Technical Report
TR-20-03
May 2020

Strategy, adaptive design and quality control of bentonite materials for a KBS-3 repository

Magnus Kronberg
Lars-Erik Johannesson
Peter Eriksson

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

ISSN 1404-0344
SKB TR-20-03
ID 1882847
May 2020

Strategy, adaptive design and quality control of bentonite materials for a KBS-3 repository

Magnus Kronberg, Lars-Erik Johannesson, Peter Eriksson
Svensk Kärnbränslehantering AB

Keywords: KBS-3, Bentonite, Adapted design, Quality Control, Forsmark, KBP1015.

A pdf version of this document can be downloaded from www.skb.se.

Abstract

This report describes quality control and adaptive design of buffer and backfill. The report discusses the quality steps required between mining of the bentonite and approved bentonite components that can be used in a repository. The work has been focused on packaging and standardising earlier developed technology.

Results from an evaluation of seven bentonites according to the material evaluation process are presented. Three of the materials were subject to the complete process, including manufacturing of buffer blocks in full scale. The test shows that the methods, selected by SKB in order to quality control bentonite, constitute a good basis for evaluating a material against the technical design requirements and to develop a material specific adapted design. The data generated with the selected methods also provide vital information for future material selections.

Methodology for adapted design of buffer components is presented, considering the tolerances of the components and the deposition holes. Furthermore, an adapted buffer design for the seven tested materials is included. Additionally, methodology for adapted design of backfill is presented.

Sammanfattning

Den här rapporten beskriver nyligen genomfört utvecklingsarbete med fokus på kvalitetskontroll och anpassad utformning av buffert och återfyllning. Rapporten behandlar de kvalitetssteg som krävs mellan brytning av bentonit och godkända bentonitkomponenter som kan användas i ett slutförvar. Arbetet har varit inriktat på att ytterligare paketera och standardisera tidigare framtagen teknik.

Rapporten presenterar även resultaten från utvärdering av sju olika bentoniter i enlighet med processen för materialutvärdering. Tre av materialen har gått igenom hela processen, inklusive tillverkning av buffertblock i full skala. Undersökningen visar att de metoder SKB valt för att kvalitetkontrollera bentonit är väl lämpade både vid utvärdering av materialet mot konstruktionsförutsättningarna samt för att ta fram en materialspecifik anpassad utformning. Data, framtaget med de valda metoderna ger även viktiga underlag för framtida materialval.

Metodik för att anpassa utformningen av buffertkomponenter, med hänsyn tagen till komponenterna och deponeringshålens toleranser presenteras. Anpassad utformning av buffert för de sju testade materialen anges. Även metodik för att anpassa utformningen av återfyllning presenteras.

Contents

1 Introduction

1.1 Background

SKB is developing a method, denoted KBS-3, for disposal of spent nuclear fuel from the Swedish nuclear power plants. In the KBS-3 method (Figure 1-1) the radioactive waste (solid fuel pellets of mainly uraniumdioxide) is to be placed in a copper canister with a cast iron insert which is sealed by friction stir welding. The copper gives long-term chemical stability while the cast iron insert gives structural rigidity. The canisters will be placed at a depth of around 500 m in crystalline rock where the space between the canister and the rock will be filled with specially designed compacted bentonite blocks and pellets. The bentonite in the vertical deposition holes, just around the canister, is denoted buffer, while the bentonite used to fill the horizontal deposition tunnels is denoted backfill.

Because of the slow radioactive decay, the radioactive waste is considered hazardous for a very long time (100 000 to 1 000 000 years). This puts high requirements on the engineered barriers, primarily on the canister, but also on the buffer, Section 3.1, and the backfill material, Section 3.2.

The main purpose of the bentonite buffer is to protect the canister. It has to limit transport of dissolved corroding agents to the canister and it has to reduce bacterial activity around the canister. In order to accomplish this, the buffer has to reduce groundwater flow, excerpt a swelling pressure and hold the canister in position. Additionally it must not jeopardize the canister function by chemical or mechanical interaction and the thermal conductivity of the buffer must be sufficient to allow heat transport from the canister surface to the bedrock.

There is a wide range of bentonites available with varying mineralogical and chemical compositions as well as varying hydro-mechanical properties. SKB will use in the order of 5 000 tons of buffer and 35 000 tons of backfill on a yearly basis and all of the installed buffer and backfill made of the materials will have to fulfil the technical design requirements (TDRs) when installed in the repository, Chapter 3.

In order to evaluate that the TDRs are fulfilled, a process for quality control is being developed. While the quality control process includes a large set of tests which analyse the TDRs, it should be noted that they will have to be complemented with further information with respect to long term performance when it comes to making decisions on material selection.

The installed dry density defines the shear strength, swelling pressure, hydraulic conductivity and thermal conductivity. The harmful substances are different and mainly defined by their specific concentrations in the installed mass. The unique relationships between the selected dry density and the yielded shear strength, swelling pressure, hydraulic conductivity and thermal conductivity allows for an optimisation of the design, i.e. different bentonites, with slightly varied properties can be used by tailoring the dry density. The water content can also be tailored and is an essential parameter for both the manufacturing and handling (integrity of the components). SKB calls this process, **adaptive design.** The dimensions of the bentonite components and the rock excavations could also be optimised, but in the recent study it's primarily the dry densities and water contents of the components that are adapted.

As long as the long term performance of the installed buffer and backfill can be fulfilled, the adaptive design provides a tool for both selecting and changing materials during the repository operation. This is important both from an operational and commercial standpoint as it lowers the risk in the supply chain and allows material purchases to be exposed to competition.

The **adaptive design** allows for fine-tuning. However, for industrial application, it has to be applied to relatively large batches of material, both for practical and economic reasons. Ideally, a full bulk shipment, in the order of 20 000–50 000 tons of bentonite would be homogenous enough to allow for one iteration of the adaptive design.

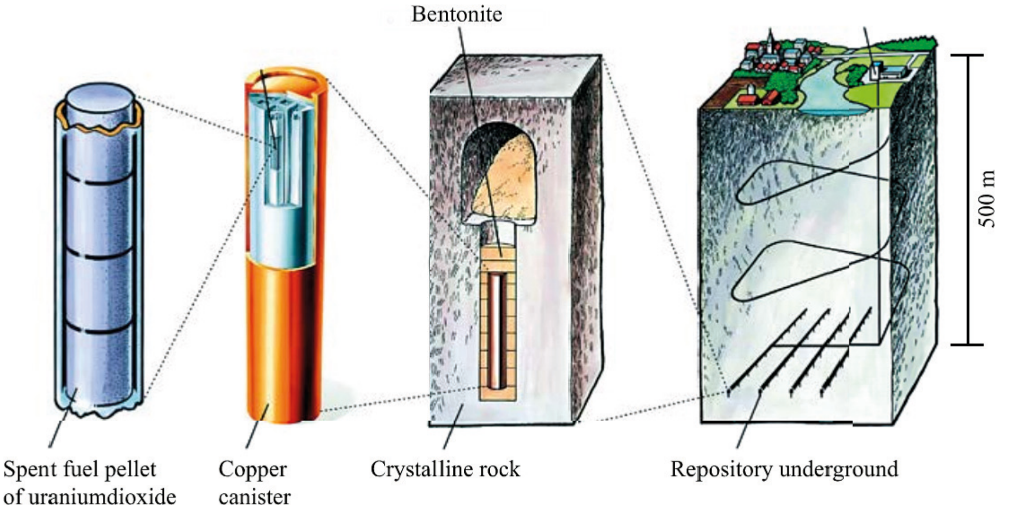

Figure 1-1. *The protective barriers in the KBS-3 method of SKB (copper canister, bentonite clay, and crystalline rock) to keep the radioactive waste isolated from the environment. Buffer and tunnel backfill are made of pure bentonite clay.*

1.2 Purpose and scope

SKB is developing methodology and techniques for bentonite acquisition, quality control, component design and manufacturing in a stepwise manner, with the overall objective being to establish how the future repository should be supplied with cost efficient and quality controlled buffer and backfill components.

The purpose of this report is to present recent experiences and the current stage of development for how this overall objective shall be reached. Work done to further standardise and improve the quality control procedures for bentonite is reported together with results from the material evaluation process, where different materials have been evaluated as potential buffer and backfill materials, including suggested buffer and backfill designs.

A total of seven materials have been evaluated and full scale buffer block manufacturing has been tested on three of these materials. The block manufacturing is reported in Johannesson et al. (2020).

Detailed material data on all seven materials is reported in Svensson et al. (2019). The data is referred to or reproduced when needed to explain the adaptive design work.

2 Rock excavations

This chapter introduces the dimensions of the rock excavations (deposition holes, and tunnels). Figure 2-1 illustrates the deposition hole with its bevel. The method for excavating the deposition holes are full-face down-hole drilling techniques (SKB 2010a).

The method for excavating the deposition tunnels is not decided at this stage of development, Figure 2-2 illustrates one of many possibilities, in this case excavated mechanically.

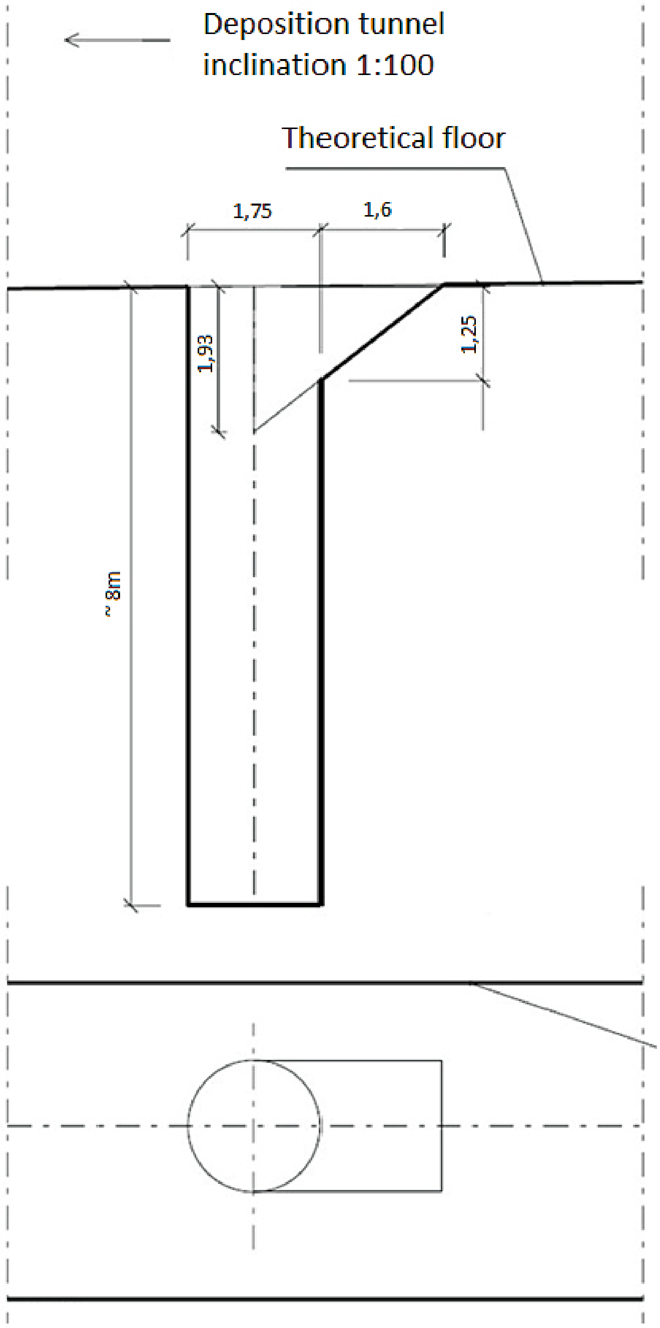

Figure 2-1. *Deposition hole geometry.*

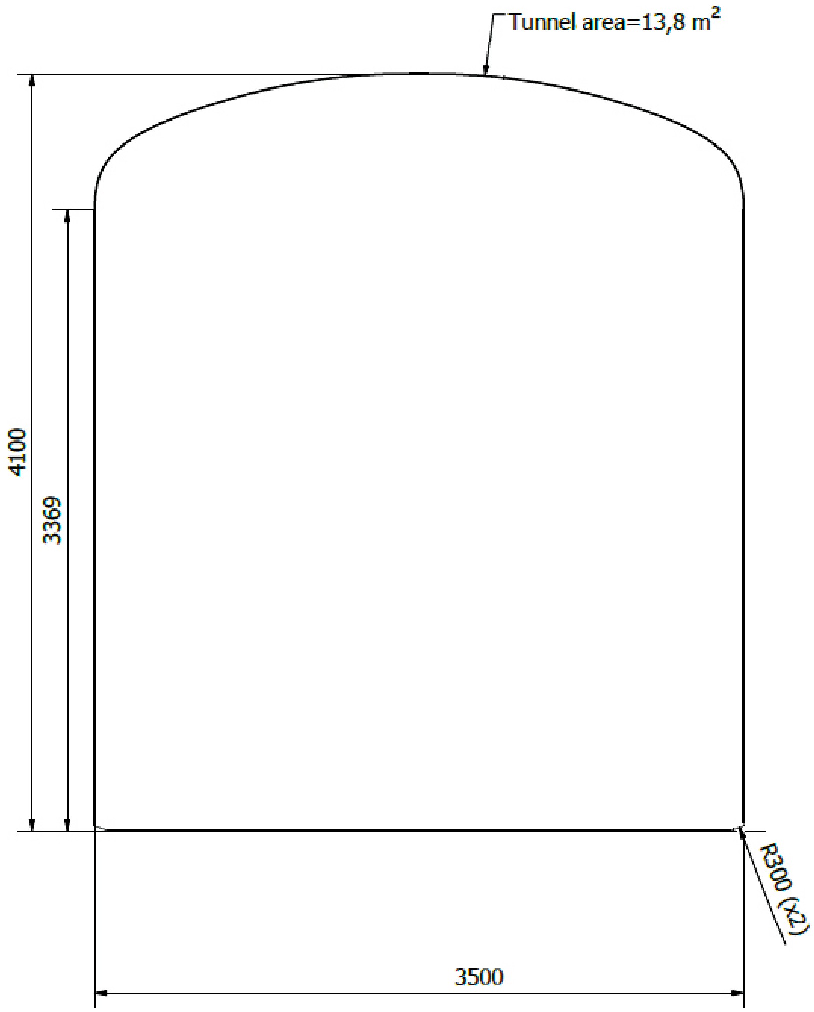

Figure 2-2. *One of many possible deposition tunnel geometries, in this case excavated mechanically with a nominal area of 13.8 m³.*

3 Technical design requirements and component dimensions

This chapter introduces the technical design requirements (TDRs) and the dimensions of the components.

3.1 Buffer

The TDRs for buffer are presented in Table 3-1 and their basis is detailed in Posiva SKB (2017).

Table 3-1. TDRs for buffer.

Characteristic	TDR	Comment
Material specific relation between dry density and swelling pressure	The minimum dry density yielding a swelling pressure > 3 MPa	Measured with 1 M $CaCl_2$ according to SKB's method *Metodbeskrivning för bestämning av Svälltryck och Hydraulisk konduktivitet*
	The maximum dry density yielding a swelling pressure < 10 MPa	Measured with de-ionised water according to SKB's method *Metodbeskrivning för bestämning av Svälltryck och Hydraulisk konduktivitet*
Material specific relation dry density – hydraulic conductivity	The minimum dry density yielding a hydraulic conductivity in saturated state < 1E−12 m/s	Measured with de-ionised water and 1 M $CaCl_2$ according to SKB's method *Metodbeskrivning för bestämning av Svälltryck och Hydraulisk konduktivitet*
Material specific relation between dry density and shear strength	The maximum dry density yielding an unconfined compressive strength at failure < 4 MPa at a deformation rate of 0.8 %/min when determined with a specific laboratory test procedure, and for material specimens in contact with waters with less favourable characteristics than site-specific groundwater	Measured according to SKB's method *Metodbeskrivning Enaxliga tryckförsök på lerprover*
Harmful substances: Sulphide content Total sulphur content Organic carbon	 < wt 0.5 % < wt 1.0 % < wt 1.0 %	Corresponding to approximately 1 wt% pyrite Including sulphide
Thermal conductivity	The thermal conductivity over the installed buffer shall, given the allowed decay power in the canister, the thermal properties of the canister and the rock and the canister spacing, yield a buffer temperature, Tb < 100 °C	Tb = Temperature of selected buffer material

The TDRs, Table 3-1, apply on average over the evaluated buffer volume, which is defined as the volume from the bottom of the deposition hole (including a bottom block) to 500 mm above the canister (including a top block), equalling approximately 18 tons of bentonite (at water content 17 %). Additionally, there are four solid blocks with pellets above the evaluated volume that are made up of the same material. This section equals approximately 10 tons of bentonite (at water content 17 %).

It is also required that the buffer must not influence the other barriers in a harmful way.

A requirement is also that the buffer thickness, i.e. the distance between the canister and the deposition hole wall, shall be at least 300 mm. The thickness of the buffer below the canister bottom shall be at least 500 mm. The thickness of the buffer above the canister shall be at least 500 mm. The buffer and connecting backfill shall also be possible to install in a safe and rational way.

Along with the TDRs, there are accompanying guidance's of the materials to be purchased that might influence the production process for manufacturing the components and the planned facilities. The main ones are presented in Table 3-2.

Table 3-2. Additional material guidance on the buffer deliveries.

Characteristic	Guidance	Comment
Granular size distribution	0–25 mm	The specification for the granular size, lower and upper curve, for a material ready for compaction, is presented in SKB (2010c) and included in Figure 6-1 and this granular size must be possible to produce from the purchased 0–25 mm material. At the current stage of development, SKB is generally purchasing materials with 0–2 mm, which is suitable for material characterisation and block production.
Water content	Will be optimised	Currently not fixed, but a lower water content would reduce operational costs at Hargshamn (less drying of the material). An optimisation between the suppliers and SKB's drying may be possible. Possible changes in water content during transport also have to be taken into account.
Compaction properties	Must allow block manufacturing at purposeful dry densities.	SKB will have an adapted buffer design, i.e. a dry density and water content, for a specific material. Robust blocks must be possible to compact at that adapted design (SKB 2010c)
Montmorillonite content*	> 70 % and ± 3 %	The montmorrilonite affects the swelling pressure, and in addition to being above 70 % an even montmorillonite content is of high importance. ± 3 % is a preliminary number which may be updated when more statistics is available.
Homogeneity	Buffer manufactured from the delivery shall fulfil the TDRs (Table 3-1) and the additional material guidance's above on a buffer volume scale.	The required buffer volume scale is in the order of 18 tons, i.e. buffer made from any combination of 18 tons of the bulk delivery should ideally fulfil the TDRs, however, SKB's processing will homogenise the material further.

* Montmorillonite (direct or indirect) is a parameter which the suppliers generally measure, and which can simplify purchase discussions, both with respect to tolerances (in practice, the requested homogeneity) as well as with the required swelling pressure.

All TDRs must be fulfilled, however, a good guideline when working with multiple TDRs is to try to identify a governing TDR, which, when it is fulfilled to a large extent answers also the other ones.

SKB foresees that with a thorough evaluation of the supplier and their materials it will be possible to select a material from which buffer with relatively good margins to most of the TDRs can be installed. From an adaptive design standpoint, the dry density yielding a swelling pressure > 3 MPa and < 10 MPa, can often be used as a governing requirement.

The configuration of the buffer blocks is shown in Figure 3-1. The buffer consists of four types of blocks, see Figure 3-2.

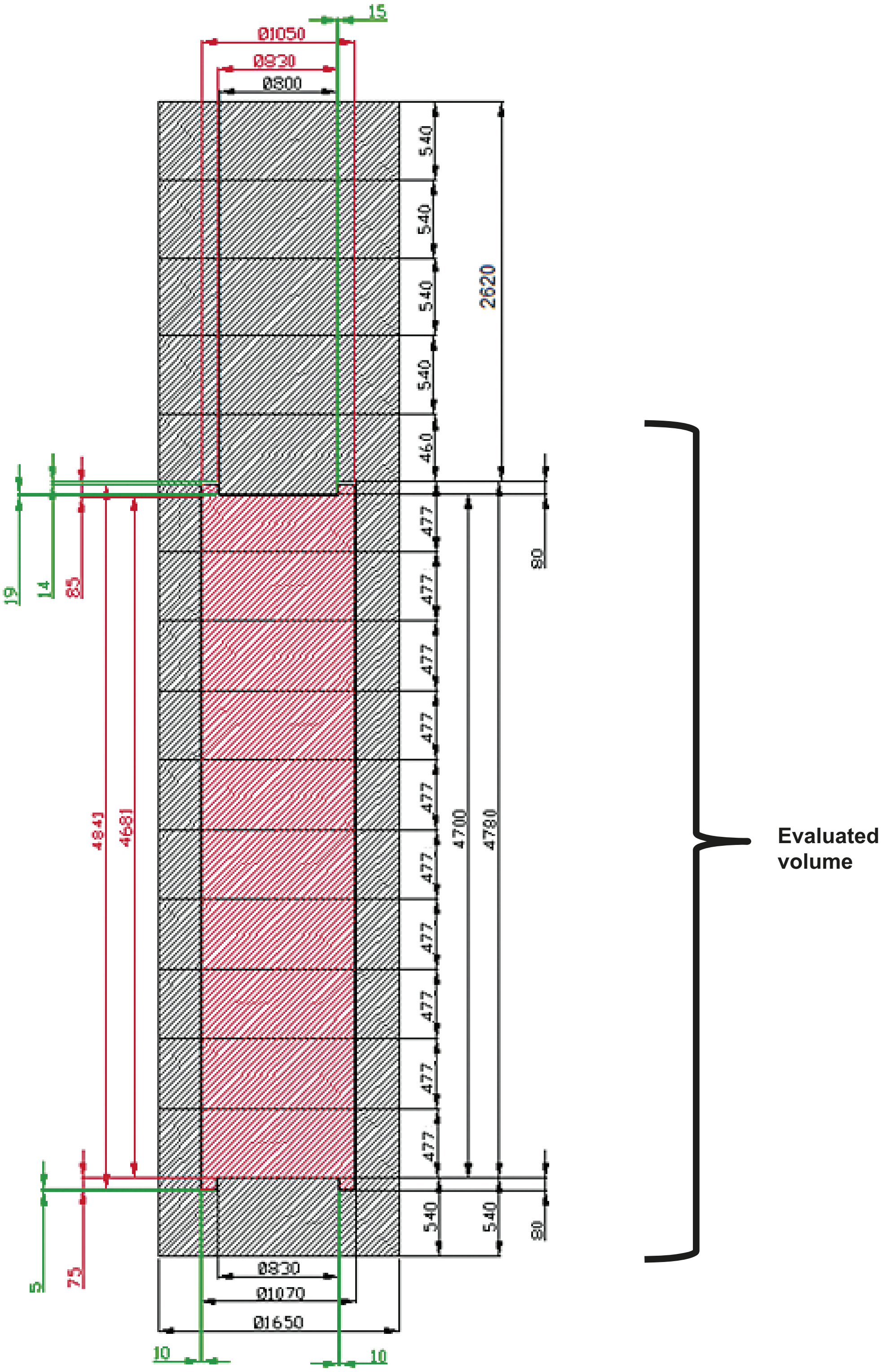

Figure 3-1. *The configuration of buffer blocks in a deposition hole. The evaluated buffer volume ends 500 mm above the canister. The void between the blocks and the rock wall is filled with pellets.*

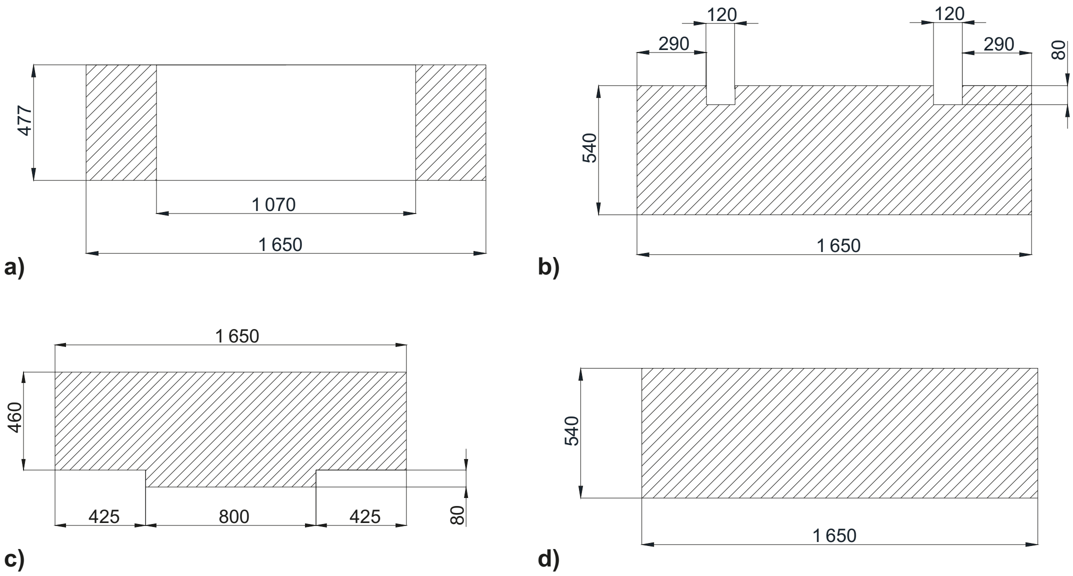

Figure 3-2. *Nominal dimensions of buffer blocks for a) the ten ring-shaped blocks surrounding the canister, b) the solid block at the bottom of the deposition hole, c) the block at the top of the canister and d) the four most upper solid blocks in the deposition hole.*

3.2 Backfill

The TDRs for backfill are presented in Table 3-3 and their basis is detailed in Posiva SKB (2017).

Table 3-3. TDRs for backfill.

Characteristic	TDR	Comment
Material-specific relation between dry density and swelling pressure	An acceptable dry density is one which gives a swelling pressure > 1 MPa	Measured with 1 M $CaCl_2$ according to SKB's method *Metodbeskrivning för bestämning av Svälltryck och Hydraulisk konduktivitet*
Material-specific relation between dry density and hydraulic conductivity	The minimum dry density yielding a hydraulic conductivity < 1E−10 m/s	Measured with de-ionised water and 1 M $CaCl_2$ according to SKB's method *Metodbeskrivning för bestämning av Svälltryck och Hydraulisk konduktivitet*
Harmful substances: Sulphide content	n.a.	At this stage of development a sulphide limit is not set, however, it may be added as a TDR for the backfill

The TDRs, Table 3-3, apply as an average in a 6 m tunnel section, which is equivalent to approximately 150 tons of bentonite at water content 17 % (highly dependent on the final deposition tunnel area, see Section 2.3).

It is also required that the overall deformation of the installed backfill both in dry and saturated state shall resist the swelling pressure from the buffer and maintain the buffer swelling pressure > 2 MPa in average over the evaluated buffer volume. This is in order to keep the buffer in place.

The additional guidance's for the backfill are presented in Table 3-4.

Table 3-4. Additional material guidance on the backfill deliveries.

Characteristic	Guidance	Comment
Granular size distribution	0–25 mm	The specification for the granular size, lower and upper curve, for a material ready for compaction, is presented in SKB (2010c), and included in Figure 6-1 and this granular size must be possible to produce from the purchased 0–25 mm material. At the current stage of development, SKB is generally purchasing materials with 0–2 mm, which is suitable for material characterisation and block production
Water content	Will be optimised	Currently not fixed, but a lower water content would reduce operational costs at Hargshamn (less drying of the material). An optimisation between the suppliers and SKB's drying may be possible. Possible changes in water content during transport also have to be taken into account
Compaction properties	Must allow block manufacturing at purposeful dry densities with a compaction load of max 50 MPa	SKB will have an adapted backfill design, i.e. a dry density and water content, for a specific material. Robust blocks must be possible to compact at that adapted design dry density (SKB 2010b). 50 MPa is the upper limit for the planned presses
Homogeneity	The backfill manufactured from the delivery shall fulfil the TDRs (Table 3-3) and the additional material guidance's above on a backfill volume scale	The required backfill scale is a 6 m tunnel section, i.e. backfill made from any combination of approximately 150 tons of the bulk delivery should ideally not exceed the TDRs, however, SKB's processing will homogenise the material further

Similar to the buffer, the dry density yielding a swelling pressure > 1 MPa can, from an adaptive design perspective, be used as a governing TDR. Given that there is no upper swelling pressure limit for backfill this TDR can generally be fulfilled with good margins by selecting a relatively high dry density. The presses planned for Forsmark have a maximum compaction capacity of 50 MPa given the chosen block sizes. Work is ongoing how to best asses the requirement on the backfill to keep the buffer in place and it could be that the strength of the installed backfill blocks may govern the adaptive design work.

The method for excavating the deposition tunnels is not yet decided, which also means that the geometry of the tunnels and backfill blocks are not decided either. Figure 3-3 illustrates one of the studied deposition tunnel geometries where a mechanical excavation method has been used. The block dimensions and configuration in the deposition tunnel are optimised for this specific tunnel area and could thus be modified if another deposition tunnel geometry was used.

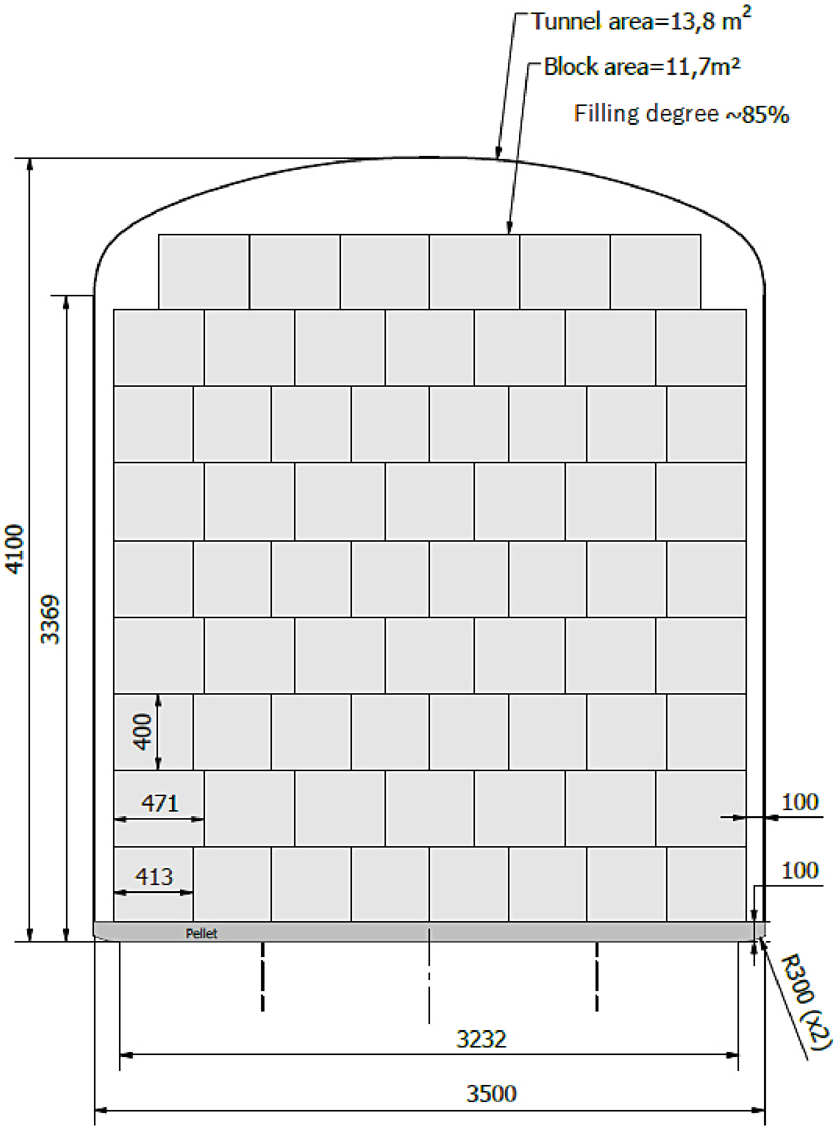

Figure 3-3. *One example out of several deposition tunnel geometries studied by SKB. The block size and configuration have been optimised for this specific deposition tunnel geometry.*

4 Strategy for quality assurance and quality control

4.1 General strategy

There are several possible strategies available for reaching the overall objective which is to supply the repository with cost efficient and quality controlled buffer and backfill components. These spans from purchasing ready-made and approved components from a qualified supplier with SKB doing spot-checks to confirm the suppliers quality management system to purchasing raw material and manufacturing and quality controlling the material and components in-house at SKB. Current development is based on the premise that the bentonite components shall be manufactured and quality controlled in-house. This means that SKB has to establish a procedure for quality assurance covering all stages of the process, from the delivering of the material to approved components, ready for installation in the repository.

Storage-keeping of components, transports to and within the repository, and installation has its own procedures for quality assurance which are not covered in this report.

Figure 3-1 illustrates the facilities currently planned by SKB. A receiving facility at Hargshamn, which has a stacker/reclaimer system with conveyor belts used to transport the material into and subsequently out from a main storage. The system will distributes the material in one direction over the storage area and then reclaim it in the opposite direction, and thus increase the homogeneity of the material. Crushing and drying of the material is also done at Hargshamn. The production facility is located in Forsmark, where the materials will be mixed to the required water content and blocks will be manufactured.

Given the adaptive design methodology which allows SKB to optimise the buffer and backfill design for a selected material, different deliveries (ship scale) can be allowed to vary somewhat, however, the material parameters in a specific delivery (ship scale) must not vary too much within. A shipload (buffer or backfill) can ideally be used as one batch in the manufacturing facilities with one corresponding adapted design.

The size of the buffer deliveries remain to be decided, however, bulk shipping > 20 000 ton, is available which would correspond to over 700 deposition holes and thereby approximately 12 % of SKB's planned canisters.

The size of the backfill deliveries, similarly to buffer, remains to be decided. However, bulk shipping in the order of 50 000 ton may be possible. This corresponds to approximately 330, 6 m long, backfill sections, i.e. 6–7 deposition tunnels.

The suppliers generally have good capabilities for homogenising materials and several assert that they are able to deliver according to SKB's specifications. SKB's current buffer tolerance guidance for montmorillonite content is ± 3 % with the guidance being > 70 % and ± 3 %. In addition to the supplier's capabilities, the stacker/reclaimer system which spreads the material in one direction and reclaims it in another (with a 90 degree difference) at Hargshamn is an efficient way to further homogenise the material.

Efficient sampling together with analysis of appropriate parameters are fundamental in order to fulfil the overall objective of supplying the repository with cost efficient buffer and backfill components fulfilling the requirements. SKB has decided to establish an in-house laboratory, which at the current stage of development is located to the Äspö Hard Rock Laboratory. The current plan is to set up the standard operation procedures (SOPs) needed as part of SKB's management system, gain experience, build statistics, and when desired to mirror the SOPs to Forsmark in order to speed up establishing of a laboratory there.

SKB's Chemistry laboratory at Äspö operates according to SS-EN ISO/IEC 17025:2018*,* which ensure that the operation is managed in a competent way and that the laboratory has the capability to produce reliable results. The material laboratory is still under development and will be more and more integrated into the Chemistry laboratory operation.

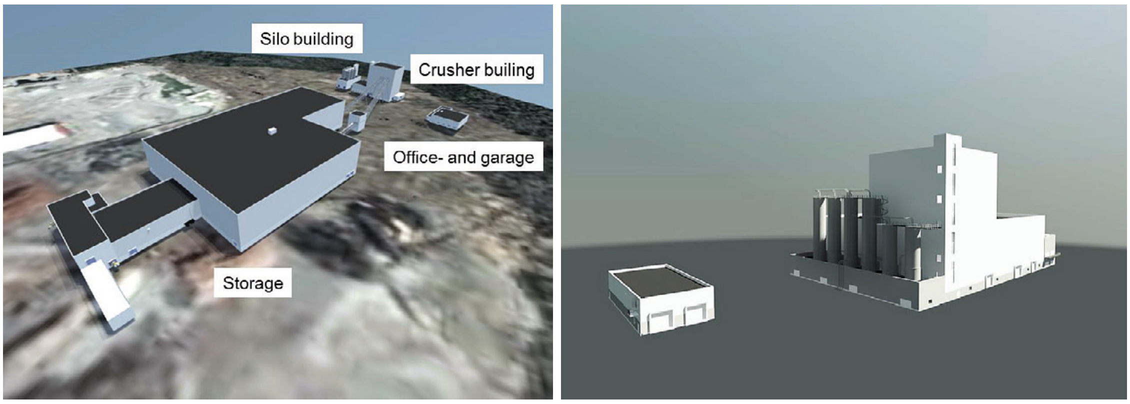

Figure 4-1. *Left, the Hargshamn receiving facility, right the Forsmark facility.*

4.2 Material and production quality management strategy

The suggested strategy for supplying the repository with quality control components is divided into three main steps:

Step 1. Material evaluation process

1. Supplier and deposit evaluation
2. Material quality evaluation, adaptive design and potential to fulfil TDRs
3. Initial evaluation of the long term performance, costs and production aspects and finally acceptance for industrial application

Step 2. Material selection and purchase

1. Final evaluation of long term performance, costs and production aspects. Comparing several potential materials
2. Material selection
3. Purchase

Step 3. Production process at SKB

1. Incoming Quality Control
2. In-Process Quality Control
   a. Hargshamn
   b. Forsmark
3. Outgoing Quality Control

The first step is the material evaluation process; it is intended to evaluate possible suppliers and materials. The potential for the material to fulfil safety functions and TDRs is evaluated and material specific adapted designs are tested. This step can be done in advance or in direct connection to actual industrial purchases.

At **the second step** the material is selected and purchased. Long term performance of the material is evaluated together with the adaptive design, cost and production aspects. If a long time has passed since the material evaluation process was carried out a renewed iteration of parts of that step for the selected material may be required. This is due to material properties potentially changing over time as the supplier exploits new areas of a deposit.

The third step is the production process, which covers quality control from the time the material is purchased until components are manufactured and approved.

Figure 4-2, illustrates the main activities in each step. Further details are provided in the following sections.

The overall strategy can be applied for both buffer and backfill with somewhat fewer analyses for the backfill materials, for example shear strength measurements would not be required for backfill.

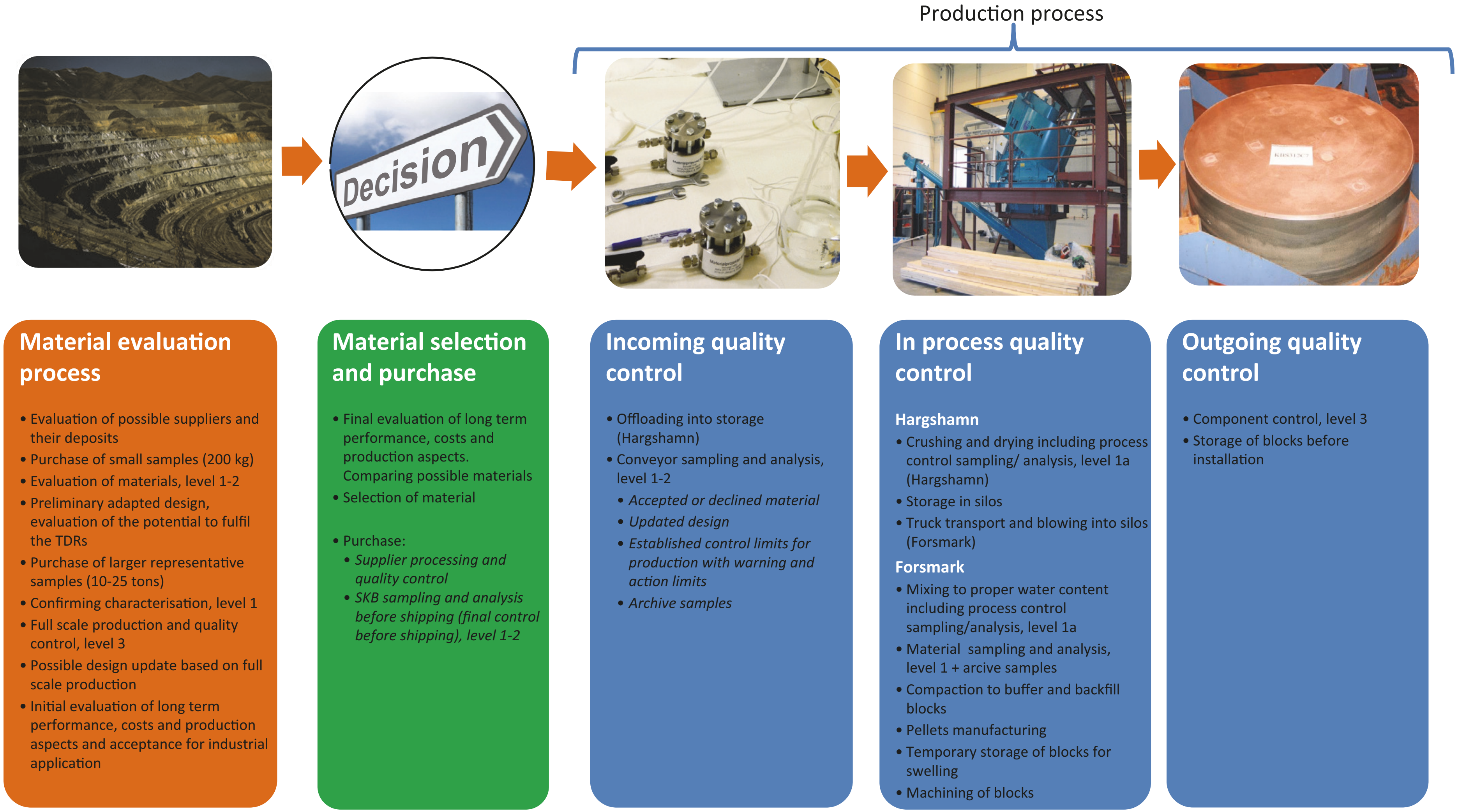

Figure 4-2. *Division of the activities and quality control procedure into three main steps. For the referred analysis levels, see Section 5.3.*

4.3 Material evaluation process

4.3.1 General

With bentonite being a natural material that has numerous industrial applications, there is a wide range of qualities available on the market. Different qualities have different mineralogical and chemical compositions as well as varying hydro-mechanical properties.

SKB's TDRs, Chapter 3, limits the number of materials that can be used in a repository. However, several suppliers can provide suitable materials, although each material will require its own specific adapted design. This process, where the components of the system are adapted in order to fulfil the buffer or backfill TDRs for a specific material is called **adaptive design** by SKB. The requirements regarding harmful substances are exceptions in that respect that they rather depend on the concentration in the material itself and are thus not influenced by the adapted design.

On a reference design scale, parameters such as bentonite block and deposition hole dimensions, tunnel geometries, amount of pellets and allowed voids can also be modified in order to target the TDRs. However, this is considered during KBS-3 development work, while the adaptive design work is done continuously during the repository operation.

In the most recent stage of development (this report) the geometries and their tolerances are fixed and it is only the selected dry densities and water contents of the buffer and backfill blocks which are adapted.

4.3.2 Process

The different steps in the material evaluation process are illustrated in Figure 4-3. It is a step-by-step process, where the next step is only started if a material passes the previous one. The process starts with the selection of a number of possible materials, after which supplier and deposit evaluations are carried out. These include commercial aspects, long term availability of the material, the supplier's willingness to cater to SKB specific needs such as extra homogenisation, sample deliveries or possibilities to introduce some of SKB's analysis methods on site.

For the next step, smaller samples, around 200 kg, are purchased from those suppliers who are deemed to be able to provide a required quality in sufficient volumes. These samples are characterized in detail, according to characterization level 1–2; see Section 5.3 for details on the characterization levels. The potential to fulfil the TDRs is evaluated and the most promising materials are selected and a preliminary adapted designs are developed for the different components, see Section 6.4 for further details on adapted design.

At the next step, a representative sample in the order of 10–25 tons is purchased and characterization level 1 is performed to confirm that the material corresponds to the one previously analysed. If it does, with acceptable variation, a full-scale production of components is carried out, characterization level 3. At this stage several blocks are manufactured and the full-scale compaction parameters are optimised. The design is subsequently fine-tuned based on the full scale production experience. An initial evaluation of long term performance, costs and production aspects is carried out and those materials that pass all the steps are approved for industrial application. For material selection see Section 4.4.

In addition to the adapted design another key delivery from the material evaluation process is an updated material specification. It should include, selected water content and possible extra requirements on the supplier's process, for example if extra homogenisation is needed for SKB. It should also include recommended batch size(s) and suggestions how the supplier's quality controls should be set up.

The process described above is tailored to SKB's present development and laboratory capacity, including the initial step where smaller amounts of materials are purchased, approximately 200 kg. In a future, repository scenario, it is foreseen that SKB will have a list of approved suppliers and possible materials, both for buffer and backfill, and it would be more efficient to start the process at the 10–25 ton stage and carry out the full characterisation, level 1–3, in order to confirm that a material which has previously been approved hasn't changed in any significant way before a large scale industrial purchases is made.

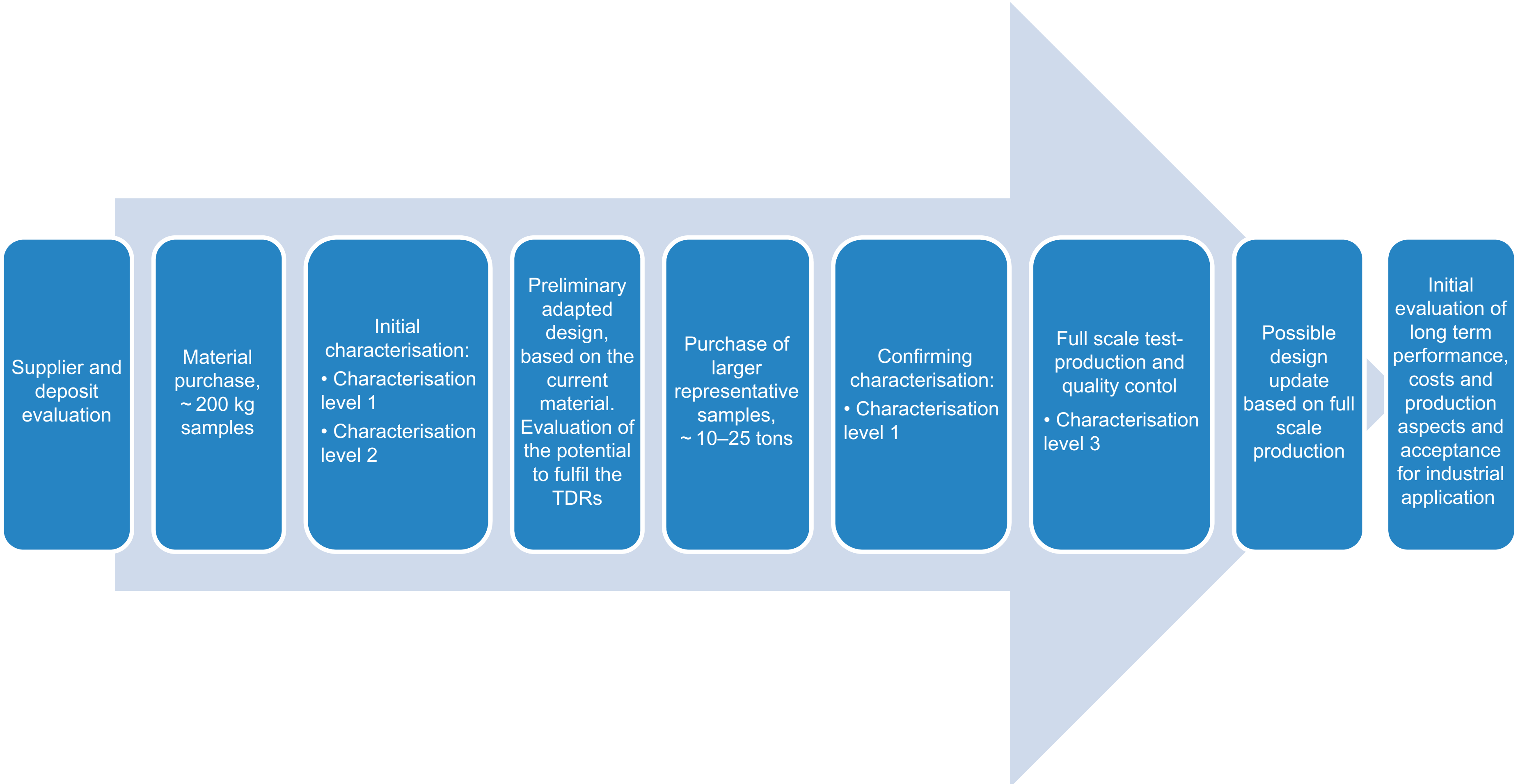

Figure 4-3. *Illustration of the key steps in the material evaluation process applicable for both buffer and backfill. For details on the characterisation levels, see Section 5.3.*

4.4 Material selection and purchase

By the time the first material delivery for the repository is to be purchased it is expected that SKB will have a list of possible materials and approved suppliers with material specific specifications. Buffer or backfill made from their materials will have suggested adapted designs which should fulfil the TDRs and which have been test-manufactured in full scale, Section 4.3.

The material selection will thus come down to further material specific information on long term performance. Cost and other commercial aspects are also considered. A renewed, in-depth long term performance evaluation is done and different materials are weighed against each other. A material may for example stand out with a very low bacterial activity or it may be more resilient against chemical erosion.

Dependent on how long time has passed since a material was evaluated, it may be necessary to make a renewed smaller purchase and make a new characterisation including block manufacturing before a larger volume, for industrial production, is purchased.

The contract with the supplier will have to include, not only the material specific specification, but also acceptance criteria's on how to assure that the specification is fulfilled. For example SKB should be able to audit the quality management system of the supplier's laboratory when they are evaluating a delivery to SKB and the supplier should know and accept how SKB will control the material in Hargshamn.

The supplier is responsible for the fulfilment of the material specification. In order to minimise the risk that SKB receives a material which doesn't fulfil the specification (due to unforeseen errors), a sampling and analysis by SKB or a third party should be carried out prior to loading the ship.

4.5 Production process

4.5.1 Incoming quality control

The incoming quality control have several objectives; to confirm that buffer and backfill manufactured from the incoming materials can fulfil the TDRs, to define warning and action limits (Norden 2008) that can be used during the manufacturing process and for fine-tuning the adapted design.

It will be important to control both the potential to fulfil the TDRs and the homogeneity of the incoming material, and ideally, if XRF analysis could be measured automatically at the conveyor belts, it could be a possible control method for analysing the homogeneity of the material (Svensson et al. 2019).

Physical samples will also be required and ISO 11648-1:2003 and ISO 11648-2:2001 Statistical aspects of sampling from bulk materials establish general principles for the application and statistical treatment of the sampling of bulk materials. ISO 10725:2000 Acceptance sampling plans and procedures for the inspection of bulk *materials* specifies acceptance sampling plans by the determination of variables and use of acceptance inspection procedures for bulk materials.

Sampling will probably be done on the conveyor belts of the stacker/reclaimer system that feed into the Hargshamn storage, see Section 4.1. The actual homogeneity of the material reclaimed from the piles will thus be further improved after sampling. In addition to this, basically all subsequent process steps, crushing, drying and mixing involves blending of the material and should thus improve the homogeneity further.

Combining all aspects that influence the quality and homogeneity of the incoming material along with the homogenising procedure of using a stacker/reclaimer system remains to be done and the exact number of samples for buffer and backfill thus remains to be determined. For example, for a 18 000 ton ship at a 1 000 tons/hour unloading rate, it would take 18 hours to unload, which corresponds to a flow rate in the order of 16.7 tons/min. If increments are taken every 7 minute (approximately 1 increment every 120 tons) it would correspond to approximately 160 increments over 18 hours, which could be combined into 8 composite samples. Note that one part of the increment would not be combined and XRF analysis would be done on all 160 increments in order to evaluate homogeneity, see Section 5.2.

The composite samples are analysed according to characterisation level 1–2 (Section 5.3) in order to verify that the delivered batch fulfils the requirements. If needed, the adapted design is fine-tuned to the actual incoming material. The results from the analyses are also used in order to define warning- and action limits that can be used when controlling the production. These limits can be tighter than the requirements, but can be useful in order to detect smaller variations in the material, and if needed prompt actions before requirements are compromised, such as an extra investigation or control.

Radioactivity could also be considered and measured during off-loading, in order to ensure that no unforeseen nuclides are brought into the repository. Possible metal scrape could also be checked, detected and removed.

4.5.2 In-process quality control

Hargshamn

The delivered material (0–25 mm) from the main storage will be dried and crushed at Hargshamn, which will require water content and granular size distribution control (level 1a) to steer the process. The amount of sampling and analysis for these process steering analyses will have to be established on site when test-running the process, and optimised as more statistics is made available.

The material is transported by truck to Forsmark.

Forsmark

At Forsmark, several process steps are made. The first step involves mixing of the material to a specified water content which will require water content measurements. The amount of sampling and analysis for this process steering analyse will also have to be established on site when test-running the process, and optimised as more statistics is made available.

The next step is the manufacturing process of blocks and pellets. The amount of sampling and analysis needed at this stage remains to be assessed in detail. It is likely that a detailed sampling when a new batch (ship size) is introduced would be favourable in order to build statistics. Possibly, a double composite sample each day (including 2 × 20 XRF sub samples and archive samples) analysed according to characterisation level 1, see Section 5.3.

At this stage the results can be compared to the warning and action limits from the incoming quality control data.

It is likely that this sampling and analyses can be greatly reduced if the material is very homogeneous and has margins to the requirements.

For the buffer blocks there is a final step which is machining of the blocks to their required final dimensions, which is done a couple of days after compaction, since the blocks expand for some time after compaction. The milling equipment shall ensure that the dimensions are within the allowed tolerances.

4.5.3 Outgoing quality control

The outgoing quality control for the blocks constitute level 3 and is expected to be fully automated in the handling process, i.e. each block will be weighed and its dimensions measured. Together with the material and process control this will provide a basis to approve the components for use in the repository.

Each pallet on which the components are stored will have a specific ID with connected information from its production, such as dates.

The final products will be stored and protected to ensure proper environment. This is done in order to avoid drying and cracking which is a potential risk for handling with vacuum tools.

With respect to pellets production, the material control is similar and the level 3 pellet control methods are used.

5 Sampling and characterisation levels – standardising

5.1 Incentive for sampling and analysis

Sampling and analysis of bentonite materials are done for several reasons within SKB's repository system:

- To provide a basis to develop a material specific adapted design.
- To provide a basis for material selection.
- Quality control of industrial scale deliveries – basis to approve or reject.
- Ensure that a delivery isn't contaminated – radioactivity and metal scrap.
- To provide data for steering the production process.

Additionally, the dimensions and weights of the final buffer and backfill components are measured in order to approve or reject them.

5.2 Sampling

The uncertainty in the results from the investigation of the materials will be dependent both on the uncertainty derived from sampling i.e. how well the samples represent a delivery or batch (ship size) and from the performed investigations and analyses.

At the Äspö laboratory, a standardised sampling procedure is being evaluated, see Figure 5-1. It draws on experiences from available ISO standards, ISO 10725:2000 Acceptance sampling plans and procedures for the inspection of bulk materials, ISO 11648-1:2003 and ISO 11648-2:2001 Statistical aspects of sampling from bulk materials with modifications to suit the current development stage. In principle, it is based on 20 samples (increments) for each delivery. If a delivery consists of 20 big-bags, each of them is sampled, while if it is 100 big-bags, every 5th big-bag is sampled. Each of the 20 samples (increments) are divided into two sub-samples (secondary increments) and XRF analysis is done on the first of these sub-samples (secondary increments), i.e. totalling 20 XRF analyses in order to evaluate the homogeneity of the delivery, while the remaining 20 sub-samples (secondary increments) are combined into one composite sample, which in turn is divided into one part on which the remaining laboratory measurements are carried out and one part for archiving.

At the current development level for the Äspö material laboratory, one composite sample is reasonable, although double samples generally are preferable and should be evaluated for some deliveries.

In Hargshamn and Forsmark, the current layout of the facilities includes conveyor belts which will be used for transporting the material which is favourable when it comes to sampling the materials, since samples can be taken from the conveyor belt at selected intervals.

The methodology can, thus, be adapted for Hargshamn and Forsmark. However, the number of sub-samples (increments) and composite samples will be optimised based on the size of the industrial deliveries together with other factors which influence the quality and homogeneity of the material.

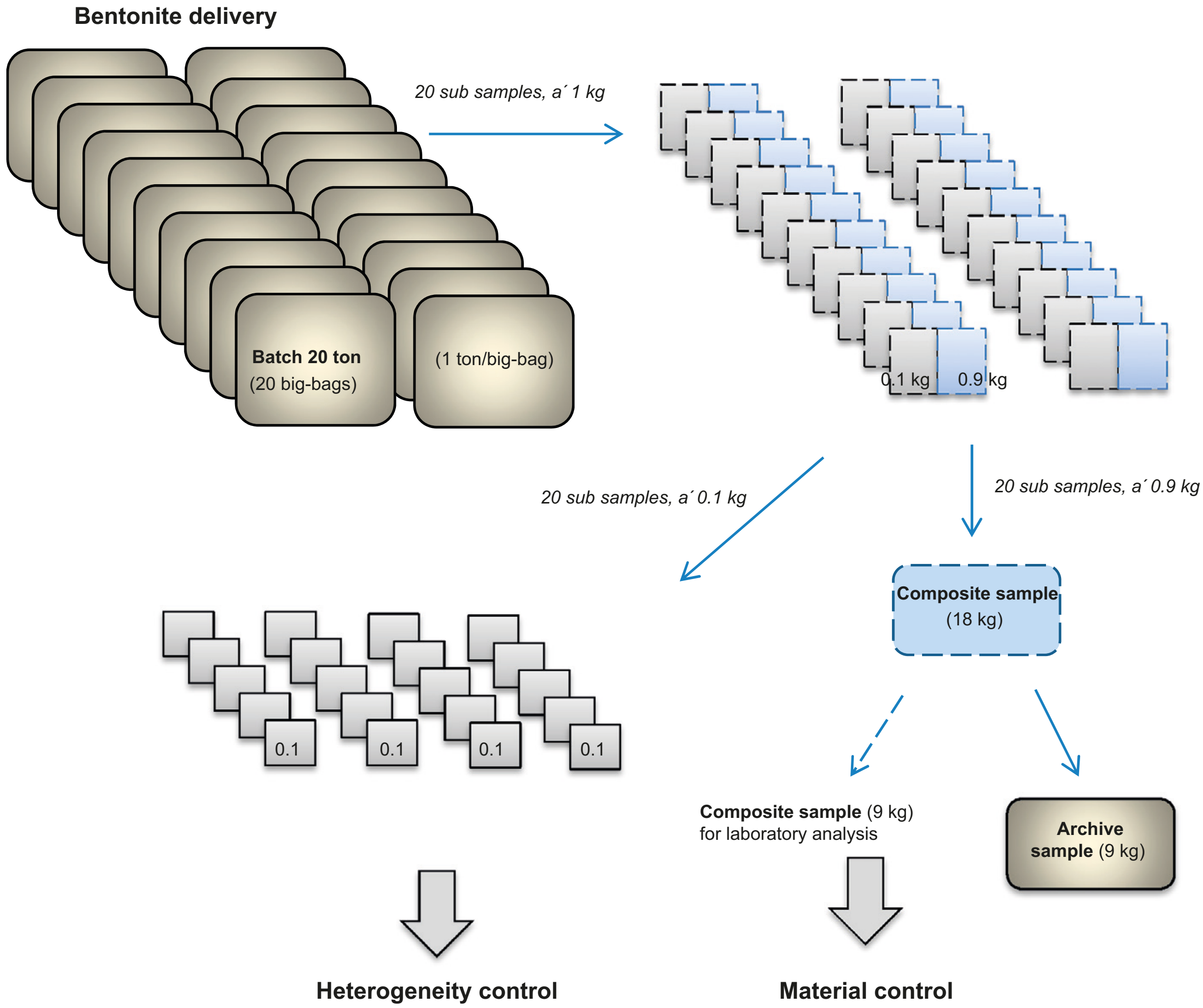

Figure 5-1. Sampling plan for Äspö material laboratory, 20 ton bentonite delivery.

5.3 Characterisation levels and analysis

SKB has been working on the quality control of bentonite for a long period and a set of methods have been selected in order to characterise and control different materials (Karnland 2010, Svensson et al. 2017).

Different methods will be needed at different stages of the future process. Three different characterisation levels are currently suggested, see Table 5-1. Both the listed methods and characterisation levels will be updated when more experience and statistics are available. Details on each characterisation level are provided in the sections below.

Table 5-1. Buffer characterisation methods under development at the Äspö material laboratory. In principal the same set of parameters are used for backfill but shear strength and thermal conductivity are not directly applicable as they are not directly connected to the TDRs for backfill.

Level	Parameter	Comment
Characterisation level 1		**Level 1 should provide basic acceptance data**
1a	Water content (water/dry mass)	1a) Includes process control parameters
	Granular size distribution	
1b	Chemical composition (XRF)	1b) Includes methods aimed at confirming acceptable homogeneity in the material
	Swelling pressure, quick	
	Cation Exchange Capacity (CEC)	
	Combustion analysis, (C_{org}, S_{tot}, $S_{sulfide}$)	Currently external
Characterisation level 2		**Level 2 should provide the basis to develop an adapted design**
	Hydraulic conductivity and swelling pressure	
	Exchangeable cations (EC)	Currently external
	Mineralogical composition (montmorillonite) XRD	
	Grain density	Currently external
	Compaction properties	
	Unconfined compression strength	
	Thermal conductivity	
Characterisation level 3		**Level 3 should confirm the component quality**
	Pellets, dimensions and abrasion resistance	
	Block dimensions, weights and visual inspection	Under development

5.3.1 Characterisation level 1

Characterisation level 1 is used for a quick inspection of materials and provides basic information such as water content and granular size distribution but also the basic chemical composition via XRF and combustion analysis as well as a judgement of the swelling properties evaluated from quick swelling pressure measurements (Svensson et al. 2019) and CEC.

The XRF-analysis is also carried out on the sub samples (increments), see Figure 5-1, which provides a picture of the batch homogeneity.

SKB's TDRs for buffer and backfill; C_{org}, S_{tot}, sulphide and the relation between dry density and swelling pressure is included in characterisation level 1.

The quick swelling pressure determination which has been recently developed (Svensson et al. 2019) can be done either as a full swelling pressure curve (9 measurements at different dry densities) or as double samples aiming for a selected dry density. The latter design of the test has the potential to become an important control method of the material feeding into the presses as it is targeting the adaptive designs governing requirement, i.e. the dry density yielding a swelling pressure > 3 MPa and < 10 MPa, Section 3.1, with a measurement that is expected to be possible to carry out within 24 hours.

Characterisation level 1 can be used to check that a new delivery matches earlier deliveries and at the industrial production it could be used for continuous control to ensure that there are no significant changes in the material feeding into block or pellets production compared to the investigations made on the material when it is unloaded at Hargshamn, i.e. confirming that there are no contamination or unexpected heterogeneities in the material flow. It should be noted, that the extent of the continuous control will be dependent on the available statistics for a specific material, i.e.it is likely with tighter sampling intervals initially and probably more spread out as more statistics become available.

The water content and granular size distribution is also denoted characterisation level **1a**, and will be used for process control in the production facilities, when drying, grinding and mixing (1a excluding granular size) the materials.

5.3.2 Characterisation level 2

Characterisation level 2 requires more time to execute and includes the design-parameters for the buffer and backfill, such as the relation between dry density and swelling pressure, hydraulic conductivity and compression strength, compaction curves, particle size and thermal conductivity. Mineralogical composition (XRD) and exchangeable cations (EC) are also included.

In general, characterisation level 2 is set up to be able to develop an adapted design for the components, and should mainly be required when new materials are evaluated or a new main delivery is offloaded at Hargshamn.

5.3.3 Characterisation level 3

Characterisation level 3 is directly connected to the quality of the final blocks and includes visual inspection, and dimension and weight control of the blocks.

Control of pellets is also included in the form of measurements of dimensions, density, and abrasion resistance.

In general, characterisation level 3 is set up to be used for evaluating new materials and in the production as the final confirmation that blocks and pellets fulfil their specifications. As long as the manufactured components have repeatable dimensions when compacted with consistent weight and compaction load, it is a strong indication of a good homogeneity in the material flow. This, combined with material analyses (level 1) of the material flow, taken at proper interval, should provide the basis to confirm that all specifications are fulfilled for all components with a high statistical accuracy.

In order to produce backfill blocks with small variation in dimensions, the compaction could possibly be controlled on dimension rather than load. In such case, the load would be automatically adjusted during production and repeatable dimensions would be less suitable for quality control. However, the load changes would be monitored and could possibly provide some information on changes in the material flow.

6 Results buffer

This chapter primarily deals with results from investigations of buffer materials included in this study, for backfill see Chapter 7.

A total of seven materials have been evaluated as buffer according to the material evaluation process described in Section 4.3, excluding long-term performance evaluation. The main steps of the process were followed. However, availability of materials and laboratory recourses meant that some parallel work was carried out, rather than the stepwise process originally intended. For example, characterisation level 2 analyses were initiated, before all level 1 analyses were finalised.

6.1 Supplier and deposit evaluation

SKB has purchased bentonite of different qualities for a long period and several suppliers are well aware of the type of bentonite needed for the future repository.

The adaptive design gives SKB flexibility to change the suppliers and material. However, future long-term availability of a specific material is still of interest for SKB. This is however in many cases restricted information due to commercial interests. In general, materials of similar quality can be provided from one supplier for many years (even decades in some cases) and by using the adaptive design methodology, SKB can also accept some material changes in-between deliveries, as long as the variation within each delivery is limited.

Due to the amounts of material that SKB will purchase, cost is also central, both the material cost itself, and the transportation cost. One of the main incentives of evaluating several materials both as buffer and backfill is cost optimisation.

Ethical aspects, related to workers conditions and environmental issues are also important when selecting possible materials.

Since the suppliers don't measure all parameters of interest for SKB the current material specifications primarily targets the montmorillonite- and chemical content, see Table 6-1 and 6-2.

It is an area for future development to define how in-depth the cooperation with the suppliers must be, and if methods used by SKB possibly can be implemented in the suppliers QA/QC system.

Table 6-1. Material specification buffer, used for purchases.

Parameter	Nominal value (wt%)	Accepted variation (wt%)	Suggested method
Montmorillonite	>70	±3	XRD, XRF, CEC
Sulphide	<0.5		Combustion analysis
Total Sulphur	<1		Combustion analysis
Organic carbon	<1		Combustion analysis

Table 6-2. Material specification backfill, used for purchases.

Parameter	Nominal value (wt%)	Suggested method
Montmorillonite	>65	XRD, XRF, CEC
Sulphide	<0.5	Combustion analysis

The seven materials which are tested were provided by five different suppliers, while the company and mining operation varies in size, as well as in-house laboratory capabilities, all of them operate on the international market and can in general fulfil SKB's common supplier requirements.

6.2 Material purchase

The seven different materials purchased and studied are presented in Table 6-3.

Table 6-3. Materials evaluated in the recent study.

Material	Initial characterisation		Confirming characterisation	Comment
Milos	20 kg (2017)			A low montmorillonite material was purchased in order to evaluate if it anyway could fulfil backfill requirements
Morocco	20 kg (2017)			
Bulgaria	20 kg (2017)	200 kg (2017 F)	20 tons (2018)	Two smaller deliveries were studied in parallel
Turkey		200 kg (2017)		
India			20 tons (2018)	Only studied in the 20 ton scale due to relatively long delivery times
Sardinia		200 kg (2017 F)		
BARA-KADE		200 kg (2017 F)	40 tons (2018)	Wyoming bentonite

6.3 Characterisation

The material evaluation process is divided into an initial characterisation (200 kg sample), followed by a preliminary adapted design, which in turn is followed by a purchase of a larger representative quantity (10–25 tons) used for full scale production. A confirming characterisation is done on the 10–25 ton delivery in order to check that it is similar to the first delivery.

Both the initial and the confirming characterisation (Figure 4-3) are reported in this section. A section of confirming characterisation of the larger purchases is included (see Section 6.6); however, it mainly discusses where there are differences between deliveries of the same material.

6.3.1 Water content

Water content data is presented in Svensson et al. (2019).

Since the material evaluation process involves small purchases (compared to an industrial scale), the materials used were those the supplier had available and water contents adjustments were not requested. The Bulgarian material had relatively high water content at 19–20 % while the Turkish material had the lowest about 9 %.

For the material evaluation process, the as delivered water content doesn't have to be specified since it is adjusts before compaction. However, it must not vary too much within a delivery as it would complicate the mixing to the required water content.

6.3.2 Granular size

Granular size distribution data is presented in Svensson et al. (2019). A copy of the data including the lower and upper specification (SKB 2010c) is presented in Figure 6-1.

The granule size distribution is mainly related to manufacturing issues. For discussion on the how compaction is affected by powder type materials see Section 6.3.11.

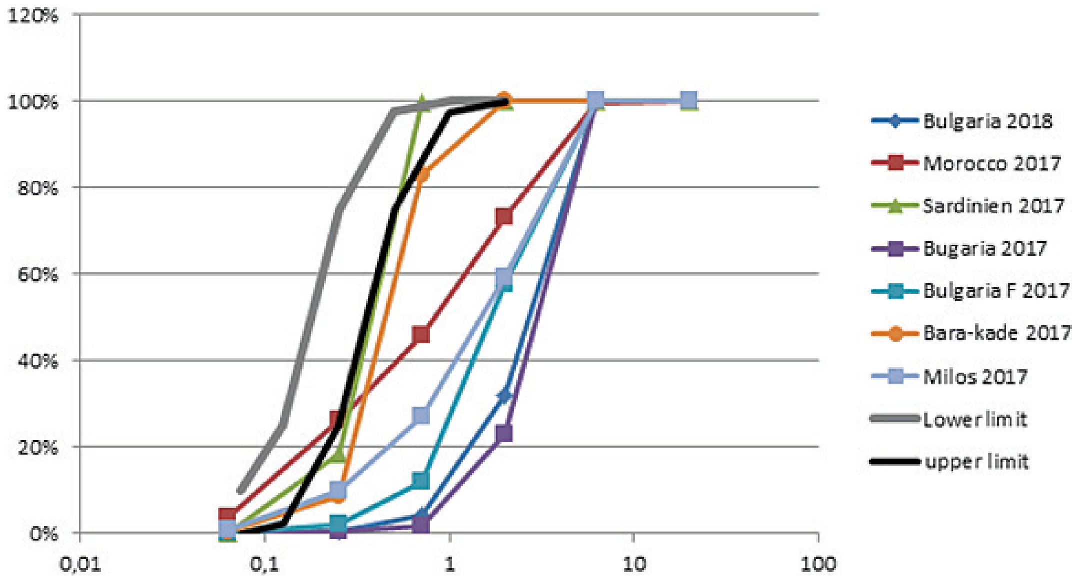

Figure 6-1. *Granular size distribution for the materials studied including lower and upper specification. The Turkish and Indian materials were fine powders and are thus not included.*

BARA-KADE and Sardinia basically matched the 0–2 mm material specification.

The Moroccan, Bulgarian and Milos materials all had quite a lot of granules above 2 mm. The granule size distribution will affect both the compaction properties of the bentonite and the block strength (Sandén et al. 2016, Eriksson 2017). A large difference in size between finest and coarsest granules in the material will make the material prone to segregation which will also affect the manufacturing of the blocks. However, the deviations from the specification seen for the three materials are not expected to affect the outcome of the design.

Two of the delivered materials, the Turkish and the Indian, were fine powders with 100 % passing the finest sieve and are thus not included in Figure 6-1.

6.3.3 Chemical composition, XRF

XRF data is presented in Svensson et al. (2019).

XRF data shows the elemental composition of the bentonite (elements heavier than or equal to Na). XRF analysis was carried out on both the composite sample and for four of the materials on the 20 sub-samples (increments). Changes in the chemical composition of a specific bentonite (between increments) are an indication that it would need further characterisation in order to identify the origin of the change.

6.3.4 Cat ion exchange capacity, CEC

CEC data is presented in Svensson et al. (2019).

The CEC method is used to indirectly estimate the montmorillonite or smectite content of the bentonite. It is a function of several factors but most importantly the smectite layer charge and the unit cell mass, hence different smectites have different CEC. The measured CEC-data of the seven materials matches up quite well with the XRD montmorillonite data, Section 6.3.9.

6.3.5 Combustion analysis

Organic carbon, total sulphur and sulphide data is presented in Svensson et al. (2019).

Organic carbon is well within the 1 % buffer TDR for all materials; the Bulgarian clay which also had the largest scattering in the data (triplicates) had a maximum value of 0.37 % (mean 0.16 %) and BARA-KADE had a maximum value of 0.26 % (mean 0.23 %). Morocco, Sardinia, India, Milos, Morocco and Turkey show low concentrations, around 0.1 % or lower.

For total sulphur, buffer TDR < 1 %, the Milos clay stands out with a maximum value of 0.87 % (mean 0.80 %) which is slightly higher than what is seen in for example in the IBECO RWC (MiR1) at 0.65 % in Karnland (2010). Turkey, Sardinia, Morocco and Bulgaria show low concentrations, well below 0.1 %. India is around 0.15 % and BARA-KADE is at 0.21 %.

With respect to sulphide, buffer TDR < 0.5 %, it's again mainly the Milos clay standing out with a maximum concentration of 0.43 % (mean 0.36 %), BARA-KADE is detectable at 0.04 % while all other materials are under the detection limit at < 0.02 %.

In summary, all buffer TDRs are fulfilled for all materials. The Milos clay, which is purchased with lower montmorillonite content, shows relatively high sulphur and sulphide content. Previously studied Milos clays have shown lower concentration and would be preferred compared to the current one due to larger margins to the requirement (if studied as a potential buffer material).

6.3.6 Swelling pressure, quick method

With the dry density yielding a swelling pressure > 3 MPa and < 10 MPa often being the governing TDR for both buffer and backfill from an adaptive design standpoint, the one month long measurement time in the full method is not ideal. Recent development (Svensson et al. 2019), includes an analysis where swelling pressure is measured with deionised water followed by direct terminations of the test, i.e. skipping both the 1 M $CaCl_2$ and hydraulic conductivity steps of the analysis. Currently, this allows for a one week test time, but there is potential to speed it up further.

The swelling pressure data is presented in Svensson et al. (2019).

The method requires nine different densities for each material in order to produce a swelling pressure vs dry density curve. This curve, together with the system dimensions is generally the main basis for developing an adapted design, see Section 6.4.

One material stands out with exceptional high swelling pressures, the Bulgarian material. Two smaller deliveries of the same Bulgarian material was studied (Table 6-3) and they did come out somewhat differently with respect to swelling pressure. The 20 kg delivery had somewhat higher swelling pressure compared to the 200 kg delivery. The 20 ton delivery on the other hand matched well with the 200 kg delivery. Their quick swelling curves are so similar that they cannot be distinguished. With respect to usability, there could be both pros and cons with the high swelling pressures at relatively lower dry densities which the Bulgarian material shows but the reason for it will have to be better understood and further studies will be needed.

For the other studied materials the swelling pressure curves were similar.

When comparing the scattering of the data for the seven materials the Milos, Indian and Bulgarian materials have somewhat larger scattering in their data sets compared to the other materials. Considering the uncertainties of the method, too much conclusions should not be drawn from this. However, it matches up relatively good with the scattering of the first 20 sub-increments in the separate XRF measurements (Svensson et al. 2019).

The curves from all materials can be used for adaptive design work. However, more data would be valuable to further lower the uncertainties.

More data will be available when a material should be selected and industrial purchases made. The incoming control of the material at Hargshamn will also include several composite samples; see Section 4.3, corresponding to a much larger data-set for the selected material.

In summary, the dry density TDR for both buffer and backfill regarding swelling pressure can be fulfilled for all materials. The reason for the extreme swelling pressure of the Bulgarian material must be better understood before it could be selected for industrial application. However, the material is still of interest and was eventually also selected for full scale test production, see Section 6.7.

6.3.7 Hydraulic conductivity and swelling pressure

The hydraulic conductivity and swelling pressure measurements are part of characterisation level 2 and both measurements are used to derive TDRs.

All hydraulic conductivity and swelling pressure data is presented in Svensson et al. (2019).

The Milos material stands out compared to the other investigated materials with higher hydraulic conductivity. This makes sense since it is a lower montmorillonite content material (Section 6.3.9). Other Milos materials which SKB have studied earlier have much lower (i.e. better) hydraulic conductivity values. When looking at the buffer dry densities yielding a swelling pressure between 3–10 MPa, the lower part of that dry density span corresponds to a dry density that would not yield a hydraulic conductivity < 1E−12 m/s. This particular material would thus not be suitable as buffer as the margins in the adapted design would be worse than they generally have to be. However, the backfill TDR, a dry density yielding a hydraulic conductivity < 1E−10 m/s can be fulfilled so it is valid as a potential backfill material.

The hydraulic conductivity of the 20 kg and 200 kg Bulgarian deliveries were very similar and could not be distinguished in the same way as their corresponding swelling pressures, see Section 6.3.6.

The Indian material also has a slightly higher hydraulic conductivity when plotted against dry density. However, in this case, it is likely due to its grain density; see Section 6.3.10, being higher than in the other materials due to higher iron content.

In summary, the dry density TDR for buffer regarding hydraulic conductivity can be fulfilled for all materials except for the Milos material with its lower montmorillonite content. With respect to backfill, its dry density TDR regarding hydraulic conductivity can be fulfilled for all materials.

6.3.8 Exchangeable cations, EC

EC data is presented in Svensson et al. (2019).

There is no requirement on the EC, but the analysis is used to differentiate interlayer Na, Ca, Mg and K in the elemental analysis from any non-exchangeable structural counter parts.

The data shows that the Turkish, Indian and BARA-KADE materials are sodium dominated. The Bulgarian material is calcium dominated, and the Sardinian material is magnesium dominated. The Milos material is mixed of mainly calcium and magnesium while the Moroccan material is mixed of sodium, magnesium and calcium.

6.3.9 Mineralogical composition, XRD

XRD data is presented in Svensson et al. (2019).

XRD is used to characterise the mineralogical composition of the bentonites, and to measure and monitor the smectite content. The determined overall mineralogy is compared to the elemental analysis, and the smectite content is compared to the CEC.

The material guidance for buffer is currently set to montmorillonite content > 70 and ± 3 % and the > 70 % was fulfilled for all materials except the lower montmorillonite content Milos material which has 44 %.

6.3.10 Grain density

Grain density data is presented in Svensson et al. (2019).

The grain density is another supporting parameter which is used for a number of calculations, for example to calculate porosity and saturation.

The Indian material stands out with a higher grain density at 2931 kg/m^3 due to high iron content. The Milos and Turkish materials are on the lower side, with a grain density around 2605 kg/m^3 while the others average around 2770 kg/m^3.

6.3.11 Compaction properties

Compaction data is presented in Svensson et al. (2019).

The compaction properties are important as input for the adapted design of the buffer and backfill components.

The Bulgarian and Milos material stands out with a lower dry density at similar compaction loads and water contents compared to the other materials. For the Bulgarian material this correlates with its high swelling pressure at lower dry densities. The reason for this is at this stage unknown. For Milos it is more unexpected, but could possibly be partly due to its lower grain density, see Section 6.3.10. The Indian material has higher dry densities at similar compaction loads, again, matching its high grain density, see Section 6.3.10.

In relation to potential adapted designs for buffer, the required dry densities, and hence compaction pressures are quite low for all of the materials except for the Moroccan and Milos materials. There is a lower limit for the compaction pressure at which the blocks will become too fragile for handling. At this stage, this limit is unknown for full scale blocks and there is no TDR connected to tensile strength. However, with compaction pressures as low as 30 MPa for several of the materials, the failure point is closer than for earlier compaction tests of MX-80 (Johannesson 2014).

The method for determining the compaction properties includes measurement of the minimum bulk density and the Indian and Turkish materials which were purchased as fine powders both had low bulk densities. These powders are requested by other customers and are thus readily available. However, for SKB's application they proved problematic. For the Turkish material, the bulk density was so low that the currently available mould and press could not be used due to height limitations. The Indian material could fit in the mould and was tested in full scale production. However, the powder did not allow for a proper vacuum to be reached prior to the compaction and air was trapped inside the block, which lead to fractures in the block. This is by no means a drawback either for the Turkish or Indian bentonite; it is merely an outcome of the used granular size and currently available mould and press.

Strictly staying within the lower and upper granular size distribution in Figure 6-1 for development and demonstration work would limit the number of interesting materials too much, but too course and too fine materials should be avoided.

In summary, all materials can be used from a compaction point of view. However, the low bulk density of the Turkish material would not work with the current mould and press. The material would have to be ordered with a larger grain size distribution than powder resulting in a higher initial bulk density before compaction, to work as buffer material.

6.3.12 Unconfined compression strength

Unconfined compression strength data is presented in Svensson et al. (2019).

The TDR is the maximum dry density yielding an unconfined compressive strength at failure <4 MPa. The test is made with saturated samples at a deformation rate of 0.8 %/min.

All materials have similar strengths except the Bulgarian which shows a higher strength at corresponding dry densities. Buffer made of all the tested materials can fulfil the TDR, also the Bulgarian, due to it yielding a high enough swelling pressure at lower dry density compared to the other materials, which also means that the strength is below the maximum 4 MPa.

6.3.13 Thermal conductivity

Thermal conductivity data is presented in Svensson et al. (2019). All of the materials show results in the same range, between 1.19–1.34 W/mK at saturated conditions.

Modelling of a dry deposition hole was made in Luterkort et al. (2017), with a saturated thermal conductivity of 1.35 W/mK. The temperature drop over the buffer, when the canister reaches its peak temperature, was in this case approximately 16 °C. If the material with lowest thermal conductivity in this study (1.19 W/mK) was used instead, the maximum temperature of the canister would increase with approximately 2.2 °C. In summary, all materials are expected to fulfil the TDR.

6.4 Preliminary design, buffer

6.4.1 Potential materials and adaptive design approach

The next step in the material evaluation process is preliminary design of components.

Table 6-4 summarises the status of the materials after the initial characterisation with respect to their possibilities to fulfil the TDRs. Buffer made out of six of seven materials has the potential to fulfil the TDRs. The only material which did not fulfil the TDRs was Milos; however, it was bought as a lower montmorillonite content material.

With respect to the process steering parameters none of the materials fulfil the granular size specification entirely (Figure 6-1), although BARA-KADE and Sardinia is very close. For compaction in full scale the Turkish material (powder) had too low initial bulk density for fitting in the current mould and press. The Indian bentonite was also in powder form, with low initial bulk density, but possible to fit in the mould and press.

It is clear that a buffer with margins to all TDRs should be possible to design for six out of seven materials, see Section 6.3 about the characterisation. It will be the adaptive designs governing TDR (Chapter 3), i.e. the dry density yielding a swelling pressure > 3 MPa and < 10 MPa, which will be determinant for the adaptive design work.

The adaptive design will thus be guided by the relationship between dry density and swelling pressure data for each material (Svensson et al. 2019). The TDR stipulates that the dry density should yield a swelling pressure between 3–10 MPa which will correspond to a lower and upper dry density limit unique for each material. Given that the main processes that could affect the buffer once placed in a deposition hole, such as erosion, alteration or upward swelling (buffer expanding into the backfill) will lead to lower dry densities and lower swelling pressures a reasonable approach would be to adapt the design to target close to 10 MPa for the swelling pressure curve with deionised water. The reason that the swelling pressure curve with deionised water is used is that it provides the upper limit for swelling pressures in the repository as water with higher salt content will lead to lower swelling pressures. The $CaCl_2$ (1 M) swelling pressure curve is however used to calculate possible lows in swelling pressure.

Once it has been concluded that the relationship between dry density and swelling pressure will guide the adaptive design work, it becomes a matter of placing the right amount of mass in the deposition hole (with the installed canister) to achieve a dry density which yields an average swelling pressure of close to 10 MPa (for deionised water).

The buffer mass is made up of three different components; the bottom and top block (with slightly different machining), the ring-shaped blocks and the pellets (see Figure 3-2). A calculation can be made based on the nominal size of the canister, deposition hole and buffer components together with suggested dry densities for the buffer components. However, the tolerances of the components as well as the swelling pressure measurements will affect the accuracy in the adapted design. There are different approaches to address this question. In this case the tolerances were varied in a simulation of 10 000 deposition holes, see Section 6.4.2.

As mentioned, the accuracy of the swelling pressure curves will also affect the results. How this should be taken into account was not addressed in the recent evaluation.

Table 6-4. Summarised status of the materials after the initial characterisation, Y = Yes, acceptable, N = Not acceptable, C = Close to limit/not ideal.

	Technical design requirements					Process steering parameter (with current equipment)			SKB Guidance
Material	**C_{org}, S_{tot}, $S_{sulfide}$**	**Dry density yielding acceptable swelling pressures**	**Dry density yielding acceptable hydraulic conductivity**	**Dry density yielding acceptable shear strength**	**Dry density yielding acceptable thermal conductivity**	**Granular size**	**Water content**	**Compaction properties**	**Montmorillonite**
Milos*	C	Y	N	Y	Y	C	Y	Y	N
Morocco	Y	Y	Y	Y	Y	C	Y	Y	Y
Bulgaria	Y	Y	Y	Y	Y	C	Y	Y	Y
Turkey	Y	Y	Y	Y	Y	C	Y	N**	Y
India	Y	Y	Y	Y	Y	C	Y	C	Y
Sardinia	Y	Y	Y	Y	Y	Y	Y	Y	Y
BARA-KADE	Y	Y	Y	Y	Y	Y	Y	Y	Y

* Purchased as a lower montmorillonite content material, other Milos materials can be adapted to fulfil all TDRs.
** The Turkish material has to low bulk density for the current mould, with another granular size it should work fine (current delivery was fine powder).

6.4.2 Adaptive buffer design

The swelling pressure data was used to calculate exponential curves, which in turn was used to calculate the dry densities corresponding to 3 MPa ($CaCl_2$ 1 M) and 10 MPa (deionized water). Figure 6-2 illustrates an example for the Moroccan material which has a possible adaptive design window between 1 441 and 1 550 kg/m^3.

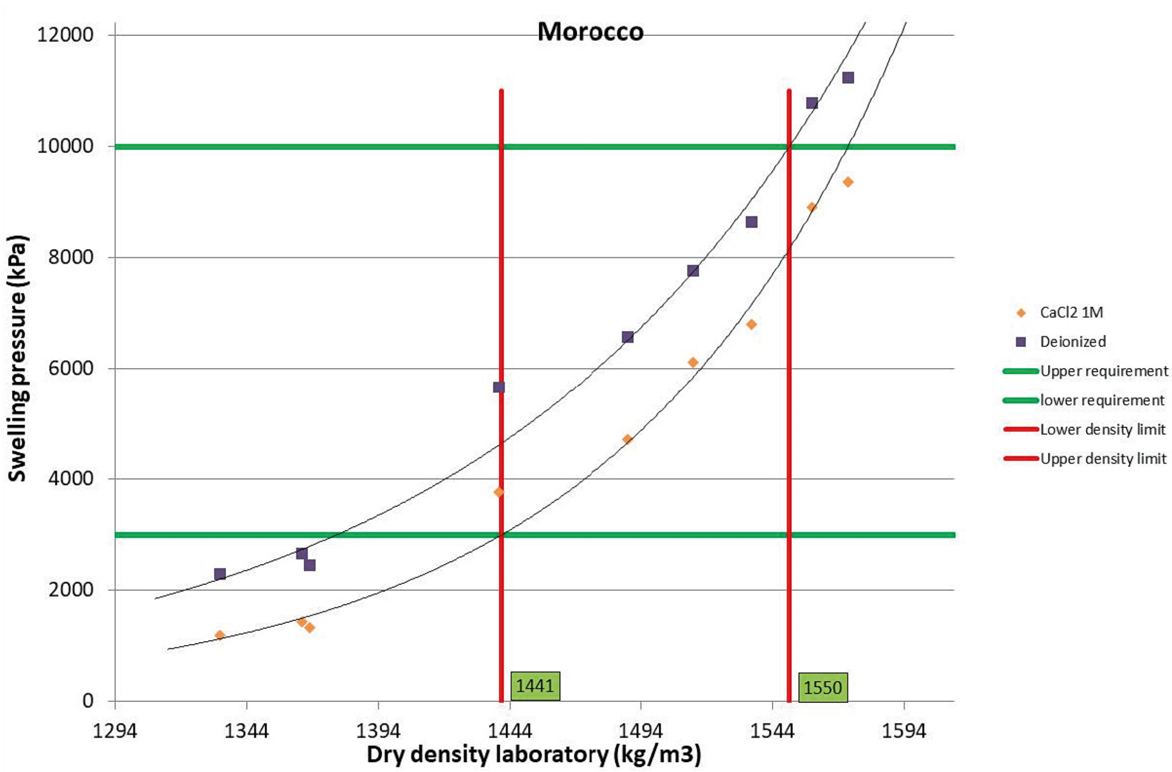

Figure 6-2. *Swelling pressure vs dry density for the Moroccan material, with deionized water and $CaCl_2$ (1 M).*

Start values were set to the block dry densities (this is what is being adapted), and then the analysis was carried out by varying the tolerances of the solid blocks, rings and the deposition hole. Table 6-5 presents the components which were varied in the analysis. Mainly triangular distributions were used with a few parts of the system simplified as constants.

10 000 deposition holes were simulated using the input in Table 6-5, which generated standard deviations for the average installed dry density (kg/m^3). Confidence intervals, 95 %, were then used to provide an upper and lower average dry density of which the upper was assessed with the deionised water swelling pressure curve, and the lower was assessed with the $CaCl_2$ (1 M) swelling pressure curve. This gives the maximum and minimum buffer swelling pressures for the selected block and ring dry densities.

Table 6-5. Components in the analysis.

Component	Nominal	Tolerance	Type of distribution
10 separate x Rings height	477 mm	± 1 mm	Triangular
10 separate x Rings outer diameter	1 650 mm	± 1 mm	Triangular
10 separate x Rings inner diameter	1 070 mm	± 1 mm	Triangular
10 separate x Rings dry density	Variable	± 20 kg/m^3	Triangular
Bottom block height	540 mm	± 1 mm	Triangular
Bottom block diameter	1 650 mm	± 1 mm	Triangular
Bottom block dry density	Variable	± 20 kg/m^3	Triangular
Bottom block, milled away for flange	0.029 m^3	constant	Simplified as constant
Top block height	540 mm	± 1 mm	Triangular
Top block diameter	1 650 mm	± 1 mm	Triangular
Top block dry density	Variable	± 20 kg/m^3	Triangular
Top block, milled away for flange	0.131 m^3	constant	Simplified as constant
Pellets dry density*	1 000 kg/m^3	± 20 kg/m^3	Triangular
Deposition hole diameter	1 750 mm	± 5 mm	Triangular
Deposition hole depth	5 770 mm	Based on Σ 10 rings + end blocks heights above	
Canister volume	4.097 m^3	constant	Simplified as constant

* There is no dry density data available for pellets for the materials studied. The 1 000 kg/m^3 value is based on MX-80 experience.

By optimising block and ring starting dry densities towards the value corresponding to 10 MPa (via the swelling pressure curve), a suitable adapted design can be suggested. For the Moroccan material, a dry density of 1 695 kg/m^3 for rings and 1 650 kg/m^3 for blocks gives the swelling pressures presented in Table 6-6.

The geometries of the system entails that the saturated density will vary in different parts of the deposition hole. The rings and blocks are therefore adapted to different dry densities which partly even out these variations. This is preferable, but not necessary and for some materials the rings and blocks are adapted to the same dry density in order to avoid too low compaction pressures for the blocks.

Table 6-6. Calculated, average dry densities with corresponding maximum and minimum swelling pressures for rings of 1 695 kg/m^3 and blocks of 1 650 kg/m^3 dry densities.

Material	Installed dry density average (kg/m^3)	Stdev	Installed dry density min (kg/m^3)	Installed dry density max (kg/m^3)	Swelling pressure min, 1 M CaCl2 (kPa)	Swelling pressure max, Deionised (kPa)
Morocco	1 544	3.0	1 538	1 550	7 320	10 000

Once the component dry densities are defined, the compaction curve, Figure 6-3, can be used to calculate the pressures needed for compacting the blocks. A proven water content level, which gives good blocks is selected, 17 % in this case. For the Moroccan material, the compaction curve gives a compaction pressure of approximately 40 MPa for 1 695 kg/m³ (rings) and 30 MPa for 1 650 kg/m³ (blocks).

Similar calculations was made for all of the potential materials and Table 6-7 lists suggested adapted designs for each material, a water content of 0.17 is suggested in all cases.

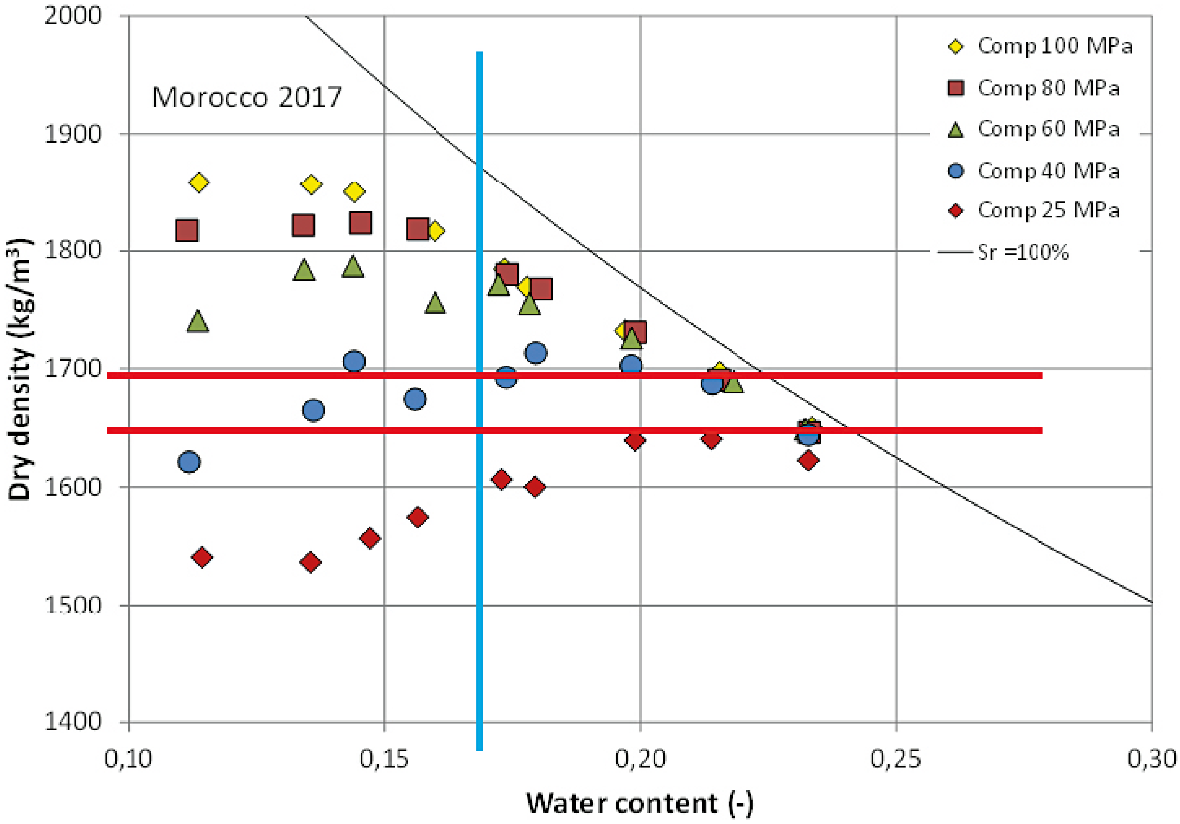

Figure 6-3. *Determined dry density as function of both water content and compaction pressure for the Moroccan bentonite. Water content 0.17 and dry densities 1 695 kg/m³ (rings) and 1 650 kg/m³ (blocks) are marked with lines.*

Table 6-7. Calculated, average dry densities with corresponding maximum and minimum swelling pressures for adapted ring and block dry densities.

Material	Rings dry density (kg/m^3)	Blocks dry density (kg/m^3)	Installed dry density average (kg/m^3)	Stdav	Installed dry density min*** (kg/m^3)	Installed dry density max*** (kg/m^3)	Swelling pressure min, 1 M $CaCl_2$ (kPa)	Swelling pressure max, Deionised (kPa)	Rings, compaction pressure (MPa)	Blocks, compaction pressure (MPa)
Morocco	1 695	1 650	1 544	3.0	1 538	1 550	7 320	10 000	40	30
Bulgaria	1 530	1 530	1 418	2.8	1 413	1 424	7 980	9 940	30	30
Turkey**	1 730	1 675	1 571	3.0	1 565	1 577	7 200	9 950	60	40
India	1 669	1 669	1 533	3.0	1 527	1 539	8 420	9 970	30	30
Sardinia	1 634	1 630	1 503	2.9	1 497	1 509	6 510	9 980	25*	25*
BARA-KADE	1 730	1 700	1 576	3.1	1 570	1 582	7 100	10 000	53	30

* 25 MPa is below what has been tested in full scale, but likely possible based on lab scale.
** The Turkish material studied had a too low bulk density for the current mould, but it is included anyhow, as it is only a question about the granular size purchased.
*** Calculated with 95 % confidence interval.

6.5 Purchase of larger representative samples

As can be seen from Table 6-4 and 6-7, six out of the seven materials studied were possible to adapt as buffer, with the seventh bought as a lower montmorillonite content material (mainly for its potential as backfill).

The Turkish material had a too low bulk density for the current mould and press, see Section 6.3.11, while the Moroccan material had too long delivery time for this study. Sardinia was definitely an option but not included this time.

SKB's previously most investigated material, MX-80, is currently not available in Europe and BARA-KADE which is another Wyoming bentonite is therefore of extra interest and was by that selected.

The Bulgarian material is of interest due to its very high swelling pressures at relatively low dry densities (compared to the other materials studied) and was included for this reason.

The Indian material was selected as a third material even though the granular size (powder) was not ideal.

6.6 Confirming characterisation

The next step in the material evaluation process is to confirm that the larger purchase, 10–25 tons, is similar to the previous one. This is done by running characterisation level 1 analyses (see Table 5-1). If the material deviates in a way that would affect the design, additional analyses from characterisation level 2 are added.

In a future repository scenario it is expected that SKB will have lists of possible suppliers and materials in which case characterisation work aiming at an industrial purchase could start at this step and would include all characterisation levels.

Data from the confirming characterisation is presented in Svensson et al. (2019). For improved readability it was also included already in the method specific discussions in Sections 6.3.1 to 6.3.13 and only the most important variations are discussed below.

Starting with BARA-KADE, the larger delivery was very similar to the previous one, and the quick swelling curves cannot be distinguished between deliveries. This is also valid for the other characterisation level 1 analyses, Table 5-1.

For the Bulgarian material there were two smaller purchases made (20 kg and 200 kg, see Table 6-3), which hade somewhat different swelling pressure curves, see Section 6.3.6. The larger 20 ton delivery matched up very well with the 200 kg delivery with respect to quick swelling pressure. With respect to CEC the 20 ton delivery showed 79.4 cmol(+)/kg while the 200 kg delivery had 76.2 cmol(+)/kg which isn't a perfect match but within the measurement uncertainty for the method. The 20 kg delivery stood out also with respect to CEC with 73.1 cmol(+)/kg. Combustion analyses ($S_{Tot,}$ $S_{Sulfide}$, C_{org}) showed some scattering but similar results for all three deliveries. XRF measurements showed some smaller differences between deliveries (see Svensson et al. 2019 for detailed discussions). With respect to adaptive design the 20 ton delivery matched up relatively well with the 200 kg delivery, but less so with the 20 kg delivery. A complementing XRD measurement (characterisation level 2) was done on the 20 ton delivery providing a montmorillonite content of 82.6 wt% which compares to the 79.2 wt% of the 200 kg delivery while the 20 kg delivery had the somewhat lower 73.8 wt%. Further analyses and discussions on the variations in the Bulgarian material are provided in Svensson et al. (2019).

The Indian material was only purchased as a large, 20 ton, delivery.

6.7 Full scale test production and quality control

The next step in the material evaluation process is full scale test production. Detailed information of the full scale test production is reported in Johannesson et al. (2020). For context, parts from the report are reproduced in the sections below.

6.7.1 Limitations with the current equipment

At this stage of development, there are some practical production limitations that have to be taken into account, Table 6-8.

Table 6-8. Manufacturing limitations for the currently used equipment (Johannesson et al. 2020).

Characteristic	Current limit	Comment
Compaction pressure	25–100 MPa	Lower limit, integrity of the blocks Upper limit, press capacity
Bulk density	The density when filling the mould must not be less than half of the final block density	Limited height in the available buffer mould
Water content (wc)	< selected design wc	Limited drying capabilities

There are very few presses available that has both the height and load capacity required to compact the full scale buffer components.

There is both a lower (25 MPa) and an upper manufacturing limit (100 MPa) for the compaction pressure. The lower limit is based on the integrity of the blocks, i.e. at too low compaction pressures the blocks will be difficult to handle without the risk of breaking, 25 MPa is an estimate. The upper limit is based on what is possible to achieve with the press currently used.

In the current mould, the initial bulk density of a material, i.e. in the mould prior the compaction has to be above half the density of the compacted blocks. A material with to low bulk density can thus not be compacted with the used mould and press.

The limitation of the water content is due to the currently limited capacity to dry materials. SKB currently has the capability to increase the water content of bentonite at Äspö using a large Eirich mixer. However, drying a material is more problematic and would require activities which have not been tested by SKB. In a future industrial facility, the materials will be possible to dry.

6.7.2 Compaction of blocks

Up to now, all of the manufactured large scale blocks have been compacted with the bentonite MX-80. As a part this study, blocks with three bentonites, denoted India 2018, Bulgaria 2017 and BARA-KADE 2017, were manufactured. Both ring shaped and solid blocks were compacted of the three bentonites, see Figure 3-2. For component design see Section 6.4.

The compaction of the bentonite was made with a press which, after upgrading, has a maximum capacity of about 10 000 tons, see Figure 6-4. It is situated at a workshop owned by the company KELVION AB in the city of Ystad. In total 18 blocks, nine ring-shaped and nine solid blocks were planned to be manufactured. The expected outcomes from the pressing are listed in Table 6-9.

The current technique for producing buffer blocks, i.e. uniaxial compaction of large blocks in a rigid mould, requires that the press is used for removing the block from the mould by lifting the block with the mould from the bottom plate and use the piston to press out the block. The conical shape of the mould is essential to facilitate this since only a small axial displacement is required in order to detach the block from it. Furthermore a lubricant is used on the surfaces of the mould to reduce the friction between the bentonite and the mould at compaction.

Figure 6-4. The mould placed in the press (Johannesson et al. 2020). For block manufacturing the press is limited to 10 000 tons.

Table 6-9. The planned compaction pressure and load at compaction with the conical shaped mould together with the expected dimensions, mass and bulk density of the compacted blocks (Ring and Solid blocks) (Johannesson et al. 2020).

Type	No	Material	Water content (%)	Compaction Pressure (MPa)	Expected outcome from the pressing Height (mm)	D1 (mm)	D2 (mm)	D3 (mm)	Bulk density (kg/m^3)
Solid	3	BARA-KADE 2017	17	30	500	1776	1800	0	1989
Ring	3	BARA-KADE 2017	17	53	500	1776	1800	1055	2024
Solid	3	India 2018	17	30	500	1776	1800	0	1953
Ring	3	India 2018	17	30	500	1776	1800	1055	1953
Solid	3	Bulgaria 2017	19	30	500	1776	1800	0	1828
Ring	3	Bulgaria 2017	19	30	500	1776	1800	1055	1828

6.7.3 Quality of the compacted blocks

The investigation of the compacted blocks included the following:

- Measuring of the dimensions and weight of the compacted blocks just after the compaction. These data were used for determining the average density of the blocks.
- Visual inspection of the compacted blocks and notation of cracks and any other damages on the blocks after compaction. Photos were also taken of the blocks.

After the compaction the blocks were stored for about two months. Previous investigations indicate that during storage there will be some swelling of the blocks (Eriksson 2014). Selected blocks were examined after the storage period. This investigation included:

- Measurement of the dimensions and weight of the blocks and calculations of the average density of them.
- Sampling and measurement of density and water content on the samples. This part of the investigation is not reported here, see Johannesson et al. (2020).

BARA-KADE 2017

Immediately after the compaction, the dimensions of the compacted blocks, the outer diameter at the top of the block (D_{out1}) and at the bottom (D_{out2}), the inner diameter (D_{inner}) and the height (H) were measured. Furthermore the total mass (m) of the blocks was measured. With the known dimensions and weight of the blocks it was possible to calculate the bulk density of the blocks. In Table 6-10 the results from the investigations of the blocks are summarised.

No large damages were observed at the examination of the blocks after compaction. Furthermore, Table 6-10 shows that there are very small variations in the average density between the solid blocks (C1A–C3A). This is also valid for the ring shaped blocks. When comparing the expected densities, which are listed in Table 6-9 with the measured densities, it is obvious that the measured densities are higher, about 40–70 kg/m^3 higher. One explanation for this might be that the expected densities are based on compaction tests made in the laboratory with a small cylindrical mould, while the large scale compacted blocks are compacted with a conical mould.

After the storage period two blocks, C3A and R3A, were examined. The measurements of the average densities are summarised in the lower rows of Table 6-10. When comparing this data with the corresponding data collected directly after compaction, it is obvious that the dimensions of blocks C3A and R3A have increased during storage, about 2 mm in height and about 1–2 mm in outer diameter, resulting in a decrease in density.

Table 6-10. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the six compacted blocks (BARA-KADE 2017) (Johannesson et al. 2020).

Block No.	σ_c	D_{out1}	D_{out2}	D_{inner}	H	m	w	ρ_{bulk}	ρ_{dry}
	(MPa)	(mm)	(mm)	(mm)	(mm)	(kg)	(-)	(kg/m^3)	(kg/m^3)
KBP1015_C1A	30	1780.4	1795.2	-	500.9	2538	0.169	2028	1735
KBP1015_C2A	30	1780.2	1795.7	-	500.8	2536	0.168	2027	1736
KBP1015_C3A	30	1779.5	1795.0	-	502.6	2546	0.170	2029	1734
KBP1015_R1A	53	1778.3	1794.9	1055.0	508.6	1725	0.170	2096	1791
KBP1015_R2A	53	1778.1	1795.7	1056.0	510.2	1731	0.168	2098	1796
KBP1015_R3A	53	1778.4	1794.7	1055.0	509.7	1731	0.170	2099	1794
Measurements on the blocks made about two months after compaction									
KBP1015_C3A	30	1780.5	1797.1	-	504.4	2544	0.169	2017	1725
KBP1015_R3A	53	1780.2	1795.5	1055.0	512.1	1723	0.169	2075	1775

India 2018

The bentonite India 2018 was purchased as a very fine powder. A first attempt to compact a solid block with the bentonite failed. After the block was pressed out from the mould, a crack about 10 cm from the top of the block was observed, see Figure 6-5. This crack was going through the entire block. The block was compacted in the same way as the rest of the compacted blocks including application of vacuum in the mould during the compaction. One possible explanation to the failure is that due to the fine powder, it was not possible to evacuate all the air from the bentonite during compaction. After the compaction the entrapped air expanded and caused the crack. It was decided to compact two more solid blocks where the bentonite was vibrated in the mould before compaction in order to increase the initial density of the powder. Furthermore, the arrangement to evacuate the air from the mould during the compaction was made more efficient.

The examination of these blocks indicates that there were some minor cracks on the blocks. However, the cracks did not cause any problems to handle the blocks with the vacuum yoke and the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.

Figure 6-5. *A block compacted with the bentonite India 2018 (Johannesson et al. 2020).*

The measurements of the average densities are summarised in Table 6-11. When comparing this data with the data collected directly after compaction it is obvious that the blocks dimensions (C3B) have increased, about 1 mm in height and about 1 mm in outer diameter during storage, resulting in a decrease in density. Furthermore, the average density of the compacted block is about 100 kg/m^3 higher than the expected, Table 6-9.

Table 6-11. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the two compacted blocks (India 2018) (Johannesson et al. 2020).

Block No.	σ_c	D_{out1}	D_{out2}	D_{inner}	H	m	w	ρ_{bulk}	ρ_{dry}
	(MPa)	(mm)	(mm)	(mm)	(mm)	(kg)	(-)	(kg/m^3)	(kg/m^3)
KBP1015_C2B	30	1779.7	1793.5	0.0	496.6	2546	0.175	2055	1749
KBP1015_C3B	30	1779.5	1793.1	0.0	494.9	2538	0.166	2056	1763
Measurements on the blocks made about two months after compaction									
KBP1015_C3B	30	1780.6	1796.25	0.0	496.0	2528	0.169	2039	1744

Bulgaria 2018

The bentonite Bulgaria 2017 was delivered as a rather coarse material, compared to the other investigated bentonites. Its initial water content was also high, above 0.19 and consequently, no adjustment of the water content was made prior to compaction.

With the known dimensions and weight of the blocks it was possible to calculate the bulk densities of the blocks which are summarised in Table 6-12. All the blocks of the bentonite Bulgaria 2017 were compacted with the same compaction pressure, 30 MPa. When comparing the two types of blocks it is obvious the ring shape blocks had a significantly lower density compared to the solid blocks, about 25 kg/m^3 lower. At the compaction of the ring shaped blocks there is friction between the bentonite and the mould both on the outside, as for the solid blocks, as well as on the inside and this is probably the reason for the lower average density on the ring shaped blocks although the compaction pressure is the same for both types of blocks.

The examination of these blocks indicates that there were some minor cracks on the ring shaped blocks. However, the cracks did not cause any problems to handle the blocks with the vacuum yoke and the judgement is that the cracks are neither affecting the function of the block nor the possibility to handle the blocks during storage and installation.

Table 6-12. The compaction pressure (σ_c), the dimensions (D_{out1}, D_{out2}, D_{inner}, H), the mass (m), water content (w) and the calculated densities of the compacted blocks (ρ_{bulk}, ρ_{dry}) listed for the six compacted blocks (Bulgaria 2017) (Johannesson et al. 2020).

Block No.	σ_c	D_{out1}	D_{out2}	D_{inner}	H	m	w	ρ_{bulk}	ρ_{dry}
	(MPa)	(mm)	(mm)	(mm)	(mm)	(kg)	(-)	(kg/m^3)	(kg/m^3)
KBP1015_C1C	30	1784.6	1798.9	-	496.1	2354	0.185	1891	1596
KBP1015_C2C	30	1784.3	1799.0	-	498.9	2380	0.189	1902	1599
KBP1015_C3C	30	1784.0	1799.5	-	497.8	2380	0.190	1906	1601
KBP1015_R1C	30	1782.4	1800.0	1058.0	508.3	1556	0.194	1883	1577
KBP1015_R2C	30	1783.1	1800.0	1052.5	512.1	1572	0.197	1876	1568
KBP1015_R3C	30	1783.0	1801.0	1057.0	514.7	1564	0.197	1864	1558
Measurements on the blocks made about two months after compaction									
KBP1015_C3C	30	1785.5	1798.0	-	499.4	2378	0.188	1898	1598
KBP1015_R3C	30	1785.5	1804.2	1059.0	517.1	1564	0.194	1850	1549

6.8 Design update based on full scale production

As described in Section 6.7, the same load on the same amount of material produces blocks with dry densities with relatively good repeatability, although the statistical data is limited. This is in line with earlier experiences with compaction of blocks of MX-80. It is also clear that the small scale laboratory compaction tests cannot provide exact figures for the required load in full scale, and it will be necessary to make a series of blocks in order to fine-tune the material mass and load to achieve the required dry density of the blocks. The expansion of the blocks, which continue for some days after compaction, should also be taken into account at the fine-tunings of the compaction process. However, when this is done, it should be possible to produce large series of blocks which can provide a buffer that is fulfilling the TDRs.

The fine-tuned masses and loads should be used for that specific material. If the work was done as a test-compaction for a new large scale delivery at Hargshamn/Forsmark the updated design would be used for that entire batch (ship-size) as long as the compacted blocks are fulfilling their requirements, i.e. weight and dimensions.

The required fine-tuning could not be carried out in the recent study as there was limited time available at the workshop in Ystad.

It is also likely that the compaction technique will be a developed which might affect how the compaction will be done but also the quality of the blocks. Example on this are:

- Minimise the use of lubricant on the mould.
- Adapt the construction of the mould and the press for production of buffer blocks.
- If possible compact blocks with cylindrical outer diameters.

6.9 Initial evaluation of long term performance, cost and production aspects

Adapted buffer designs which can fulfil the TDRs can be produced for six out of the seven materials, see Table 6-7. Three of the materials were compacted in full scale with two of them working essentially as planned. The dry densities of the preliminary design step were not fully met, but with a larger production series it is expected that blocks with the required densities can be manufactured with good repeatability. A more in-depth evaluation of long-term performance and costs, beyond what has been presented was not carried out in this study.

The results from the material evaluation process are compiled in a PM for each material.

It is expected that SKB will have several materials with an accepted adapted design available at the time for the first material selection for the repository.

7 Results backfill

Backfill design has not been in focus in this study. However, the material evaluation process, see Section 4.3, can be used in a similar way for backfill and the measurements which are suggested for buffer, see Table 5-1, are adequate for designing backfill.

The final methods for excavating the deposition tunnels has not been decided yet which means that the deposition tunnel and block area are not fixed at this stage of development, see Section 3.2. Figure 3-3 shows an example of a tunnel excavated mechanically. A mechanical excavation would produce deposition tunnels which are closer to the theoretical tunnel cross section area. However, this is not the case for a tunnel excavated by drill and blast where up to 30 % extra voids could be expected. With respect to adaptive design the voids outside the theoretical area, which will be filled with pellet, has to be taken into account.

Similarly to buffer, the relationship between dry density and swelling pressure would be used for the adapted design work at this stage. The Milos material, see Figure 7-1, is used as an example here. The $CaCl_2$ (1 M) curve describes the lowest possible swelling pressure and a dry density of 1 358 kg/m^3 of the backfill would yield a swelling pressure of 1 MPa. Corresponding value on the hydraulic conductivity is approximately 1E−11 m/s (Svensson et al. 2019) which is below the required < 1E−10 m/s. However, it should be noted that this material with low montmorillonite content has the largest scattering in the swelling pressure data in this study, which most likely is directly connected to heterogeneities within the material, even at lab scale. Much more measurements would thus be required to produce a more accurate swelling pressure curve.

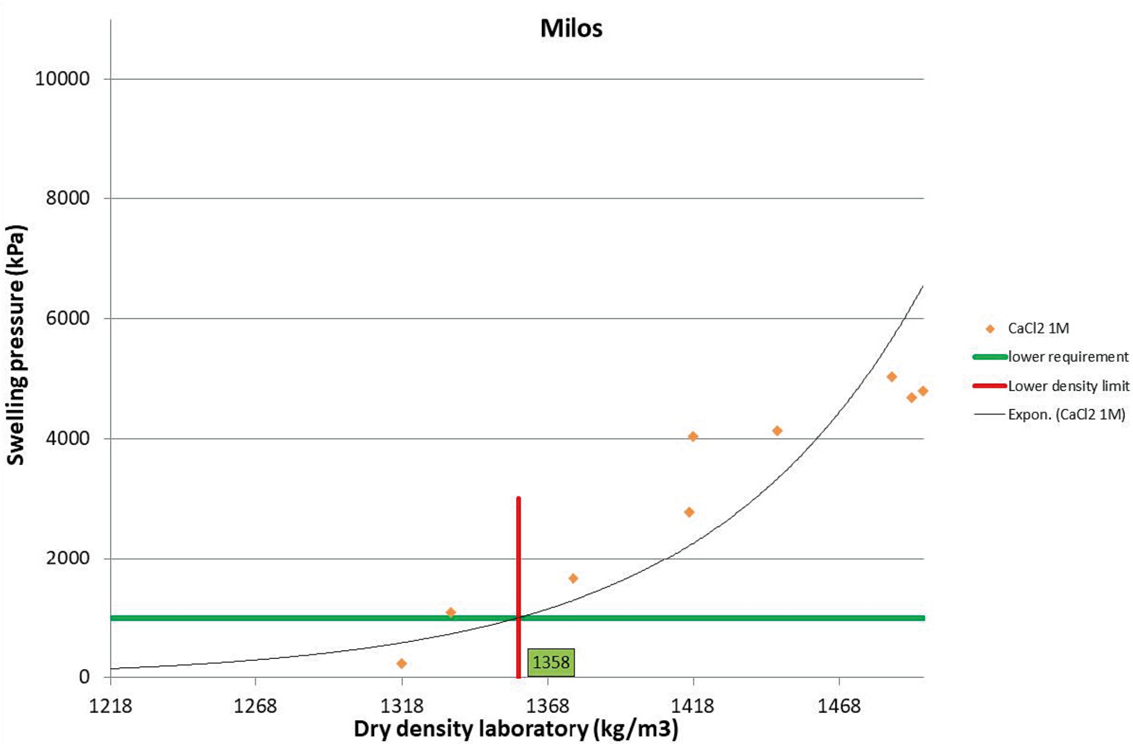

Figure 7-1. *Swelling pressure vs dry density for the Milos material using $CaCl_2$ (1 M).*

The next step in the design would be to calculate the dry density on the blocks and pellets of the backfill which would be required in order to achieve the 1 MPa. This is done by the equation below (note that possible voids in the stack of block are not included in this case). The installed dry density of the pellets is assumed to be 1 000 kg/m^3 which give a required block dry density of 1 422 kg/m^3. The pellets are assumed to fill the space between the blocks and the rock walls.

$$\rho_{Dep\ tunnel} = (\rho_{Pellets} * A_{Pellets} + \rho_{Block} * A_{Block})/A_{Dep\ tunnel}$$

The required dry density of the blocks is compared with the compaction curve for the material, Figure 7-2. If a water content of 17 % is used, which is favourable both at compaction and handling, a compaction pressure of 25 MPa would give a dry density of the blocks of approximately 1 530 kg/m^3 which is well above the required 1 422 kg/m^3. Blocks with a dry density of 1 530 kg/m^3 would correspond to a dry density of 1 449 kg/m^3 in the backfill corresponding to a swelling pressure around 3 MPa compared to the required 1 358 kg/m^3 and 1 MPa respectively.

The calculations above are done with a theoretical tunnel area. With the assumption of additionally 10 % voids (filled with pellets), which is quite a lot for a mechanically excavated deposition tunnel, the dry density of the backfill would decrease to approximately 1 408 kg/m^3. However, this would still be well above the required average dry density of 1 358 kg/m^3. At 30 % additional voids (also filled with pellets), possible in a drill and blast tunnel, the block dry density would have to be increased to approximately 1 550 kg/m^3 in order to fulfil the TDR, and actually even further to take into account some uncertainties.

The presses which are planned to be used at Forsmark can compact blocks at a maximum pressure of 50 MPa, assuming the dimensions of the backfill blocks shown in Figure 3-3. This means that there is a large margin in respect to the required dry density of the backfill, although as seen above, very large voids outside of the theoretical tunnel area (filled with pellets) will require a higher dry density of the blocks.

All the other materials studied, see Table 6-3, can also be designed as described above.

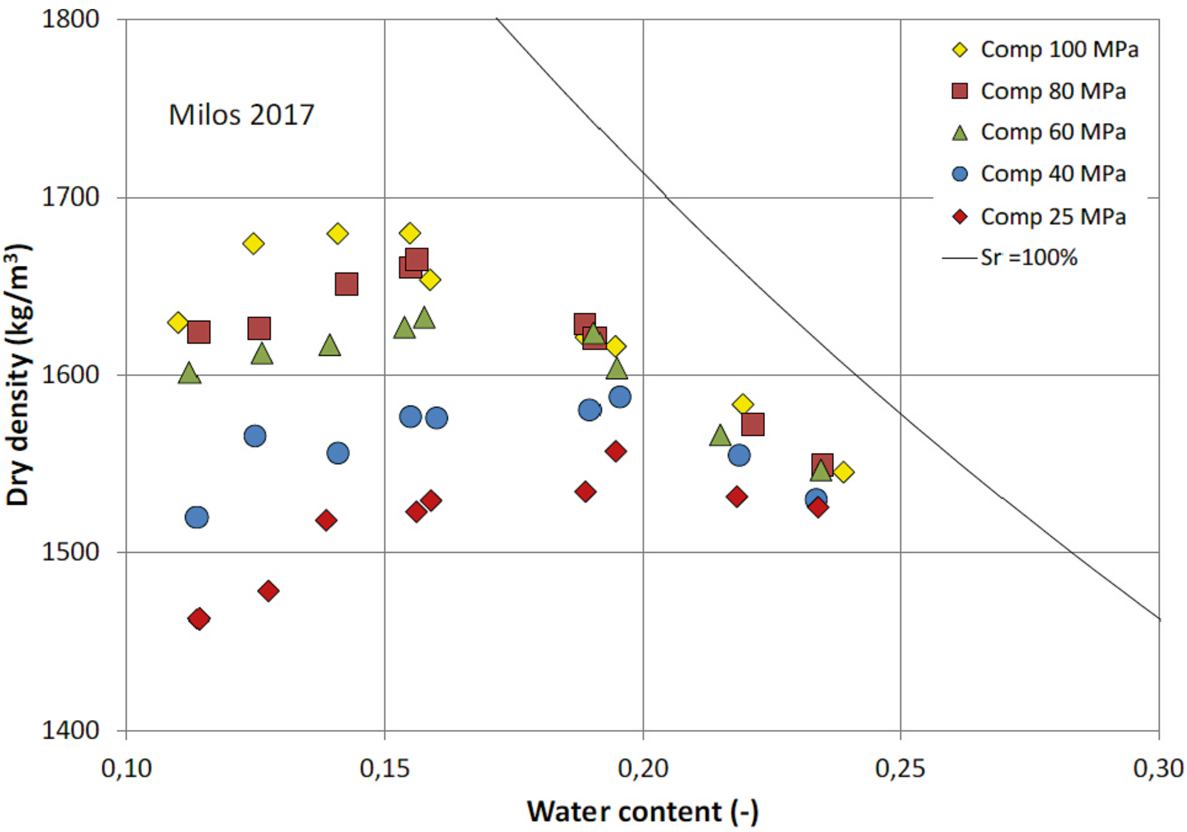

Figure 7-2. Determined dry density as function of both water content and compaction pressure for the Milos bentonite.

8 Conclusions and discussions

This report aims at presenting the current status of SKB's stepwise development of methodology and techniques for bentonite acquisition, quality control, component design and manufacturing.

Most of the analysis methods used by SKB to study bentonite are selected and developed over a longer period, see Table 5-1. However, the recent work includes a more detailed breakdown of when and where different methods should be used. Three characterisation levels are suggested in order to simplify this task. level 1 should provide basic acceptance data while level 2 should provide the basis to develop an adapted design and level 3 should confirm the component quality.

A suggestion for how the methodology can be implemented at the repository is presented. The process is divided into incoming, in-process and outgoing quality control and it utilises the suggested characterisation levels in different parts of the production process. This is the current stage of development and it will be continuously updated and optimised. Especially the amount of samples needed for proper statistics has to be further studied. In the future it might also be possible that some of the investigations described here could be adapted and executed by the suppliers.

The material evaluation process was further developed and tested, see Figure 4-3. It includes all the steps needed to evaluated the potential of a supplier and material, including the question whether the material can be adapted to fulfil the technical design requirements (TDRs) or not. It also provides vital information for the material selection.

Seven materials were evaluated and three of the materials passed the complete process, including manufacturing of buffer blocks in full scale. Although the production series are small, the results clearly indicate that there are several materials which might be suitable both as buffer and backfill. The results also show that the methods, see Table 5-1, selected by SKB in order to control the quality of a bentonite constitute a good basis for evaluating whether a buffer manufactured of the material fulfils the TDRs, and to establish a material specific adapted design.

SKB will continue to standardise the methodology and evaluate materials. This will enable expansion of the database of potential bentonite materials which have been sampled and analysed in a comparable way.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

Eriksson P, 2014. Basic engineering of buffer production system. SKB P-14-11, Svensk Kärnbränslehantering AB.

Eriksson P, 2017. Compaction properties of bentonite clay. SKB TR-16-16, Svensk Kärnbränslehantering AB.

ISO 10725:2000. Acceptance sampling plans and procedures for the inspection of bulk materials. Geneva: International Organization for Standardization.

ISO 11648-1:2003. Statistical aspects of sampling from bulk materials – Part 1: General principles. Geneva: International Organization for Standardization.

ISO 11648-2:2001. Statistical aspects of sampling from bulk materials – Part 2: Sampling of particulate materials. Geneva: International Organization for Standardization.

Johannesson L-E, 2014. KBS-3H. Manufacturing of buffer and filling components for the Multi Purpose Test. SKB P-14-07, Svensk Kärnbränslehantering AB.

Johannesson L-E, Hermansson F, Kronberg M, Bladström T, 2020. Manufacturing of large scale buffer blocks. Uniaxial compaction of block – test made with three different bentonites. SKB R-19-28, Svensk Kärnbränslehantering AB.

Karnland O, 2010. Chemical and mineralogical characterization of the bentonite buffer for the acceptance control procedure in a KBS-3 repository. SKB TR-10-60, Svensk Kärnbränslehantering AB.

Luterkort D, Johannesson L-E, Eriksson P, 2017. Buffer design and installation method. Installation report. SKB TR-17-06, Svensk Kärnbränslehantering AB.

Norden, 2008. Intern kvalitetskontroll: handbok för kemilaboratorier. Borås: SP Tekniska Forskninginstitut. (Nordtest rapport TR 569) (In Swedish.)

Posiva SKB, 2017. Safety functions, performance targets and technical design requirements for a KBS-3V repository. Conclusions and recommendations from a joint SKB and Posiva working group. Posiva SKB Report 01, Posiva Oy, Svensk Kärnbränslehantering AB.

SKB, 2010a. Design, construction and initial state of the underground openings. SKB TR-10-18, Svensk Kärnbränslehantering AB.

SKB, 2010b. Design, production and initial state of the backfill and plug in deposition tunnels. SKB TR-10-16, Svensk Kärnbränslehantering AB.

SKB, 2010c. Design, production and initial state of the buffer. SKB TR-10-15, Svensk Kärnbränslehantering AB.

Sandén T, Nilsson U, Andersson L, 2016. Investigation of parameters influencing bentonite block quality. Laboratory investigation. SKB P-16-06, Svensk Kärnbränslehantering AB.

SS-EN ISO/IEC 17025:2018. Allmänna kompetenskrav för provnings- och kalibreringslaboratorier (ISO/IEC 17025:2017). Stockholm: Swedish Institute for Standards. (In Swedish.)

Svensson D, Lundgren C, Johannesson L-E, Norrfors K, 2017. Developing strategies for acquisition and control of bentonite for a high level radioactive waste repository. SKB TR-16-14, Svensk Kärnbränslehantering AB.

Svensson D, Eriksson P, Johannesson L-E, Lundgren C, Bladström T, 2019. Development and testing of methods suitable for quality control of bentonite as KBS-3 buffer and backfill. SKB TR-19-25, Svensk Kärnbränslehantering AB.

Arkitektkopia AB, Bromma, 2020

SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

skb.se