentonite at Olkiluoto, where the natural local groundwater-clay system would be approximately pH 8 (Bradbury and Baeyens, 2002). This is a much lower pH state than would be generated by low alkali cement or silica sol grouts (pH of 11 or less) and so a considerable alkalinity differential will exist. Oscarson et al. (1997) noted that even at this level of pH differential between the components that the potential still exists for clay minerals to alter over long periods of time if in contact with low pH concrete.
Effect of organic additives in low alkali cement

In any low alkali cement there is typically several weight percent of organic additives present to provide improved handling characteristics (fluidity, compressive strength etc) of the cement (Kronlöf, 2004). These additives are commonly complex compounds that may contain a wide variety of recorded and unrecorded components (Bodén and Sievänen 2006). It has also been suggested that the release and degradation of these compounds is poorly understood and that they may actually increase the solubility and mobility of certain radionuclides (Baston et al. 1992; Serne et al. 2002; Hakanen and Ervanne 2006).

A further potential issue is the presence of organic additives introduced in low alkalinity cementitious materials to improve their fluidity during placement. These materials might affect the canister’s copper overpack, increasing degradation by influencing copper (Hakanen and Ervanne 2006).

Posiva is involved in ongoing studies of low-alkali cement but is also examining other options such as silica sol (colloidal silica) (Bodén & Sievänen, 2006; Ahokas et al. 2006) particularly as a potential grout material. Silica sol grouts typically contain 20 – 50% silica, 1.5 - 10% salt (NaCl or CaCl2) and the remainder water, with a leachate pH of approximately 10.

Summary

The information provided by Alexander and Neall (2007) and others shows that even with the considerable advances in understanding and development of specialized low pH cementitious materials whose express purpose is repository use, there is still uncertainty regarding their long-term behaviour. In particular OPC-based grouts (or other similarly formulated cementitious materials) are likely to induce a hyper alkaline plume (from leaching of the cement). Use of low alkali materials would mitigate the magnitude of this phenomenon but the long-term behaviour of these materials is not established.

The estimated volume of the basic access tunnels, shafts and ramps in Posiva’s SFR is in the order 365 000 m³ (Alexander and Neall 2007). Additional volumes excavated for emplacement tunnels and drifts brings the total to 1 311 000 m³ in the KBS-3V geometry (Saanio et al. 2007). This volume excludes the boresholes that would be filled by the canisters and buffer materials. The exact volumes necessary for the KBS-3H concept are not clearly established and are expected to be less than those required for the 3V geometry. Despite this, the excavations needed in 3H are substantial (in the order of 1 000 000 m³). Based on a very simple calculation that a cementitious backfill would be used to fill all the tunnels, shafts and ramps and that the backfill contains an average of 5% OPC (not necessarily a conservative assumption), placed at a density of 2.0 Mg/m³ the resulting cement usage would be in the order of 36 500 Mg (for 365 000 m³) to 131 000 Mg (for 1 311 000 m³). These masses do not include the approximately 3 000 Mg of cementitious materials anticipated to be used in grouting and shotcrete (Alexander and Neall 2007). Estimates provided by Hansen (2004) and Vieno (2004) put the quantity of cement remaining in a repository (not backfilled by cementitious materials), after closure is in the range of 10 000 to 23 000 Mg.
Given the well-documented concerns and uncertainties related to widespread use of cementitious materials for shotcrete and grout, particularly with respect to the effect of high-pH materials such as conventional cement on bentonite (Alexander and Neall 2007), it is not likely that a 5 to 15 fold increase in the quantity of cementitious material present in the repository will be acceptable. Use of low-pH alternatives to OPC will certainly result in less disruptive conditions in a repository but will still generate large volumes of material that are of (discernibly) higher pH (~10) than the natural groundwater or clay-aggregate backfill (~8-9) and so their unrestricted use is not likely to be desirable.

It would therefore seem most prudent to continue to focus backfill development on clay-based materials with concrete, shotcrete and grout development focusing on specialized applications of more limited volume. Application of cementitious materials should focus on engineering construction requirements, to control water inflow, rock stabilization and ultimately construction of concrete seals and bulkheads as part of a composite sealing system approach.

5.4 Backfilling of Shafts

Backfilling of shafts will involve many of the same materials that are used in filling of drifts and ramps, with the exception that there will not be overhead space constraints to the type of equipment that can be used. Most concepts for shaft backfilling include recognition that there will be a variety of materials used to achieve effective sealing of these vertical features. Figure 5-18 shows the type of shaft backfill that is proposed by Nagra for closing a facility built in Opalinus clay and shows the installation of concrete, aggregate and bentonite – based components (Nold 2006). Similar multicomponent geometries were tested by Canada for use in sealing and plugging in a granitic repository are shown in Figure 5-20. (AECL 1994). A full-scale tunnel (shaft) plug was built and tested where an artificially high permeability region was present between two plugs (Chandler et al. 2002; Martino et al. 2006). Although designed to evaluate two separate components of a composite tunnel plug, the TSX can also be considered as a situation where a compartment section (or if rotated 90 degrees, a shaft), intersects a high permeability region (pressurized and heated section between plugs). The effectiveness of the TSX concrete and and clay bulkhead demonstrated how a high permeability geologic feature could be hydraulically isolated from the repository excavations.

All of these concepts for shaft sealing are essentially the same as the compartment concept described by Autio et al. (2002; 2005) excepting that they are vertical rather than horizontal in orientation. The shaft backfill (and plugs) would be designed to suit the rock conditions encountered. Additionally, the shaft regions could likely tolerate a higher degree of cementitious materials, as they are further away from the canisters and less likely to interact geochemically with them. There will still be the issue of the longevity of the cementitious materials and their durability once the more oxygenated and fresher-water regions closer to the surface are reached. These are all topics that will require consideration as development of shaft sealing approaches and materials options are evaluated.
Figure 5-18. Nagra shaft sealing concept. (Nold 2006)

Figure 5-19. AECL Tunnel Seal (Shaft Plug) Experiment. (Chandler et al. 2002a,b; Martino et al. 2006)
6 SUMMARY

A brief review of backfilling materials and installation options for a spent fuel repository has been provided. A wide range of materials and combinations of materials have been proposed for use and they have been briefly reviewed and discussed with reference to their potential suitability for use in a repository.

Clay-based materials have been the focus of most of the backfill development since the start of developing repository concepts in the late 1970’s. These materials were not selected without an extensive review of materials options and the potential for practical implementation in a repository. Work over a 30+ year period has led to the development of a number of workable clay-based backfilling options, although discussion persists as to the most suitable materials and placement technologies to use. There are also certain interactions between clay-based materials and other engineered barriers system components that may be detrimental to system performance but these are mainly associated with processes occurring closer to the canister (in buffer barrier). These issues are the subject of ongoing study and assessment and are not discussed in this document.

Cementitious materials were included in the list of candidate materials initially screened in the early 1980’s for use in backfilling of repository opening. These materials were recognized to have a potential advantage with respect to the relative ease of their placement and initial development of a stiff and strong barrier material. However conventional cement-based materials were quickly identified as having some serious technical limitations with respect their ability to fulfil the identified requirements of backfill. Of greatest concern was, and still is, the pH generated by cementitious materials during their curing and the impact of large volumes of alkaline groundwater on the repository. The elevation of the pH (high alkalinity groundwater) within large volumes of the repository is a very undesirable condition and puts the effectiveness of other engineered barriers at risk.

It was recognized during concept development that some cementitious materials will be used and will be useful in the repository, either as part of construction activities, groundwater control (grouting, shotcreting) or as part of composite seals installed in critical locations within the repository. In order to minimize the adverse affect of cementitious materials within the repository, considerable work has been and continues to be done on developing of low pH (alkalinity) cementitious and pozzolan materials that can provide the positive properties of strong, stiff materials without the negative aspects of conventional concretes and cements.

Table 6-1 presents a brief summary of the ability of various materials considered as backfill in the repository to meet the basic performance requirements set out by Posiva (Posiva 2006). It should be noted that the properties requirements described in Table 6-1 do not specifically address any particular backfilling or repository concept (e.g. compartment versus uniform backfilling) but examine the general suitability of various materials for use in backfilling.
Table 6-1. Backfill Requirements, Goals and Suitability of Selected Options

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Restrict advective transport in tunnels</td>
<td>?¹</td>
<td>?¹</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>No¹</td>
</tr>
<tr>
<td>Low hydraulic conductivity (≤10⁻¹⁰ m/s)</td>
<td>No</td>
<td>No</td>
<td>√⁶</td>
<td>√⁶</td>
<td>No¹</td>
<td></td>
</tr>
<tr>
<td>Stiffness to resist buffer swelling</td>
<td>√</td>
<td>√ ?</td>
<td>No</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>KBS-3V</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA²</td>
<td>NA²</td>
<td>NA²</td>
</tr>
<tr>
<td>KBS-3H</td>
<td>√?</td>
<td>√?</td>
<td>No</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ability to isolate hydraulic features</td>
<td>√?</td>
<td>√?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Chemical compatibility with geosphere</td>
<td>No ?</td>
<td>No ?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
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<tr>
<td>Chemical compatibility with other EBS materials</td>
<td>No ?</td>
<td>No ?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Long-term stability</td>
<td>No ?</td>
<td>No ?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Ability to retard contaminant transport</td>
<td>No⁴</td>
<td>No⁴</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>No⁴</td>
</tr>
<tr>
<td>Support excavations to prevent development of EDZ</td>
<td>√ ?⁵</td>
<td>√ ?⁵</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>No ?⁵</td>
</tr>
<tr>
<td>Ability to maintain positive pressure at rock backfill boundary</td>
<td>No⑤</td>
<td>No⑤</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>No⑤</td>
</tr>
</tbody>
</table>

NA: Not applicable, emplacement geometry results in this property being irrelevant.

* Note: These options are only some of those discussed or proposed for use but are amongst the more notable suggestions. There are sub-varieties of each of these options and many are discussed in this document.

¹ This is accomplished by very low permeability bulkheads constructed in conjunction with backfilling.
² This concept does not have HCB in contact with backfill material, drift plugs separate the components.
³ Concerns persist regarding very-long-term stability of cementitious materials. Swelling clays are generally accepted as maintaining most of their mineralogical integrity over the life of a repository (within limits of having an initially suitable groundwater regime).
⁴ These materials will provide some retardation of contaminant movement under diffusive flow as they have very high porosity and as a result contaminant concentration will be diluted, resulting in lower chemical diffusion gradients. Crushed granite also provides some minimal sorption to selected contaminants.
⁵ Materials may tend to self-consolidate, resulting in loss of contact with crown of excavation.
⁶ Properties are sensitive to groundwater salinity and density variations, high salinity results in increased hydraulic conductivity and lower swelling pressure.
The compartment approach (Autio et al. 2001; Gunnarsson et al. 2004) requires a more flexible approach to be taken regarding identifying where some of the performance requirements provided in Table 6-1 are necessary. In the compartment approach the backfill is tailored to the local geologic and hydrogeologic conditions so that it matches its surroundings. In a region of higher conductivity in the surrounding rock mass, installing a very low permeability backfill would not likely achieve a discernible advantage with respect to contaminant transport. As a result, it is more important to concentrate on disconnecting that section of tunnel from adjacent regions of better quality.

Careful review of backfilling options related to extensive use of cementitious materials in a manner similar to that used in the mining industry does not result in the conclusion that use of such materials would provide any discernible improvement in the effectiveness of backfill in isolating the canisters. Indeed the assessment provided in Table 6-1 shows that such materials meet very few of the requirements defined as necessary in a backfilling material (Posiva 2000; 2006; Tanskanen 2007). This is not surprising given that, in general, the mining industry has a very different set of expectations and goals regarding the installation of backfill and the timeframe for maintaining its mechanical and hydraulic characteristics.

It should be noted that the mining industry has been actively developing equipment for installation of backfill that could be useful in the transportation and placement of backfilling materials, particularly aggregate materials for installation in regions where the quality of the surrounding rock is lower and a compartment concept is adopted. Similarly, considerable development is ongoing on development of low alkalinity grouts and cements (for use in shotcrete) and they have considerable importance in both mining and repository applications.

Work on development of backfill has resulted in the identification of several potentially workable materials and placement options. They are associated with clay and aggregate-based materials and should be able to be installed in a manner capable of achieving the performance requirements of the backfilling system. There are still issues that need to be addressed with regards to the best methods to install backfill and what backfill materials are most appropriate for use. Ongoing research and demonstration of materials and concepts are needed in order to optimize the backfilling and sealing system. This is being accomplished through ongoing work by Posiva as well as in joint research activities with SKB and other organizations.
REFERENCES


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Gray M N and Shenton B S. 1998. For better concrete, take out some of the cement. In Proceedings of the 6th ACI/CANMET symposium on the durability of concrete,


Korkiala-Tanttu L and Ritola J. 2006. Compaction methods of the tunnel backfill material, Research Report VTT-R-03124-06. (Provided in Appendix A)


APPENDIX A. UNPUBLISHED MEMORANDUM
