Technical Report

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System design of backfill
Project results

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Summary

The license application for the Final Repository for Spent Nuclear Fuel is based on the KBS-3V method. In the KBS-3V method the spent nuclear fuel is encapsulated in copper canisters which are deposited in vertical deposition holes in crystalline rock. The canisters are surrounded by a buffer which protects them and limit the flow of water. The deposition tunnels are filled with backfill material after the deposition of canisters and buffer.

The reference concept for backfilling involves use of pre-compacted bentonite blocks to fill the majority of the tunnel volume. Bentonite pellets are used as bed material to even out the blasted tunnel floor and provide an even surface before placement of the backfill blocks. Pellets are also used to fill the gap between the deposition tunnel walls and the backfill blocks to protect the blocks from direct water flow.

The concept for installation and manufacturing of backfill in deposition tunnels has been further developed during the project "System design of the backfill". The main conclusions and results from this project are presented in this report. The development and testing of methods for manufacturing, installation and quality assurance of the backfill are also described.

Backfill material

As mentioned above bentonite is used to manufacture backfill blocks and pellets. Material studies were carried out on the different backfill material candidates; Ibeco RWC-BF from Greece and Asha NW BFL-L from India. Three batches of bentonite were delivered; 250 tons of Asha in 2010, 100 tons of Ibeco in 2011 and 600 tons of Asha in 2012. The batches are abbreviated Asha 2010, Asha 2012 and Ibeco 2011 in this report.

The materials were used for tests of block and pellet manufacturing as well as laboratory investigations. Water content determination, swelling index determination, CEC (cation exchange capacity) determination, hydro-mechanical tests, chemical and mineralogical analyses have been carried out.

The laboratory investigations showed that Ibeco 2011 was a homogenous bentonite with moderate smectite content. However the hydraulic conductivity was relatively high and the swelling pressure low compared to other bentonite deliveries of Ibeco RWC-BF.

Both of the batches of Asha had low hydraulic conductivity and high swelling pressure. The scatter between samples for swelling index, granule size distribution and water content was however high which indicated a rather inhomogeneous bentonite.

Backfill blocks

Backfill blocks were manufactured of bentonite from Asha 2010, Asha 2012, Ibeco 2011, Minelco and MX-80. Blocks with required density, geometry and strength could be produced of all the different bentonites after adjustment of the water content, except for Asha 2010. Asha 2010 contained a rather large amount of coarse material which resulted in blocks with undesirably low strength. Blocks with required strength were achieved after crushing the material.

Performed laboratory tests showed that water content, granule size distribution and material composition affect the strength of the blocks and the quality of the block surfaces. Investigations of how the blocks were affected by the relative humidity in the surrounding air were carried out both in laboratory scale and in full scale. The tests showed that the full-sized blocks are very sensitive to the surrounding atmosphere. The block exposed to 75% relative humidity was little affected since it was almost in equilibrium with the surrounding. Cracks were formed in the blocks exposed to both higher and lower relative humidity after rather short exposure to the surrounding air.

Blocks required for a full scale demonstration test, described in this report, were produced at Höganäs Bjuf with bentonite from the Asha-2012 delivery. The block press and the related manufacturing equipment worked as intended and no problems related to the equipment were observed. However larger stones were discovered in the bentonite causing production disturbances. In total 1,820 blocks were produced with an average dry density of 1,642±11 kg/m^3.

Backfill pellets

Different backfill pellet candidates (extruded, roller compacted and granules) were tested and evaluated in order to optimize the properties regarding water storing capacity and sensitivity to erosion. Extruded pellets with a diameter of 6 mm were assessed to have the best overall characteristics of the tested pellet types. This pellet type is suitable both as bed material and as gap filling in the deposition tunnel.

Bentonite pellets were produced at five different times as part of the project. Based on the manufacturing tests pellet extrusion is considered an applicable method for manufacturing of bentonite pellets.

Handling of water inflow during backfill installation

A main problem in the backfilling process is to handle water inflow into the deposition tunnels during backfill installation. The inflowing water may affect the stability of the backfill stack and cause erosion of the backfill. One function of the pellet filling is to buffer inflowing water and protect the blocks during installation. At high water inflows, the pellet filling is not sufficient and alternative methods for water handling are needed. Geotextiles can be used to distribute the inflowing water more evenly in the pellet filling. Different geotextiles and fastening methods were investigated during the project. Backfill pellets in combination with geotextiles were assessed to be applicable for inflow rates 0.5–1 L/min into one 6 meter tunnel section. This assumes that maximum two 6-meter sections in a 300 meter long deposition tunnel have inflow rates of this magnitude. The maximum water inflow to a 300 meter long deposition tunnel that can be handled by letting the inflowing water be stored in the pellet filling, and distributed by geotextiles, is 2.5–5 L/min.

Methods for handling higher water inflows were theoretically studied during the project.

Installation of backfill

The installation equipment and process as well as the geometric configuration of the backfill were further developed during the project. A robot was suggested to be used for installation of backfill blocks in order to provide a backfill stack with high quality in short time. An industrial robot was purchased and developed for installation of backfill, which included development of a gripper, a platform, a measurement system and a control system. The conceptual functionality of the robot was tested in a laboratory.

Large scale installation test

A large scale installation test was performed underground to demonstrate that the installation of backfill can be carried out as intended in a realistic environment. In total 12 meters of backfill was installed in the TASS tunnel, situated at a level of –450 meters, at Äspö HRL. The installation was performed with prototype equipment and temporary solutions that will not be used in the future repository. The installation of the blocks and pellets was carried out without any major problems. The block filling degree was 71% and the installed density about 1, 420 kg/m^3. In total, 89 hours was used for the installation.

Backfill production system

Further development of the backfill production process, from bentonite delivery to finished backfill blocks and pellets, has been done based on experiences gained during test productions and a supplier analysis. Equipment with sufficient capacity for production of backfill components is suggested in this report.

Quality assurance and control

The main purpose of quality assurance and control is to verify that the backfill meets the requirements and hence function as intended in the final repository. Product- and process mapping was carried out as a basis for further development of a quality assurance system for the backfill. In the product mapping the key parameters needed to verify that the requirements are met were identified. In the process mapping activities, quality assurance measures and decisions that affect the quality of the backfill were identified.

Conclusions

The two major functions of the backfill are to limit the flow of water (advective transport) in the deposition tunnels and to restrict upward buffer swelling/expansion. New geometries for backfill blocks and pellets and an updated backfill configuration are suggested based on the project investigations and results. Based on the backfill material tests and pellet tests it is shown that the suggested backfill configuration fulfils the requirement of limiting the flow of water. The ability to restrict upward buffer swelling was initially investigated in this project, but further investigations are needed to be able to evaluate if the backfill fulfils the requirement.

The process for manufacturing of backfill components has been further detailed. Standard equipment for production of blocks and pellets are available on the market and has been tested during the project. A conclusion from the manufacturing test is that the tested equipment fulfils the requirements regarding quality and capacity and hence no development of special equipment is necessary.

Regarding the installation of backfill, prototype equipment for installation of backfill blocks have been developed. Based on laboratory tests and on the large scale installation test, the installation concept is assessed to be suitable for installation of backfill. Further development is however needed to achieve an automatic process that fulfils the requirements on installation time.

Sammanfattning

Ansökan om Slutförvar för använt kärnbränsle som SKB har lämnat in till Strålsäkerhetsmyndigheten baseras på KBS-3V-metoden. KBS-3V-metoden innebär att det använda kärnbränslet placeras i kopparkapslar som deponeras i vertikala deponeringshål i urberget. Kopparkapslarna omsluts av en buffert med uppgift att skydda kapslarna och minska vattenflödet i deponeringshålen. Själva deponeringstunnlarna återfylls med bentonitlera.

SKB har tidigare tagit fram ett referenskoncept för återfyllning av deponeringstunnlarna som innebär att dessa fylls med förkompakterade benonitblock. För att blockstapeln ska stå stadigt sprids en bädd av bentonitpelletar ut på tunnelgolvet innan blocken installeras. Hålrummet mellan blockstapeln och bergväggen fylls med pelletar för att skydda blocken från direkt vattenflöde.

Konceptet för installation av återfyllning har vidareutvecklats i projektet ”Systemkonstruktion av återfyllning”, resultat och slutsatser från projektet presenteras i denna rapport. Utvecklingen av produktionsmetoder, installationsmetoder och kvalitetssäkring för återfyllningen beskrivs också.

Återfyllningsmaterial

Som tidigare nämnts används bentonit för tillverkning av återfyllningsblock och pelletar. Tre sändningar av potentiella återfyllningsmaterial levererades under projektet; 250 ton Asha NW BFL-L år 2010, 100 ton Ibeco RWC-BF år 2011 samt 600 ton Asha NW BFL-L år 2012. Dessa leveranser benämns Asha 2010, Ibeco 2011 samt Asha 2012 i rapporten.

Bentonitmaterialen har använts för tester av block- och pellettillverkning, dessutom har omfattande materialundersökningar genomförts i laboratorium. Testerna omfattade bland annat bestämning av vatteninnehåll, svällindex, CEC samt hydromekaniska, kemiska och mineralogiska undersökningar.

Materialundersökningarna visade att Ibeco 2011 var en homogen bentonit med en medelhög andel svällande mineral. Svälltrycket var relativt lågt och den hydrauliska konduktiviteten relativt hög vid jämförelse med tidigare bentonitleveranser av Ibeco RWC-BF. Båda sändningarna av Asha-material hade låg hydraulisk konduktivitet och högt svälltryck. Spridning i resultat från bestämningarna av svällindex, granulstorleksfördelning och vatteninnehåll var höga för de båda Asha-sändningarna vilket indikerar att benoniten är inhomogen.

Återfyllningsblock

Återfyllningsblock tillverkades av följande material; Asha 2010, Asha 2012, Ibeco 2011, Minelco och MX-80. Efter justering av det initiala vatteninnehållet tillverkades block som uppfyllde kraven på densitet, geometri och hållfasthet av samtliga material utom Asha 2010. Asha 2010 innehöll en stor andel grovkornigt material vilket ledde till att blocken fick låg hållfasthet. För att åtgärda detta krossades materialet och därefter kunde block som uppfyllde kraven tillverkas.

Laboratorietester visade att blockens hållfasthet och ytjämnhet påverkas av vatteninnehållet, granulstorleksfördelningen och materialsammansättningen.

Undersökningar av hur blocken påverkas av omgivande luftfuktighet genomfördes, både i laboratorieskala och med fullstora återfyllningsblock. Vid ca 75 % relativ fuktighet befann sig återfyllningsblock med 20 % vattenkvot i jämvikt med omgivningen, och påverkades därför inte nämnvärt. Vid såväl högre som lägre luftfuktighet uppstod det snabbt sprickor i blocken.

Inför det fullskaliga demonstrationsförsöket som genomfördes i projektet producerades återfyllningsblock med bentonit från Asha 2012-leveransen på Höganäs Bjuf. Blockpressen och relaterad produktionsutrustning fungerade bra, däremot upptäcktes stora stenar i bentonitmaterialet som orsakade produktionsstörningar. Totalt producerades 1 820 block med en genomsnittlig densitet av 1 642±11 kg/m^3.

Återfyllningspelletar

Olika pellettyper (extruderade, rullkompakterade och granulater) undersöktes och utvärderades för att hitta den pellettyp som uppvisare bäst förmåga att lagra vatten och lägst känslighet för erosion. Av de undersökta pellettyperna bedömdes extruderade pelletar med en diameter av 6 mm ha bäst egenskaper avseende vattenlagringsförmåga och erosion. Denna pellettyp är lämplig för såväl pelletbädd som fyllning mellan blockstapel och bergvägg.

Bentonitpelletar tillverkades i projektet vid fem olika tillfällen. Baserat på produktionstesterna bedöms extrudering vara en lämplig metod för produktion av återfyllningspelletar.

Hantering av vatteninflöde under installation av återfyllning

Vattenflöde i deponeringstunnlarna är en av de större utmaningarna vid installation av återfyllning. Inflödande vatten kan påverka stabiliteten hos blockstapeln och orsaka erosion av återfyllningsmaterial. Återfyllningspelletarna har till uppgift att buffra det inflödande vattnet och skydda blocken under installationen. Vid höga vatteninflöden klarar inte pelletfyllningen att buffra allt inflödande vattnen, metoder för vattenhantering vid högre inflöden har därför undersökts i projektet. En metod som undersökts är användande av geotextiler som fördelar vattnet mer jämnt i pelletfyllningen och på så sätt ökar pelletfyllningens kapacitet att buffra vatten. Återfyllningspelletar i kombination med geotextiler bedöms kunna hantera vatteninflöden av 0,5–1 L/min i ett 6 meter långt tunnelavsnitt. Detta förutsätter att enbart en eller två 6-meterssektioner i en 300 meter lång deponeringstunnel har så höga inflödeshastigheter. Det maximala vatteninflödet i en 300 meter lång deponeringstunnel som kan hanteras med hjälp av pelletfyllning och geotextiler är 2,5–5 L/min.

Metoder för att hantera större vatteninflöden har studerats teoretiskt i projektet.

Installation av återfyllning

Såväl installationsprocessen som installationsutrustningen har utvecklats i projektet. För att snabbt kunna installera återfyllningsblock med en hög blockfyllnadsgrad, precision och säkerhet föreslogs att en industrirobot används för installationen. En industrirobot köptes in och utvecklades för att kunna installera återfyllning, vilket inkluderade utveckling av greppverktyg, robotplattform, mätsystem och styrsystem. Hela robotsystemet provkördes sedan både i laboratorium och i underjordsmiljö.

Fullskaligt installationsförsök

Ett fullskaligt installationsförsök under jord genomfördes för att demonstrera att installation av återfyllning kan genomföras i en miljö som överensstämmer med den som förväntas i Kärnbränsleförvaret. Totalt installerades 12 meter återfyllning i TASS tunneln, Äspölaboratoriet, på nivån –450 meter. Installationen genomfördes med prototyputrustning och tillfälliga lösningar som inte kommer att användas i det framtida Kärnbränsleförvaret. Installationen av block och pelletar genomfördes utan några större problem. Blockfyllnadsgraden var 71 % och den installerade densiteten ca 1 420 kg/m^3. Installationen tog totalt 89 timmar.

Produktionssystem

Fortsatt utveckling av produktionsprocessen för återfyllning har gjorts baserat på erfarenheter från produktionstester samt på en leverantörsanalys. I rapporten ges förslag på utrustning som är lämplig och har tillräcklig kapacitet för att tillverka återfyllningsblock och -pelletar.

Slutsatser

De två viktigaste funktionerna för återfyllningen är att begränsa vattenflödet i deponeringstunnlarna (advektiv transport) samt att motverka buffertuppsvällning. Baserat på utredningar och tester genomförda i projektet föreslås nya geometrier för återfyllningsblock och -pelletar samt en uppdaterad utformning av återfyllningen. Baserat på materialtester och pellettester verifieras i rapporten att den nya utformningen av återfyllning uppfyller kravet att begränsa advektiv transport. Förmågan att motverka buffertuppsvällning studerades inledningsvis i projektet, men fortsatta utredningar krävs för att kunna verifiera att kravet uppfylls.

Produktionsprocessen för återfyllningsblock och -pelletar har vidareutvecklats. Standardutrustning för såväl block- som pellettillverkning finns på marknaden och har testats i projektet. En slutsats från produktionstesterna är att utrustningen uppfyller krav avseende kvalitet och kapacitet, ingen specialutrustning behöver alltså utvecklas.

Gällande installation av återfyllning har prototyputrustning för installation av återfyllningsblock utvecklats och testats i projektet. Baserat på tester i laboratorium och det fullskaliga installationsförsöket bedöms installationskonceptet vara lämpligt för installation av återfyllning. För att få en automatisk process som uppfyller kraven på installationstid behövs dock fortsatt utveckling.

Contents

1 Introduction

The license application for the Final Repository for Spent Nuclear Fuel is based on the KBS-3V method developed by SKB (SKB 2010a). The spent nuclear fuel is encapsulated in copper canisters which are deposited in vertical deposition holes in crystalline rock at a depth of 400–700 meters. The canisters are surrounded by a buffer which protects them and limit the flow of water. The deposition tunnels are filled with backfill material after the deposition of canisters and buffer, see Figure 1-1.

The design and production of the tunnel backfill is described in SKB (2010b). The reference concept for backfilling involves use of pre-compacted bentonite blocks to fill the majority of the tunnel volume. Bentonite pellets are placed on the tunnel floor just before the placement of blocks. The function of the bentonite pellets is to provide an even surface before placement of the backfill blocks. Pellets are also used to fill the gap between the deposition tunnel walls and the backfill blocks to protect the blocks from direct water flow.

The reference concept for installation and manufacturing of backfill has been further developed in the project "System design of backfill". This project was initiated to ensure that the reference method for backfilling of deposition tunnels work as intended. Further development of methods for manufacturing and control of the backfill has been an important part of the project. This report summarizes the main conclusions and results from "System design of backfill".

The project "System design of backfill" was initiated to detail and verify the conceptual design and production of the backfill described in SKB (2010b). The objective of the project was to ensure that the reference method for backfilling of deposition tunnels works as intended. The overall goals were to:

- further develop the conceptual design of the backfill and the backfill production,
- develop a plan for industrialization including implementation of control systems to ensure that the quality requirements are met,
- verify the conformity of the backfill design to the design premises,
- demonstrate that the method is feasible, through a large scale test in realistic environment.

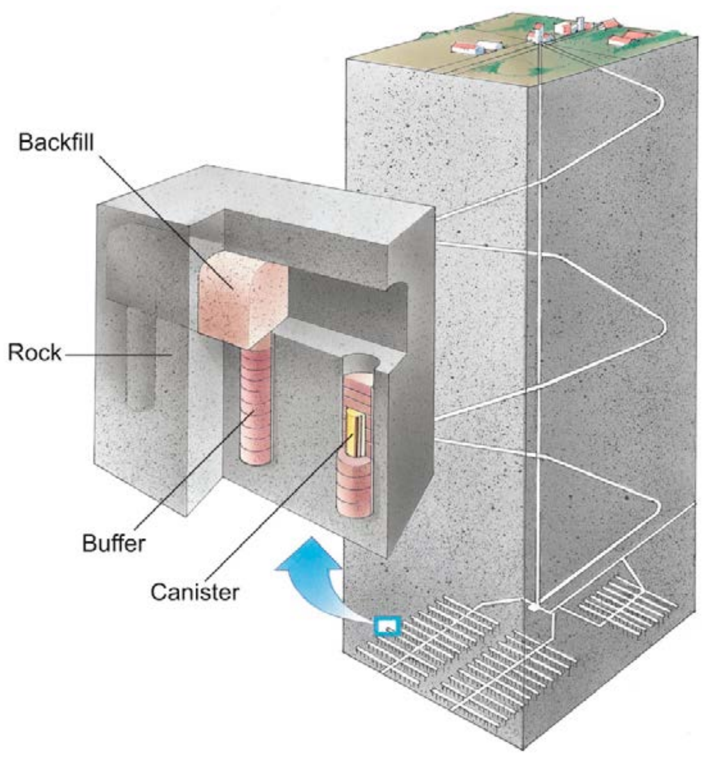

Figure 1-1. *KBS-3 with vertical deposition.*

1.1 Objectives

The objective of this report is to summarize the main conclusions and results from the project "System design of backfill" and to provide recommendations for further work.

1.2 Delimitations

The project was carried out with the following delimitations:

- The backfill consists of backfill blocks and pellets; alternative backfill methods were not studied.
- The development was carried out with respect to the conditions expected in Forsmark.
- Transportation of backfill blocks and pellets within the KBS-3V repository was not a part of the project.

The ability of the backfill to restrict upward buffer swelling was investigated through FEM-modelling. The results are presented in Börgesson and Hernelind (2013), the results from the investigations are however not discussed in this report since the buffer swelling is further investigated by another SKB project.

1.3 Reference design

The reference design for the backfill is summarized in this chapter, for a detailed description, see SKB (2010b).

The reference backfill material is a bentonite clay with a montmorillonite content of 50–60% and an accepted variation of 45–90%.

The reference design of the backfill blocks and pellets are based on bentonite clay from Ibeco and is presented in Table 1-1. Other materials than Ibeco may require different specifications.

The reference design of the installed backfill is presented in Figure 1-2 and Figure 1-3.

Block part of the blast round volume, including the upper part of the deposition hole should be ≥ 60%. The free space between the blocks and the tunnel wall should be ≥ 100 mm. The volume between the installed block and deposition tunnel walls is filled with pellets.

The thickness of the bottom bed should be 100 mm from nominal tunnel floor. The pellet bed is compacted with a density > 1,200 kg/m^3.

Table 1-1. Reference block, pellet and bottom bed material (based on Ibeco).

Design parameter	Nominal Design	Accepted variation
Bentonite blocks		
Dry density (kg/m^3)	1,700	±50
Water content (wt-%)	17	±2
Dimensions (mm)	700×667×510	±2×2×2
	700×600×250	±2×2×2
Blocks in deposition hole bevel		
Dry density (kg/m^3)	1,710	±17
Water content (wt-%)	17	±1
Dimensions (mm)	Height: 500	±1
	Diameter: 1,650	
Pellets and bottom bed pellet		
Dry density separate pellets (kg/m^3)	1,700	±50
Dimensions (mm)	~16×16×8	–
	1,000	±100
Water content (wt-%)	17	±2

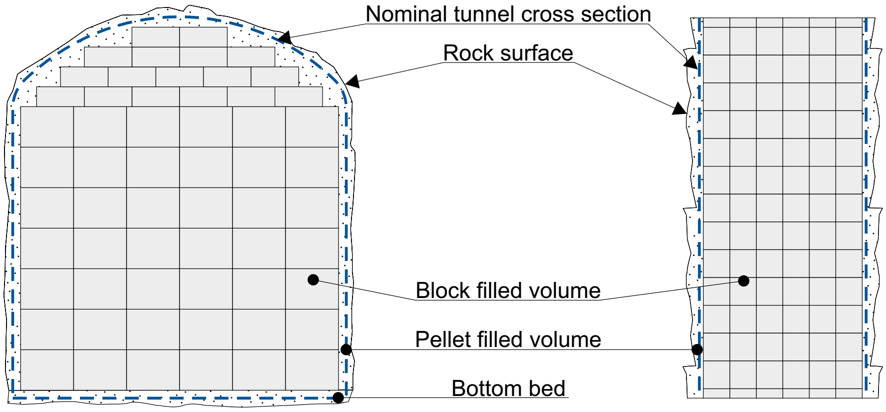

Figure 1-2. *Reference geometry of the installed backfill in a schematic tunnel.*

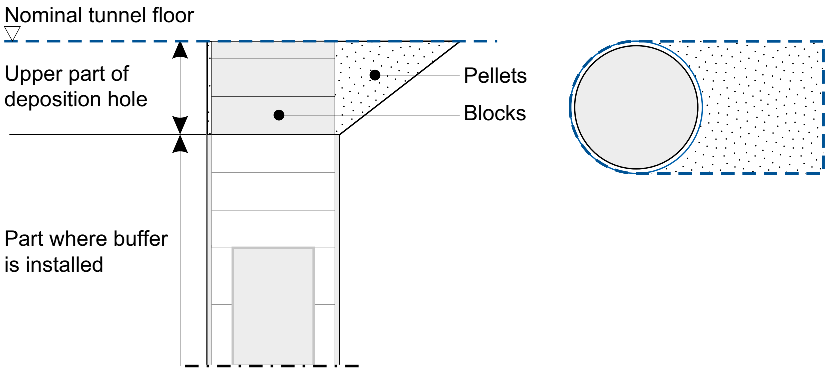

Figure 1-3. *Reference geometry of the backfill in the upper part of the deposition hole.*

1.4 Work strategy

At the beginning of the project the backfill installation concept described in SKB (2010b) was studied, and how the concept could be further developed was discussed. One conclusion was that the stacking geometry presented in Figure 1-2 could be improved. A uniform block size would simplify the manufacturing and the installation process and a block stack with overlapping joints would increase the stack stability as well as enable block stacking on a non-compacted pellet bed.

Different block sizes and stacking patterns were evaluated and a block size of 571×500×400 mm (L×W×H) was suggested in combination with the stacking geometry shown in Figure 1-4. In order to achieve a backfill according to the suggested geometry at high pace an industrial robot was assessed to be suitable for the installation. For a more detailed description of the suggested installation concept and stacking geometry, see Chapter 7.

With the initial investigations described above as basis it was decided that the work in the project "System design of backfill" should be based on:

- Bentonite pellets to even out the tunnel floor, and a non-compacted pellet bed should be considered.
- Bentonite blocks with geometry 571×500×400 mm and the stacking geometry shown in Figure 1-4 is used.
- Bentonite pellets to fill the space between the block stack and the tunnel walls.
- The installation of backfill blocks is performed by an industrial robot.

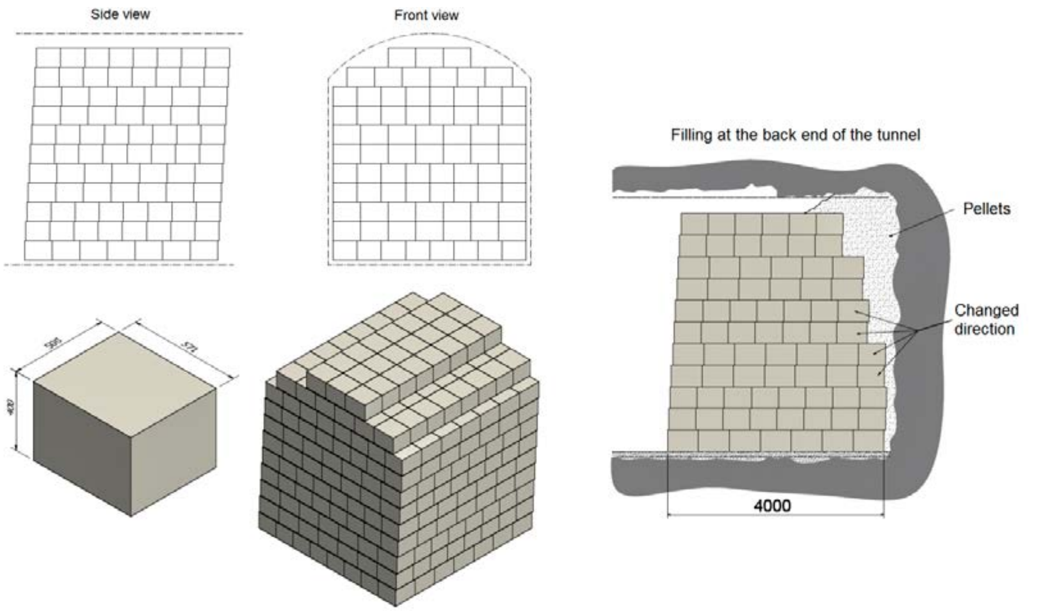

Figure 1-4. *Suggested geometry of the installed backfill in a schematic tunnel.*

1.5 Report overview

The main conclusions and results from "System design of backfill" is summarized in this report and structured as described below.

Chapter 1 The background and scope of the report and the project "System design of backfill" are given.

Chapter 2 The overall design premises and requirements on the backfill are presented.

Chapter 3 Bentonite material is used to manufacture backfill blocks and pellets. Material studies on different bentonite materials have been carried out to gain a greater understanding of the bentonite and to verify that the backfill meets the requirements. The results from the material studies are presented.

Chapter 4 Backfill pellets have been studied, with the objective to find the optimal pellet properties for backfilling, and a suitable manufacturing method. Pellet manufacturing tests in full scale have also been performed. The results from the pellet studies are presented.

Chapter 5 Block manufacturing tests in full scale have been performed to verify that backfill blocks of required properties can be manufactured in industrial scale. Laboratory investigations of the manufactured blocks have also been carried out in order to determine the homogeneity and presence of cracks. The results from the block manufacturing and laboratory investigations are presented in this chapter.

Chapter 6 A main problem in the backfilling process is how the water inflow into the tunnels should be handled during block emplacement. An important function of the pellet filling is to protect the backfill blocks from direct water flow. The water storing capacity of the pellet filling and the ability of geotextiles to distribute the inflowing water in the pellet filling has been investigated and is presented. In addition alternative methods for handling of large water inflows are discussed.

Chapter 7 The installation concept and the development of block installation equipment are described.

Chapter 8 A large scale installation test was carried out underground at Äspö HRL and is presented. The aim of the test was to demonstrate that installation of backfill can be carried out as intended in a realistic environment. The test was done with prototype installation equipment and the transportation system was not included.

Chapter 9 The process for manufacturing of backfill components has been further detailed and is presented. A suggestion on equipment needed for the manufacturing of backfill is given.

Chapter 10 Quality assurance and control of the backfill manufacturing and installation is discussed.

2 Design requirements for the backfill

The design premises for the backfill are presented in SKB (2010b) and the overall requirements are summarized in this chapter.

The purpose and function of the backfill in the deposition tunnels is to sustain the multi-barrier principle by keeping the buffer in place and restrict groundwater flow through the deposition tunnels. In order for the multi-barrier principle to be maintained in the KBS-3 repository the backfill shall:

- Limit the flow of water (advective transport) in deposition tunnels.
- Restrict upward buffer swelling/expansion.
- Not significantly impair the barrier functions of the other barriers.
- Be long-term durable and maintain its barrier functions in the environment expected in the final repository.

In order to be able to verify the design, the requirements on the installed backfill have been specified as follows:

- The hydraulic conductivity should be less than 10^{-10} m/s.
- The swelling pressure should be higher than 0.1 MPa.
- The backfill should have a compressibility that ensures a minimum saturated density of 1,950 kg/m^3 of the buffer.
- The backfill should not contain substances that may cause harmful buffer degradation or canister corrosion.
- The barrier functions of the backfill shall be maintained over the long term.

The following design considerations shall be regarded in the design of the backfill and in the development of methods to manufacture, install and inspect the backfill:

- The design and the methods for preparation, installation, test and inspection shall be based on well-tried or tested technique.
- Backfill with specified properties shall be possible to prepare and install with high reliability.
- The properties of the backfill shall be possible to test and inspect against specified acceptance criteria.
- The design of the backfill and the methods for preparation, installation, test and inspection shall be cost-effective.
- The backfill installation shall be possible to perform at the prescribed rate.

3 Investigation of backfill material

Bentonite material is used to manufacture backfill blocks and backfill pellets. The reference backfill material is a bentonite with medium montmorillonite content (SKB 2010b).

Studies on different backfill material candidates were carried out with the following purposes:

- to gain more knowledge of the variation between different backfill candidate materials and deliveries,
- to obtain increased reliability in the verification of requirements,
- to provide a base for the definition of requirements for the manufacturing of backfill blocks and pellets.

Results and conclusions from performed material studies are summarized in this chapter. The material study in full is presented in *Investigation of backfill candidate materials* (Sandén et al. 2014b).

3.1 Material requirements

The overall requirements presented in Chapter 2 are further detailed in SKB (2010b). The detailed requirements on the bentonite material are summarized below:

- The montmorillonite content should be between 50 and 60%. Accepted range is 45 to 90%.
- The amount of the potentially harmful substances sulphide, sulphur and organic carbon should be determined. No threshold values have been set regarding the content of these substances.

One of the aims of the material investigations was to verify that the requirements, presented in Chapter 2 and above, are fulfilled. Another aim was to verify that the manufactured backfill blocks have a sufficiently high strength, so that they can be handled during the installation phase. The storage stability of the blocks was also investigated.

3.2 Tested materials

Different bentonite clays with medium montmorillonite content have been tested in earlier SKB studies (SKB 2010b). Of the tested bentonites Asha, Ibeco and MX-80 bentonites were shown to have the ability to fulfil the material requirements and were therefore assessed to be good backfill candidate materials. Considering the material cost, high grade bentonite from MX-80 has a higher price than medium grade bentonite from Asha and Ibeco. Laboratory investigations where therefore performed on three different batched of the candidate materials Ibeco RWC-BF and Asha NW BFL-L, which are listed below. Photos of material samples are shown in Figure 3-1. These bentonites were also used for production of backfill blocks and pellets, see Chapter 4 and 5.

1. **Ibeco RWC-BF 2011** (abbreviated Ibeco 2011 in the text) is a material that originates from Milos in Greece. It is a natural calcium bentonite with medium montmorillonite content. 100 tons were delivered (81 big bags) in 2011.
2. **Asha NW BFL-L 2010** (abbreviated Asha 2010 in the text) is produced by Ashapura Minechem Co. The bentonite is sodium dominated with a montmorillonite content of about 70%. 250 tons were delivered (200 big bags) in 2010.
3. **Asha NW BFL-L 2012** (abbreviated Asha 2012 in the text). Sodium dominated bentonite with a montmorillonite content of about 70%. Granule size < 3 mm. 600 tons were delivered (480 big bags) in 2012.

The three batches of bentonite were ordered according to the following specification:

Figure 3-1. *Photo showing the different bentonite materials tested.*

Asha 2010 and Ibeco 2011:

- Granule size distribution between 0–5 mm.
- Maximum 20% particle size < 0.063 mm.
- Water content 16±1.5%.
- Montmorillonite content > 55%.

Asha 2012:

- Granule size distribution: All granules smaller than 3 mm.
- Water content 16±1.5%.
- Montmorillonite content > 55%.

The specification on granule size distribution was changed for Asha 2012 since problems occurred with production of backfill blocks using the Asha 2010 material, see Chapter 5. Granule size distribution and water content are important parameters for the manufacturing process, and their optimal value might vary for different materials, there are therefore no strict requirements on these parameters.

3.3 Acceptance test

The aim of the acceptance testing in the final repository is to be able to perform a rather fast evaluation of the delivered material; if it is suitable as backfill material or not. Which tests that will be included in the acceptance testing in the final repository are yet not defined. In this section, results from a number of tests that was performed on the Asha and Ibeco deliveries and could be used for acceptance testing are presented.

The acceptance testing included control of water content, swelling index and CEC (cation exchange capacity). The testing of Asha 2012 also included determinations of liquid limit and granule size distribution.

Swelling index, CEC and liquid limit were measured in order to give an estimation of the amount of swelling mineral in the bentonite. Water content and granule size distribution were determined to provide input to the manufacturing process of backfill blocks and pellets.

The acceptance tests showed that the Ibeco 2011 batch was a homogeneous bentonite, which fulfilled the specification regarding water content and granule size distribution. The swelling index, liquid limit and CEC indicated that the amount of swelling minerals in this bentonite was moderate.

The average water content was according to the specification for both Asha 2010 and Asha 2012. However, the variation within the batches was high which implies a heterogeneous material. The swelling index, liquid limit and CEC indicated that the amount of swelling minerals in both Asha batches was high, but the variation between the samples was rather large.

The granule size deviated significantly from the specification, having 20% of granules or aggregates with a size larger than 5 mm for both batches. For Asha 2012 a visual inspection indicated that the material had been crushed between two rollers with a gap set at 3 mm. This procedure had disintegrated, or reshaped, the large granules but at the same time new, platy granules had formed with a thickness of 3 mm. These results highlight the need to carefully define the granularity of the bentonite purchased and to ensure that these specifications are met.

3.4 Hydro-mechanical tests

The requirements prescribe that the swelling pressure in the installed backfill should be at least 0.1 MPa and the hydraulic conductivity should be less than 10^{-10} m/s. The aim of the hydro-mechanical tests was to investigate how well the different bentonites fulfil the required swelling pressure and hydraulic conductivity if the bentonite is installed according to the reference design. The average backfill density is 1,460 kg/m^3 when the backfill is installed according to the reference design. Modelling of the homogenization process in a backfilled tunnel has shown that the dry density of the bentonite closest to the rock wall can be as low as 1,370 kg/m^3 (Åkesson et al. 2010). The achieved swelling pressure and hydraulic conductivity and the modelled density were used as a basis for the assessment of the three bentonite batches.

It should be noted that the bentonite may be relevant as backfill material even if the requirements on hydraulic conductivity and swelling pressure are not fulfilled at 1,370 kg/m^3. The backfill design can be changed so that the requirements are met, the backfill blocks could be produced with at higher density for example.

The swelling pressure and hydraulic conductivity were investigated at water salinities of 1% TDS and 3.5% TDS. In most cases the 3.5% TDS resulted in a lower swelling pressure and higher hydraulic conductivity than 1% TDS. The results are presented in Figure 3-2 and Figure 3-3. The least favourable cases are presented in the text below.

The swelling pressure for Ibeco 2011 at a density of 1,370 kg/m^3 was four times as high as the requirements, i.e. about 0.4 MPa. This is, however, five to ten times lower than the swelling pressure determined in earlier investigations of Ibeco bentonite delivered in 2004 and 2008 (Johannesson et al. 2010, Johannesson and Nilsson 2006). The scatter in measured hydraulic conductivity for dry densities below 1,370 kg/m^3 was very high. The evaluated hydraulic conductivity varied from 2×10^{-11} to 1×10^{-7}. The large variation might depend on piping in some of the specimens. Disregarding the scatter in the measured hydraulic conductivity, there are still large differences between the different batches, regarding both swelling pressure and hydraulic conductivity. The batch from 2011 was of lower quality than the batches from 2004 and 2008, as indicated in the acceptance control.

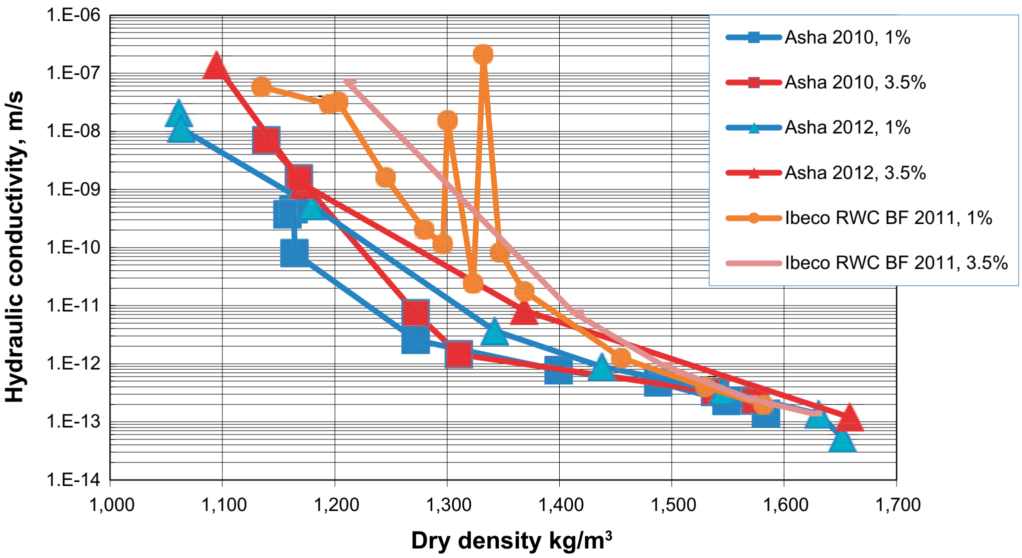

Figure 3-2. *Hydraulic conductivity plotted versus dry density for Asha 2010, Asha 2012 and Ibeco 2011.*

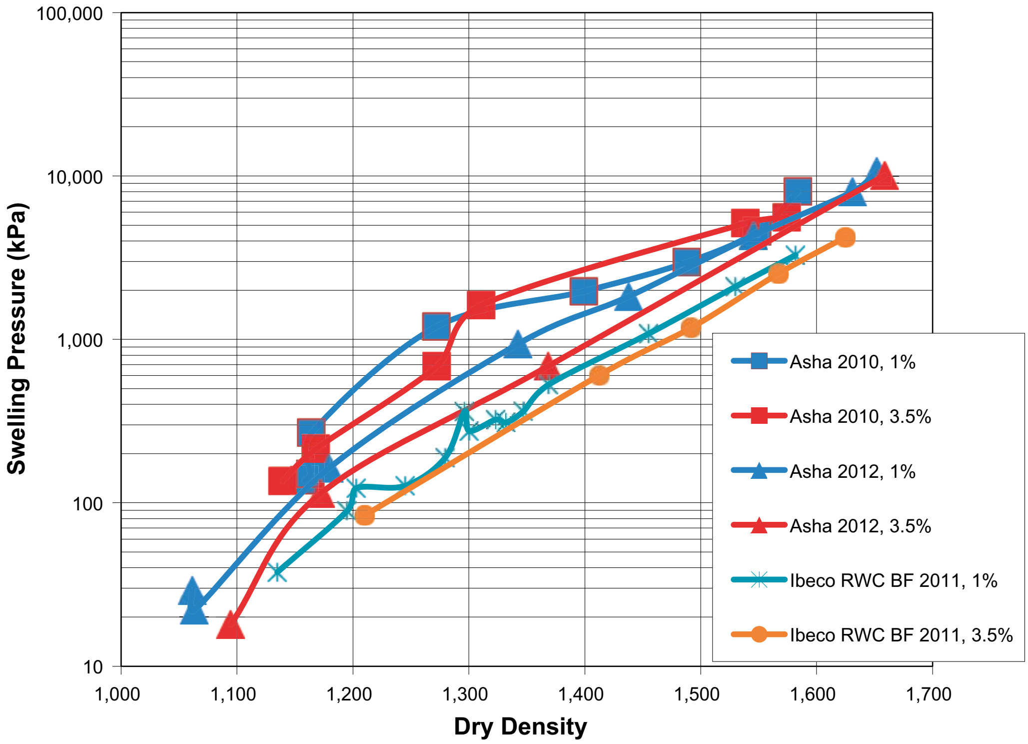

Figure 3-3. *Swelling pressure plotted versus dry density for Asha 2010, Asha 2012 and Ibeco 2011.*

The swelling pressure for Asha 2010 at a density of 1,370 kg/m^3 was about twenty times higher than the requirement and the hydraulic conductivity two orders of magnitude lower than the required 10^{-10} m/s. The swelling pressure for Asha 2012 at a density of 1,370 kg/m^3 was about seven times higher than the requirement and the hydraulic conductivity was about twelve times lower than the required 10^{-10} m/s.

It should, however, be remembered when assessing the quality of the three batches that the Asha bentonite is sodium dominated, whereas the Ibeco bentonite is calcium dominated, which should result in different swelling capacities for the bentonites.

Investigation of compression properties was only performed with Asha 2010. The compression properties are needed to be able to determine the ability of the backfill to restrict the buffer expansion. The compression properties are also important parameters for modelling of backfill homogenisation. The compression properties were determined in two oedometer tests, one saturated with water with a salinity of 1% TDS and the other with 3.5% TDS. The deformation of the samples was almost proportional to the vertical stress up to 3.2 MPa, which was the maximum stress applied in the tests. The evaluated compression modules were almost the same for both samples, 19 MPa and 18 MPa respectively, which means that the salinity of the pore water had little effect on the compressibility.

The strength of compacted bentonite blocks from the two Asha batches was investigated by unconfined one-dimensional compression tests and beam tests. The results showed a clear influence of the density on the maximum stress at failure and also of the water content of the samples. The results of the tests made on blocks of the as-delivered Asha 2010 batch showed rather low strength of the beams. After crushing of the material before block compaction, the strength doubled, which demonstrates the effects of granule size distribution on the strength. A conclusion is that blocks manufactured at full scale, using Asha with a suitable granule size distribution (according to Sandén et al. 2014b), water content of 20% and with a dry density of 1,700 to 1,750 kg/m^3, will have rather high strength.

3.5 Chemical analyses

The chemical analyses of the bentonites included determinations of total sulphur, total carbon and acid-soluble carbon. The latter carbon fraction emanates primarily from carbonates. The total sulphur content varied from a minimum of < 0.02% S in samples of Asha 2010 to a maximum of 0.19% S in samples of Asha 2012. All samples contained carbonates, but the highest acid-soluble carbon content, 3%, was found for the Ibeco bentonite. In the samples of Asha 2010 and Ibeco 2011, the difference in total and in acid soluble carbon contents was small. In the samples of Asha 2012, the total carbon content was systematically somewhat higher than the acid-soluble carbon content, indicating that small amounts of organic carbon might exist. No threshold values have been set regarding the content of these substances.

The major oxide composition, evaluated as oxide ratios, displayed a significant scatter among the Asha samples, demonstrating the heterogeneity of this bentonite. In contrast, the same ratios for the Ibeco samples were relatively constant.

The exchangeable cation pool of the samples from both Asha 2010 and Asha 2012 was sodium-dominated (~50%), and had calcium as the second most abundant cation. The Ibeco-bentonite, which contained more than 20% Ca/Mg carbonates, was calcium-dominated (45%), and the proportions of sodium and magnesium were almost equal.

3.6 Mineralogical analyses

The mineralogy was determined by XRD-analyses of randomly oriented powders and evaluated quantitatively with Siroquant software. Despite the heterogeneity of the Asha bentonite, the average mineralogy of the two batches was similar. The average smectite content in Asha 2010 was 74%, and in Asha 2012 76%. Like montmorillonite, the smectite in the Asha bentonite is dioctahedral, but XRD-examination of random powders is inadequate for distinguishing the members in the montmorillonite–beidellite series at species level.

All samples of Ibeco 2011 contained high amounts (~20%) of dolomite and calcite. No potassium-bearing phase was detected in the XRD-traces, and yet the potassium content of the bentonite was fairly high. Detailed investigations of Ibeco bentonite delivered in 2004 and 2008 indicated that the smectite in these batches was interstratified with illitic layers. Interstratified illite/smectite may consequently exist also in the bentonite batch from 2011, but the available data are inadequate for identification of mixed-layers. Therefore, the calculated average smectite content of Ibeco 2011 (64%) may include an unknown, but probably small, proportion of illite/smectite mixed-layers.

3.7 Conclusions an further recommendations

3.7.1 Ibeco

The acceptance control showed that Ibeco 2011 is a homogenous bentonite, which fulfils the supplier specification regarding water content and granule size distribution. The swelling index, liquid limit and CEC indicated that the amount of smectite was moderate but sufficiently high to match the requirements, 45–90 wt%. The smectite content was determined to be 64% in the quantitative evaluation of the mineralogy.

The hydraulic conductivity was unexpectedly high and the swelling pressure low for the Ibeco 2011. The material properties determined for Ibeco 2011 were compared with results for bentonites with the same commercial name delivered in 2004 and 2008 (Table 3-1). The swelling pressure and hydraulic conductivity of the latter were re-tested. The results indicated that the swelling pressure of Ibeco 2011 was about ten times lower than those of the other batches. The hydraulic conductivity at low densities (< 1,370 kg/m^3) suggested that the bentonite of the batch 2011 sealed poorly against the walls of the sample holder, which resulted in piping.

The chemical and mineralogical investigations of Ibeco 2011 showed that the content of potentially cementitious material, such as carbonates, was high, more than 20%, and this may affect the hydraulic behaviour. However, the batch from 2004 had equally high carbonate content (Table 3-1) but had not shown such behaviour in hydraulic conductivity tests performed at even lower densities. A certain variation can be seen in other material parameters of the different bentonite batches from Ibeco, but at present no firmly confirmed explanation of the unusual hydraulic behaviour of Ibeco 2011 can be given.

The quality assurance process must be designed so that quality deviations like Ibeco 2011 are discovered at the acceptance test. A rejection of a material delivery is undesired and could cause interruptions in the backfill production. SKB continues the work with further characterization of bentonite materials and development of more precise material specifications to avoid materials that do not conform to the requirements.

It should be noted that Ibeco 2011 may be relevant as backfill material even if the requirements on hydraulic conductivity and swelling pressure are not fulfilled at 1,370 kg/m^3. The backfill design can be changed so that the requirements are met, the backfill blocks could be produced with at higher density for example.

3.7.2 Asha

The acceptance control of both Asha 2010 and 2012 showed a rather large scatter in the results from the determination of water content, swelling index and granule size distribution. This indicates that the batches are heterogeneous.

The XRD analyses of 25 samples of Asha 2012 showed that, despite the heterogeneity of the bentonite, the variation in mineralogy between the samples was low. The average mineralogy of Asha 2010 and Asha 2012 was similar, and the smectite content in all laboratory samples conforms to the nominal range stipulated for the reference backfill material.

The granule size distribution deviated significantly from the specification for both Asha 2010 and Asha 2012. A consequence was that problems occurred in the manufacturing and handling of backfill blocks, since the granule size distribution affects the strength and physical stability of blocks. See Chapter 5 for results and discussion on the manufacturing of backfill blocks. To be able to process materials like Asha 2010 and Asha 2012 SKB needs equipment for crushing. The production process described in Chapter 9 contains crushing equipment, which means that fine grained material will not be required in the future production facility. However, the manufacturing problems that occurred highlight the need to carefully define the material specifications and to ensure that these specifications are met.

A parallel investigation of Asha 2010 (Olsson et al. 2013) demonstrated that the coarse aggregations found in the bentonite had higher smectite proportion than the fine-grained matrix of the bentonite and the mineralogy differed with respect to abundance and type of accessory minerals. Hence, there is a risk of yielding samples of poor representativeness if granules are segregated by size during handling and/or sampling of the bentonite. In order to reduce such errors a sampling plan designed for heterogeneous materials should be applied.

The swelling properties of the Asha materials are good and the overall characteristics for Asha 2010 and Asha 2012 were similar. However a higher homogeneity within the deliveries and a better compliance with the specification is needed. The co-operation with the material supplier needs to be enhanced, so that the supplier understands SKB's needs and requirements on the bentonite.

Table 3-1. Compilation of material parameters determined for different batches from Ibeco and Asha. n.d. = not detected. Data is compiled from Johannesson and Nilsson (2006), Johannesson (2008), Johannesson et al. (2010), Olsson and Karnland (2009) and Sandén et al. (2014b).

Material	Liquid limit %	Free swelling ml	Smectite %	Illite-Smectite (not detectable) %	Carbonate %	CEC meq/100g	Exchangeable cations Ca %	 K %	 Mg %	 Na %
Ibeco RWC-BF, 2004	150	5	64	5–10	24	73	41	2.7	48	9
Ibeco RWC-BF, 2008	122	4.4	73	< 3 %	< 1%	71	44	2.2	24	31
Ibeco RWC-BF, 2011	116	4	64	Inclusive possible I-S	22	65	45	1.9	25	29
Asha 230, 2004	180	8.4	78	n.d.	n.d.	97	31	0.4	13	56
Asha 230, 2008	473	13.5	80	n.d.	n.d.	89	9	0.5	11	80
Asha NW BFL-L, 2010	198	5.1	74	n.d.	4	87	28	0.7	17	48
Asha NW BFL-L, 2012	160	7.3	76	n.d.	2.6	85	31	0.5	13	47

3.7.3 Assessment of requirements and specifications

In Section 3.1 it is stated that the montmorillonite content should be between 50 and 60% with an accepted range of 45 to 90%. This requirement was fulfilled for all the bentonites delivered. However, the hydro-mechanical tests indicate that determining the montmorillonite content (at a specific density) is not enough to predict the hydro-mechanical behaviour of the bentonite. The requirement on montmorillonite content needs to be complemented by a set of material parameters better describing the characteristics of the bentonite, SKB is currently working on this.

The amount of potentially harmful substances; sulphide, sulphur and organic carbon was low for all the bentonites. The total sulphur content varied from a minimum of < 0.02% S in samples of Asha 2010 to a maximum of 0.19% S in samples of Asha 2012. All samples contained carbonates, but the highest acid-soluble carbon content, 3%, was found for the Ibeco bentonite. No threshold values have yet been defined.

Based on the experience of bentonite deliveries from Asha it can be concluded that the granule size distribution and other properties important to the block compaction, need to be more carefully specified, to enable production of blocks with high strength and physical stability. It is important to provide the bentonite supplier with a correct specification to gain a stable production process. It is also important to further develop the quality assurance process at the repository facility in Forsmark.

Based on the material investigations it was concluded that Asha 2010 and 2012 will meet the requirements on the installed backfill if the bentonite is installed according to the reference design. Ibeco 2011 fulfils the requirement on hydraulic conductivity, but the margin is low. The mechanics of homogenisation and the variations in installed density need to be further evaluated to enable assessment of whether the margin is sufficient.

3.7.4 General conclusions and recommendations

Bentonite is a natural material and the investigations made indicate that variations in material characteristics within and between material deliveries can be expected. To be able to develop reliable material specifications SKB needs to gain a greater understanding of the material itself, and of the properties of the bentonite when installed in the final repository. It is also important that the bentonite suppliers have an understanding of SKBs requirements on the material.

The bentonite can segregate by transport and handling, which means that it is important to handle the material correctly and develop a sampling procedure applicable for bentonite material delivered in bulk.

Compression tests done for Asha 2012 showed that the density and the water content of the samples clearly affected the maximum stress at failure. The scatter in the determined strength in the beam test was large, but it is clear that the strength increases with increasing density. Both the stress at failure and the strain increased with increasing water content. The granule size distribution also affected the strength of the blocks. A conclusion is that blocks manufactured at full scale, using Asha with suitable granule size distribution, water content of 20% and with a dry density of 1,700 to 1,750 kg/m^3, will have rather high strength.

4 Backfill pellets

Bentonite pellets are used as bed material to even out the tunnel floor before placement of the back-fill blocks. Pellets are also used to fill the gap between the deposition tunnel walls and the backfill blocks to protect the blocks from direct water flow.

The overall requirements in Chapter 2 are further detailed and the requirements presented below are identified for the backfill pellets. The pellet filling shall:

- Have a high water storing capacity in order to buffer the inflowing water in the deposition tunnels and thereby protect the backfill blocks.
- Not be sensitive to erosion, since material loss due to erosion is undesired.
- Be durable and cause minimal dust during installation.

The pellet filling should also contribute to the backfill fulfilling the requirements on hydraulic conductivity, swelling pressure and buffer expansion presented in Chapter 2. The pellet filling contribute to the backfill density, hence the bulk density is of importance.

Backfill pellets have been studied, with the objective to define the optimal pellet properties for backfilling, and suitable manufacturing method. Main conclusions and results from the pellet optimization are summarized in this chapter. For a more extensive summary, see *System design of backfill Pellet Optimization* (Johnsson and Sandén 2013).

4.1 Pre-Assessment

A literature study was carried out to compile information on tests previously performed regarding use of bentonite-pellet materials as part of buffer or backfill barriers. Experiences related to manufacturing and installation of bentonite-based pellet materials for use in repositories for spent nuclear fuel were compiled. From this information, potential options and limitations for the use of pellets or pellet-granule mixtures in backfill were identified. A conclusion was that, although some information is available in the literature, there is still a need to evaluate and optimize the density, shape and as-placed properties of bentonite pellets. Further investigations and tests to be performed within the subproject were suggested based on the pre-assessment. The study is presented in *Backfilling of deposition tunnels: Use of bentonite pellets* (Dixon et al. 2011).

4.2 Laboratory testing

Testing and evaluation of different backfill pellet candidates was done in order to optimize the properties regarding water storing capacity and sensitivity to erosion. The work included testing of different pellet materials (Asha, Ibeco, and MX-80) and pellet types (extruded, roller compacted and granules). The results are presented in *Optimization of backfill pellet properties* (Andersson and Sandén 2012).

The general conclusion from the laboratory tests is that extruded pellets with a diameter of 6 mm had the best overall characteristics of the tested pellet types. See Figure 4-1 for a picture of 6 mm extruded pellets. Regarding materials Asha and Ibeco had better water storing capacity and higher erosion resistance than MX-80. The extruded pellets were the most resistant to erosion, but all material and pellet types were within the limits of the theoretical model describing the erosion rate by Sandén and Börgesson (2010). The extruded pellets also had a higher water flow resistance and seemed to decelerate the water front better than the compacted according to the comparisons in the initial water storing tests. Installation tests with shotcrete equipment showed that extruded pellets were more durable than compacted pellets.

Figure 4-1. *6 mm extruded pellets of Ibeco material.*

The dry density for the non-compacted pellet filling varied between 881 and 890 kg/m^3 for the 6 mm extruded pellets of Asha, Ibeco and MX-80. The density was slightly higher for the compacted pellet types and was around 950 kg/m^3.

4.3 Experiences from pellet manufacturing

Bentonite pellets for backfill of deposition tunnels were manufactured at five different times as a part of the project. Experiences from pellet production are summarized below and described in more detail in Johnsson and Sandén (2013). Laboratory tests were performed on the produced pellets, which is described in Section 4.2.

Two different methods for pellet pressing; extrusion and compaction were tested in small scale. A lab compactor from HOSOKAWA BEPEX GmbH was used for manufacturing of roller compacted pellets. Two different pellet presses from AMANDUS KAHL GmbH & Co were used for production of extruded pellets. In total, three different clay materials were used for manufacturing tests, MX-80, Asha NW-BFL-L and Ibeco RWC-BF.

A pellet press from AMANDUS KAHL GmbH & Co was rented at two different occasions for production of larger batches (25 and 55 tonnes respectively) of 6 mm extruded pellets at the Bentonite Laboratory in Äspö, HRL. Asha and Ibeco material were used for the manufacturing tests. The manufacturing encountered problems with overheating of the press, bentonite clogging to the feeding auger and die resulting in shutdowns. An important experience is that control and adjustment of the water content in the feeding material is essential to achieve a stable production process and pellets of high quality.

The overall conclusion from the pellet manufacturing is that pellet extrusion is considered as an applicable and sufficiently robust method for production of bentonite pellets. Tuning of the production process, especially identifying the optimal water content, must be performed for every new material. This was however not considered a problem for the materials used in the experiments.

4.4 Large scale pellet test in the TASS-tunnel at Äspö HRL

A large scale pellet installation test was performed in the TASS-tunnel at Äspö HRL and is reported in Johnsson and Sandén (2013). The main purpose of the test was to determine the time from the start of the backfill installation, with controlled water inflow, until the outflowing water reaches the installation front. Since the inflowing water can complicate the installation process it is important to have an estimation of how long time it takes for the inflowing water to reach the installation front.

The large scale test showed that the pellet fill can withstand a few days of interruption in the backfilling process before outflowing water reaches the backfill front, by a combined inflow of 0.5 L/min. A combined inflow is denoted by several point flows within a limited area that together forms an inflow of 0.5 L/min. The test verified the results from a scale test (Andersson and Sandén 2012) that the water storing continues also after the first breakthrough of water at the front.

The shotcrete equipment used for installation had a relatively low capacity and may therefore not be suitable for pellet installation in the future repository. Development of pellet installation equipment is therefore needed.

4.5 Pellets as bed material

According to the reference design in SKB (2010b) the pellet bed should be compacted. A non-compacted pellet bed would reduce the installation time and simplify the backfill installation process. The density of the pellet bed is lower with a non-compacted pellet bed, around 900 kg/m^3 for extruded pellets, compared to a compacted pellet bed with a density about 1,200 kg/m^3 according to the reference design (SKB 2010b).

Pellet bed tests were performed with the aim to study the stability of the backfill blocks stacked on a non-compacted pellet bed, according to the geometry in Figure 1-4. The tests included stacking of backfill blocks on different pellet types (extruded and roller compacted pellets), on blasted and even tunnel floor, with and without concurrent water inflow. A test where the blocks were stacked over a deposition hole and bevel was also done. The tests are reported in Johnsson (2011).

The block stack showed to be very stable regardless of the pellet type and the evenness of the tunnel floor. The thickness of the pellet bed had great impact on the magnitude of settlings occurring in the pellet bed. The test showed that the settlings were relatively evenly distributed over the bed area, given that the bed thickness is uniform. Water inflow was also found to cause settlings in the pellet bed; larger inflow resulted in larger settlings, especially over time. The test also indicated that the settlings were smaller and more evenly distributed with extruded pellets compared to compacted pillows. This indicated that extruded pellets are better suited as bed materials than roller compacted pillows, but both pellet types were asses to be acceptable.

The ability of the backfill to restrict the upward buffer swelling must however be further investigated before a design of the pellet bed could be suggested.

4.6 Conclusions and further recommendations

4.6.1 Assessment of requirements

Based on the laboratory tests the 6 mm extruded pellets were chosen as the preferred pellet type for the large scale pellet test. The large scale pellet test verified that the pellet type meets the requirements regarding erosion and water storing capacity.

Based on the pellet optimization 6 mm extruded pellets with a dry density for the non-compacted filling of around 890 kg/m^3 are considered a good backfill pellet candidate that meets the requirements regarding erosion, water storing capacity and durability during installation.

In Section 1.4 it is suggested that a non-compacted pellet bed should be considered to simplify the installation process. A conclusion from the bed test performed is that a non-compacted pellet bed is a stable foundation for stacking of backfill blocks. The ability of the backfill to restrict the upward buffer swelling must however be further investigated before a design of the pellet bed could be suggested.

4.6.2 Installation method

The shotcrete equipment used to install pellets in the gap between the deposition tunnel walls and the backfill blocks can be used for installation of extruded pellets with an acceptable part of pellets crushed (5–8%). However the method is not applicable for roller compacted pellets. The equipment used has a relatively low capacity and it may be hard to fulfil the requirements of the installation rate. Hence it is recommended to further study and develop technologies for pellets installation.

5 Backfill blocks

Backfill blocks are used to fill the bulk part of the deposition tunnels. The design requirements and considerations in Chapter 2 are further detailed for the blocks:

- The blocks shall have high strength and required dimensions in order to facilitate a robust and controlled installation of the blocks.
- The blocks should be possible to handle with a vacuum lifting tool which requires smooth block surfaces, free of cracks.
- The blocks should have sufficient density (1,650–1,750 kg/m^3 is the specification given for Ibeco in SKB (2010b)).
- The material requirements shall be fulfilled, see Chapter 3.

Block manufacturing tests in full scale have been performed at Höganäs Bjuf AB and are presented in Sandén et al. (2014a). The main objective was to verify that backfill blocks of required properties can be manufactured in industrial scale.

The work carried out can be divided into the following parts:

- laboratory investigations of the tested materials,
- manufacturing of blocks in brick size to be used in tests performed in scale 1:2,
- test the technique for manufacturing of blocks in full scale (500×571×400 mm) with a number of different materials,
- extensive sampling of manufactured blocks in order to determine the homogeneity and presence of cracks.

5.1 Material tests in laboratory

5.1.1 General

Five different bentonite materials have been tested; Asha 2010, Asha 2012, Ibeco 2011, Minelco and MX-80. Asha and Ibeco are considered as main backfill candidate materials and hence the material characteristics of Asha 2010, Asha 2012 and Ibeco 2011 were investigated and are summarized in Chapter 3. Minelco was added to the material tests due to initial material problems with Asha 2010 in the full scale block manufacturing tests. MX-80 was included in the test series mainly because the bentonite material was of interest for the development of the plug in the deposition tunnels in the KBS-3V-repository.

5.1.2 Granule size distribution

The influence of the granule size distribution of the materials on the final block quality is not completely clear. It is, however, believed that the granule size affects the de-airing during compaction and also the bulk density of the loose filling and by that also the final block density.

The granule size distribution of the materials tested for block compaction is illustrated in Figure 5-1. The as-delivered Asha 2010 material contained a lot of coarse material, see Figure 3-1, therefore the block edges become very brittle and material from the edges and corners fell off during handling. After crushing of the material to a grain size distribution similar to the Ibeco material, the quality of the blocks increased considerably. A new batch from Asha was delivered in 2012. This material was ordered with the specification, that all granules should be finer than 3 mm. A visual inspection indicated, however, that the material had been crushed between two rollers with a gap spacing of ~3 mm. This procedure had disintegrated, or reshaped, the large granules but at the same time new granules had been formed with a thickness of 3 mm and of various lengths and widths. The granule size distribution of the 2012 batch was therefore very similar to the 2010 batch. The 2012 batch had, however, much better compression properties and it was therefore possible to manufacture blocks with high quality.

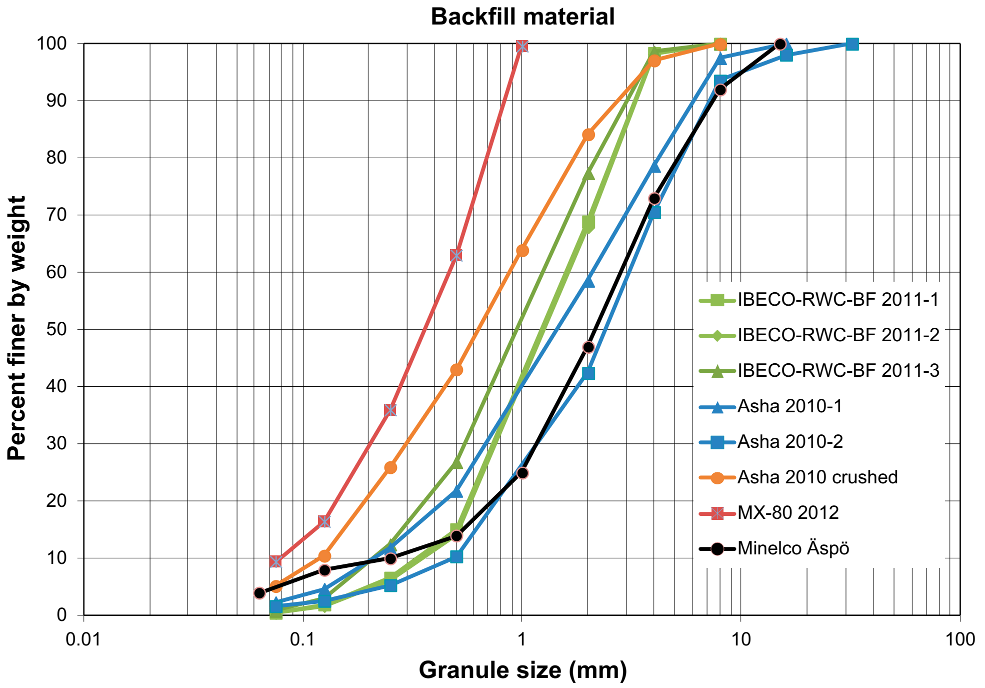

Figure 5-1. *Granule size distribution for the materials tested for block compaction.*

The Minelco material had a granule size distribution similar to the as-delivered Asha 2010. The blocks manufactured with this material were, however, of good quality. The reason for this is probably that the Minelco granules were softer than the Asha granules and due to this could be formed during the compaction.

The MX-80 material had a different granule size distribution compared to the other materials, all granules were smaller than 1 mm. Blocks of high quality was produced.

5.1.3 Compaction properties

Tests were made at two different compaction pressures, 25 and 50 MPa. None of the tested materials, Asha 2010, Ibeco 2011 and Minelco showed an explicit optimum water content. The densities achieved were similar to what was later achieved in the full scale tests.

Earlier investigations have shown that the achieved block quality is highest at water contents about 17% (SKB 2010b). The block stability when exposed to relative humidity similar to what is expected in deposition tunnels is high by water contents of 17–20%. At lower water contents the block edges become brittle and the blocks are more sensitive to the climate expected in the tunnels.

5.1.4 Relative humidity

Relative humidity tests were performed, both in laboratory scale and in full scale (see Sandén et al. 2014b).

The influence of high relative humidity (RH) on compacted blocks was investigated on compacted specimens (d=50 mm, h=30 mm) with initial water content of 20% and dry density of about 1,700 kg/m^3. The specimens were placed in vessels with a relative humidity of either 100% or 75%. The absorption rate at 100% RH was higher than at 75% RH, where almost no water was absorbed. Cracking was observed on the specimens exposed to 100% RH while the specimens exposed to 75% RH were little affected since they were almost at equilibrium with their surroundings.

Relative humidity tests were also performed with full scale blocks. Backfill blocks with a dry density between 1,700 and 1,750 kg/m^3 and water content of 20% were placed in three different climate rooms with controlled relative humidity. During the test period the weight and dimensions were measured at regular intervals. The strength was also evaluated with lifting tests using a vacuum tool.

The test showed that the backfill blocks are strongly affected by the humidity of the surrounding air. One conclusion was that it is possible to handle and install backfill blocks, regardless of level of relative humidity, within 48 hours of exposure to the surrounding air. If the exposure is longer than 48 hours, the manageability of the blocks can be affected, due to cracks and/or swelling of the blocks.

5.2 Manufacturing of brick size blocks

About 90 tons of brick size blocks (300×150×75 mm) were manufactured, 80 tons of Asha 2010 and 10 tons of Ibeco 2011. The blocks were manufactured at three different occasions during the period January to June 2011. The objective was to produce blocks for testing of geotextiles, see Section 6.2.2.

Blocks were sampled during manufacturing in order to determine the achieved density and the homogeneity of the blocks. The first blocks manufactured (Asha) had somewhat low dry density, 1,638 to 1,685 kg/m^3, but after increasing the pressure from 25 to 35 MPa the dry density increased to between 1,700 to 1,750 kg/m^3. The homogeneity of the blocks was investigated by taking samples at different positions. The dry density was found to be somewhat higher at the top side compared to the bottom side, but no large differences were found between corners and the middle of the long side.

During manufacturing of Ibeco blocks the material stuck to the upper piston which resulted in production stop and the surface of the piston had to be cleaned. The problem was found to occur with materials with high water content. The sticking problems decreased when a somewhat drier material was used.

The manufactured brick size blocks had an overall high quality and were judged to be suitable for the planned geotextile tests.

5.3 Manufacturing of full scale blocks

5.3.1 General

Blocks have been produced in full scale with all tested materials. The production was carried out at Höganäs Bjuf AB by production equipment similar to the equipment that will be used at the future production site.

The main problems were related to the as–delivered Asha 2010 material. This material contained a rather large amount of coarse material which affected the block quality. All edges and corners became very brittle and material fell off during handling of the blocks. After crushing the material to a more suitable granule size distribution the block quality increased significantly.

5.3.2 Press cycle and moulds

The first full scale mould had a limited filling height, 560 mm, hence the compaction had to be done in two steps (after the initial filling of the mould a pre-compaction with low pressure was made and thereafter the mould was filled again before the final compaction) in order to manufacture blocks with a height of 400 mm.

As a second step, a new full scale mould was manufactured. This mould had a filling height of 685 mm and a radius of 5 mm in the four vertical corners. With this mould it was possible to manufacture the blocks in one step. The small radius in the corners resulted in durable block corners.

5.3.3 Block quality

The block quality was assessed regarding the following parameters:

- achieved dry density,
- homogeneity (density distribution within the blocks),
- the presence of cracks and/or loose material,
- the sharpness and stability of the block edges.

The tests showed that it is possible to manufacture full scale backfill blocks with an average dry density between 1,650–1,750 kg/m^3, which agrees with the specification for Ibeco given in Section 1.3. See Figure 5-2 for a photograph of one of the produced blocks.

The homogeneity of the blocks was investigated by drilling cores at different positions, see Figure 5-3. The cores were cut in slices and the water content and density determined at different levels. The investigations showed that there were density gradients in the blocks especially along the four vertical corners. The density was higher at the top and the bottom, and the lowest densities were found at mid-height in the corners. The largest differences in dry density were in the order of 50 to 60 kg/m^3. Samples taken from the block centre and along the middle point of the long sides were considerably more homogeneous. The density distribution within the blocks is not expected to influence the block handling or the final density distribution within the tunnel.

During the initial tests some cracks occurred on the block surfaces. After optimizing the compaction cycle and introducing the de-airing steps, this problem disappeared. The cores drilled from the blocks, were visually judged to be of high quality, and did not show any cracks or other weaknesses. The two step compaction with an extra filling did not seem to result in any weaknesses. The biggest problem was the stability of the four vertical edges of the blocks. Especially the first batch from Asha delivered in 2010 resulted in very brittle edges, where loose material fell off. After adjustment of the material specification regarding granule size distribution and optimization of the water content, the quality of the edges increased markedly. The latest tests, which were performed with the new mould with rounded corners, resulted in blocks with very stable edges.

5.3.4 Technical aspects

The elastic expansion of the blocks manufactured in full scale was about 0.5% (at water contents around 20%). The expansion varied somewhat for different water contents and for different materials. This has to be taken into account when deciding on the size of a new mould.

Figure 5-2. *Photo showing one of the best Ibeco blocks manufactured.*

Figure 5-3. Photo showing a block after sampling.

5.4 Manufacturing of full scale Asha-2012 blocks

Blocks required for the full scale demonstration test, described in Chapter 8, were produced at Höganäs Bjuf. The mould with a filling height of 685 mm and a radius of 5 mm in the corners described in Section 5.3 was used. The Asha 2012 material described in Chapter 3 was used for production of the blocks needed for the full scale demonstration test.

The mixing with water was carried out with an Eirich mixer at Höganäs Bjuf. A mean value of the initial water content was assumed to shorten the mixing time. Hence, the same amount of water was added to all sub lots resulting in a fairly large variation in water ratio, see Figure 5-4.

The block press and the related production equipment worked as intended and no problems related to the equipment were observed. However larger stones were discovered in the bentonite material. These stones stuck into the mould filling equipment, which resulted in overheating of the equipment and production disturbances. Attempts were made to sieve away the stones, but this resulted in problems for the material to pass through the sieve.

Another material problem was that some big bags contained dispersed material while others contained a more coarse material, which resulted in large variations in block height. Since it was important to keep the block dimensions within the acceptance range to be able to perform the installation test it was decided to prioritize the block height over achieving a high density. As a consequence, the blocks gained lower densities than expected, see Figure 5-5.

In total 1,820 acceptable blocks were produced, 46 of these blocks were sampled for inspection, see the result below. About 110 blocks were rejected since the geometry acceptance criterion of ±2.5 mm was not fulfilled.

Mass:	225.2±1.4 kg
Height:	398.8±0.7 mm
Width:	500.3±0.4 mm
Length	571.4±0.4 mm
Dry density:	1,641.7±10.9 kg/m^3

The given variation is the standard deviation.

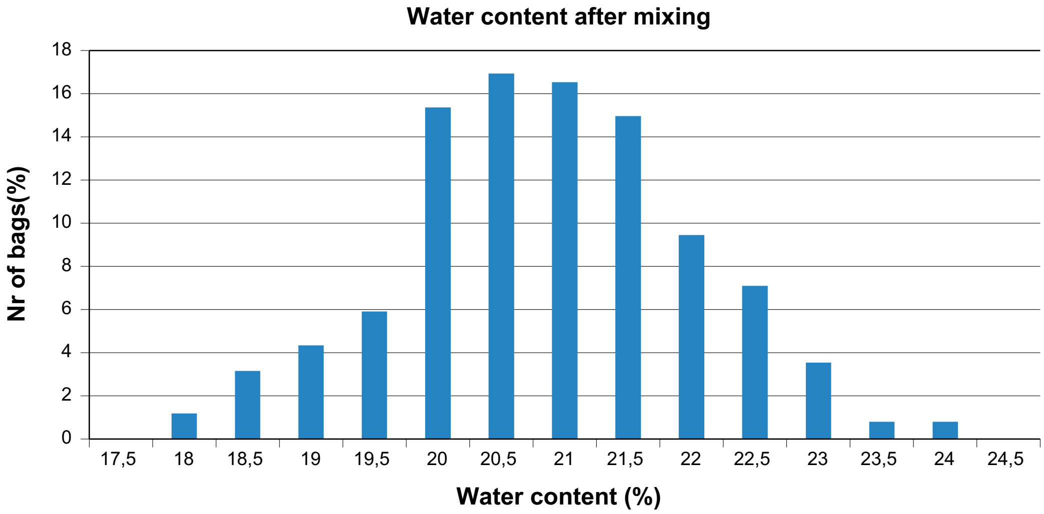

Figure 5-4. *Water content distributions of the sub-lots after mixing.*

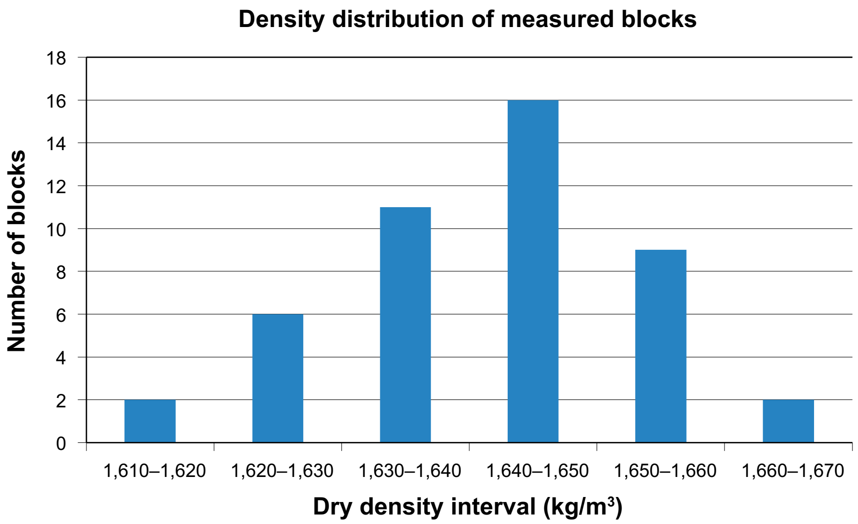

Figure 5-5. *Density distribution in the measured blocks.*

5.5 Conclusions and recommendations for further work

Results from the relative humidity tests showed that compacted blocks of Asha with a water content of 20% seemed to be well in equilibrium with air with relative humidity of 75%, i.e. the water absorption was small, there was almost no swelling and there were no indications of cracks. The relative humidity tests also showed that the full-sized backfill blocks are very sensitive to the surrounding atmosphere. One main conclusion is that, independent of the relative humidity (18 to 94%), the blocks are possible to handle and install within first 48 hours of exposure to this environment. In case of longer exposure, the manageability of the blocks can be affected, and hence it might not be possible to handle and install the blocks.

5.5.1 Assessment of requirements

It has been shown that it is possible to manufacture full scale backfill blocks with an average dry density in the range of 1,650–1,750 kg/m^3. Full scale blocks can be produced with required dimensions, 500×571×400 mm and accepted variations of ±2 mm, even though a larger variation was accepted at manufacturing of blocks for the full scale test.

The requirements of high strength and smooth block surfaces, free of cracks, were fulfilled for the main part of the blocks. The tests have however shown that the material properties are important in order to achieve blocks with high strength and block surfaces free of cracks. It is necessary to perform laboratory tests for each delivery in order to get information of the expected behaviour in full scale. Important material properties are:

1. **Water content.** Influences both internal friction of the material and also the external i.e. between the bentonite and the steel mould. This means that the water content affects both the manufacturing process (high water content implies high filling factor and risk of the bentonite sticking into the manufacturing equipment) and the quality of the produced blocks (high water content implies low shear strength of the blocks). The water content can be adjusted before block compaction by use of large mixers.
2. **Granule size distribution.** The influence of the granule size distribution on the final block quality is not completely clear. The performed tests with the as-delivered Asha 2010 material showed that material containing large and hard granules resulted in blocks with brittle block edges. The granule size distribution is important for the de-airing of the material, done in order to avoid trapped air. A press equipped with vacuum equipment will probably improve the block quality.
3. **Mineral composition.** Influences the friction during compaction, both internal in the material and also against the steel mould. The mineral composition probably influences the stiffness of the granules and by that also the sharpness of the block edges.

The manufacturing problems with the Asha-2012 material highlight the need to have a well defined material specification when ordering material, and the importance of a reliable quality assurance process. As described in Chapter 3, parameters affecting block compaction properties need to be more carefully specified.

5.5.2 Production equipment

The tests were performed in an existing press at Höganäs Bjuf AB. New moulds were built in order to produce blocks with the desired dimensions. In a future block production plant the press should be designed with:

1. **The adequate filling height of the mould.** A press designed for a suitable filling height will simplify the manufacturing significantly. Manufacturing blocks with a height of 400 mm will need a filling height of at least 600–640 mm for Asha/Minelco and 720 mm for Ibeco.
2. **Equipment for de-airing.** The present tests were made without vacuum equipment, instead a number of de-airing steps were made during the manufacturing. This technique improved the block quality. In a future production plant it is recommended that the press is equipped with a vacuum device, making it possible to de-air the powder before compaction. This will probably increase the block quality, decrease the risk of cracking and also increase the block manufacturing rate.

In a future backfill block production plant, it will be necessary to have the possibility to adjust the water content (large mixers), and the granule size distribution (crushing equipment) of the delivered materials. It is recommended to perform a number of pre-tests in laboratory e.g. determination of compaction properties and investigation of friction and how it influences the density distribution and the quality of the compacted blocks.

Another conclusion drawn from the test is that the Asha material had a tendency to segregate resulting in some blocks containing dispersed material while others contained a more coarse material. The production plant should be designed so that adequate mixing of the material is achieved before block compaction.

6 Handling of water inflows during backfill emplacement

A main problem in the backfilling process is how the water inflow to the tunnels should be handled during emplacement. Depending on flow rates and how the inflow points are distributed in the tunnel the inflowing water may affect the stability of the backfill installation and also cause erosion of the backfill.

Preliminary modelling of the crystalline rock at the Forsmark site shows that about 45 out of a total of 207 planned deposition tunnels will have an inflow higher than 10 L/min and 13 tunnels will have inflows higher than 30 L/min (Joyce et al. 2013). Since it is desired that no deposition tunnels constructed should be abandoned, it is necessary to develop methods and techniques in order to handle these expected water inflows.

Investigations and installation tests have been performed and are presented in *Early effects of water inflow into a deposition hole. Laboratory test results* (Sandén and Börgesson 2010).

6.1 Water storing in the pellet filling

An important function of the pellet filling is to protect the backfill blocks from direct water flow. The water storing capacity of the pellet filling was investigated in laboratory tests and in full scale, which is described in Chapter 4.

The results from both theoretical estimations of available time and from the latest large scale tests have been used in order to set some limits regarding the possibility to store water in a pellet filling:

- The maximum allowed inflow rate to one 6 meter section that can be handled by storing the water in the pellet filling is 0.5 L/min. If geotextile is used in order to distribute the inflowing water over a larger area, preferably in combination with a temporary drainage tube, the maximum allowed inflow rate is 1 L/min. This assumes that only one or two 6-meter sections in a 300 meter long deposition tunnel have these high inflow rates, see next bullet.
- The maximum water inflow to a 300 meter long deposition tunnel that can be handled by letting the inflowing water be stored in the pellet filling is 2.5–5 L/min. The exact figure depends strongly on how the water inflow is distributed in the tunnel. One requirement is that no water inflow to one 6-meter section is higher than 1 L/min and another is that geotextile is used in order to distribute the inflowing water in sections with inflow rates between 0.25 and 1 L/min.

6.2 Tests of geotextiles

The function of the geotextile is to distribute the inflowing water more evenly in the pellet filling, and to avoid local erosion of the backfill. The geotextile should be functional as long as the deposition tunnel is open and the effect on the long term safety of the repository should be minimal.

In order to test and show the ability of the geotextiles to improve the water storing capacity of the pellets laboratory tests, test in half scale (steel tunnel test) and fastening tests were performed. The tests are reported in Koskinen and Sandén (2014).

6.2.1 Laboratory tests

The purpose of the laboratory scale tests was to verify the potential of geotextile fabrics to distribute water between the rock and the bentonite pellets.

Three different types of geotextile were tested:

1. Standard type of geotextile with a certain content of organic materials (polypropylene). Thickness about 6 mm.
2. Fibreglass fabric (borosilicate glass) type I. This material contains no additives that can be harmful to the disposal from a long term safety perspective. The fabric is very thin and the strength is low.
3. Fibreglass fabric (borosilicate glass) type II. The fabric is thick and contains no additives that can be harmful to the disposal from a long term safety perspective.

The performed tests showed that all the tested qualities of geotextiles distributed the inflowing water well. It was, however, noticed that the thin fibre glass fabric was very fragile, especially after wetting. The fibre glass fabric type II was thicker, with higher strength and it seemed to be more suitable for use on rock walls.

6.2.2 Steel tunnel tests

The objective of the ½-scale tests was to verify and demonstrate the functionality of the inflow handling system. Based on the laboratory scale tests, a typical polypropylene geotextile was used in the ½-scale steel tunnel tests. Three separate tests were done in the steel tunnel:

- Reference test 0.25 L/min inflow, without geotextile.
- Test 1 with geotextile 0.25 L/min inflow.
- Test 2 with geotextile 0.5 L/min inflow.

The results from the ½-scale steel tunnel tests showed increasing water storing capacity of the pellet filling when using geotextile as a distributor. The use of geotextile seems to increase the water storing capacity of a pellet filling with at least 30%.

Based on the ½-scale steel tunnel tests it is assessed that the geotextile delays piping and increases the water storing capacity at least up to the tested 0.5 L/min inflow rate. In total, only three tests were performed and hence the results need further verifications.

6.2.3 Fastening tests

The fastening of the geotextile onto wet rock surface was tested in Loviisa low- and intermediate level waste repository (Finland).

A 1 meter wide and 1–3 meter long sheet of geotextile, standard type of geotextile and fibreglass fabric, was fasten onto the rock wall. The tested methods were express nails, two different types of glues and concrete.

The express nails seemed to be the most promising method for fastening the fabric onto the rock wall. The method requires minimal preparation of the rock surface and the nails can be applied fast without comprising disturbance to other activities in the repository.

The glass fibre geotextile was proved to be fragile and the fabric detached during the installation of the pellets. Concrete may be a possibility for the fastening, but is questionable in the long term safety perspective.

6.3 Water handling methods

For inflows exceeding the limits specified for the pellet filling in Section 6.1 it will be necessary to introduce other methods for water handling. **Table 6-1** shows a compilation of the estimated number of tunnels, with a certain water inflow, the maximum allowed water inflow to a single 6 m-section and the suggested water handling methods. The estimated number of tunnels with certain inflow properties is based on the proposed Forsmark site and with assumed degree of grouting success, see Joyce et al. (2013). The estimated number of tunnels with certain inflow properties will change if the grouting success differs from the assumed.

Table 6-1. Summary of different inflow scenarios and associated water handling method.

Estimated part of tunnels	Water inflow to 300 m tunnel	Max. water inflow to 6 m section	Water handling method	Remark
55%	0–1 L/min,	< 0.5 L/min	Storing in pellet filling	
2%	1–5 L/min	< 0.5 L/min	In 6 m-sections with inflow rate $0.25 < q_{6m} < 0.5$ L/min geotextiles should be used in order to distribute the inflowing water.	As an option, temporary drainage tubes can be used.
13%	1–5 L/min	$0.5 < q_{6m} < 1$ L/min (q_{6m}= inflow to 6 meter section)	1. Geotextile 2. Temporary drainage tubes[1]	The water handling method should be chosen depending on how the inflow points are distributed in the tunnel.
6%	1–10 L/min	> 1 L/min	1. Water storing sections[1] 2. Drainage through a borehole to an adjacent tunnel[1] 3. Local freezing[1]	Drainage through a borehole to an adjacent tunnel can advantageously be used in combination with a water storing section.
17%	> 10 L/min	> 1 L/min	1. Water storing sections[1] 2. Drainage through a borehole to an adjacent tunnel[1] 3. Local freezing[1] 4. Tunnel plug[1]	Drainage through a borehole to an adjacent tunnel can advantageously be used in combination with a water storing section.
7%	> 30 L/min	> 10 L/min	1. Drainage through a borehole to an adjacent tunnel[1] 2. Tunnel plug[1]	Drainage through a borehole to an adjacent tunnel can advantageously be used in combination with a water storing section.

1 The suggested methods have not been tested and further development is needed.

The choice of water handling method for different inflow scenarios in Table 6-1 have been made according to the following:

- **Total inflow of between 0 and 1 L/min in 300 m tunnel and < 0.5 L/min to a single 6 m-section.** This is, according to the models, the most common water inflow scenario and will occur in approx. 55% of the deposition tunnels. These water inflow rates can be stored in the plain pellet filling without any additional means.
- **Total inflow between 1 and 5 L/min in 300 m tunnel and < 0.5 L/min to a single 6 m-section.** This is, according to the models, not a likely scenario. Only a few tunnels are predicted to have these rather well distributed inflows. The recommended technique for water handling is to install geotextiles in sections where the inflow rates are higher than 0.25 L/min in order to distribute the water and by that access larger pellet volumes for water storing.
- **Total inflow between 1 and 5 L/min in 300 m tunnel and inflow to a single 6 m section is 0.5–1 L/min.** This is according to the models a scenario that may occur in approximately 13% of the tunnels. The recommended technique for water handling is to install geotextiles in sections where the inflow rates are higher than 0.25 L/min in order to distribute the water. In sections where the inflow rates are higher than 0.5 L/min it is recommended to use temporary drainage tubes in addition.
- **Total inflow between 1 and 10 L/min in 300 m tunnel and > 1 L/min to a single 6 m-section.** This is a scenario that will occur in about 6% of the tunnels according to the models. In the sections with highest inflow rates it will be necessary to build water storing zones. The capacity of these zones can be chosen by adjusting of the length of the zone, but it is assessed that in practice they are useful for inflow rates between 1 and 2 L/min. For higher inflow rates to a single 6 m-section it is recommended to drill a drainage borehole to an adjacent tunnel. This solution, preferably in combination with a macadam filled section, will allow drainage during a long period of time. An alternative could be a local freezing of the water bearing zone. This method will, however need further development and testing.

- **Total inflow > 10 L/min in 300 m tunnel and > 1 L/min to a single 6 m-section.** See solutions recommended in previous scenario. An alternative for the sections with highest inflow rates could be to build a Class II plug (planned plug of somewhat simpler construction than the tunnel end plug).
- **Total inflow > 30 L/min in 300 m tunnel and > 10 L/min to a single 6 m-section.** In tunnels with these high water inflow rates is it recommended to either drain the water to an adjacent tunnel (in combination with a macadam filled section) or to cut off the water bearing section with tunnel plugs of class II.

Note that the only water handling methods that have been tested during the project "System design of backfill" is water storing in pellet filling and geotextiles. Drainage tubes, water storing zones, drainage boreholes to adjacent tunnels, local freezing and class II plugs are suggestions that need to be further investigated and tested.

6.3.1 Conclusions and recommendations for further work

The purpose was to develop methods for handling all types of water inflows into the deposition tunnels. Pellets and geotextiles have been tested for lower water inflows and different methods have been theoretically developed for higher water inflows.

Water storing in the pellet filling has been tested at Äspö HRL, as also the improvement with geotextile used as a distributor of the inflowing water. The capacity of this method is assessed to be quite well known and it is recommended for use in tunnels with a total water inflow < 5 L/min and with a maximum water inflow rate to one 6 meter section < 1 L/min. It is however important to investigate how the location of the inflow points affects the installation procedure and the possibilities to adjust the installation procedure to avoid scheduled stops when a water inflow is close to the front of the backfill.

For higher inflow rates, > 5 L/min in 300 meter tunnel or inflow rates > 1 L/min in one 6 meter section, it will, however, be necessary to use other methods in addition to pellets and geotextiles. The methods assessed to have most potential and that are recommended to be studied and tested further are:

- **Macadam filled water storing sections**. This is a rather simple method that has the potential to be used in sections with medium high inflow rates (1–2 L/min). The sections are technically very simple to build and the position in the deposition tunnel can be decided before the drilling of deposition holes. The long term safety of the design must, however, be investigated.
- **Drainage through borehole to adjacent tunnel**. This is a method that has high potential to be used in sections with high water inflow rates. The technique must probably be used together with a macadam filled section which can collect and lead the water to the borehole. The technique is rather simple but the long term safety aspects of the design must be assessed.
- **Local freezing**. This technique is used during construction of road and railway tunnels in e.g. fractured rock or if high water inflows occur. The technique can potentially be used for local freezing of water bearing fracture zones in a future disposal. There are, however, uncertainties regarding whether the technique is suitable e.g. if it works at a depth of 400–500 meters, how the cooling affects the rock strength and if the procedure means that foreign material is left in the repository.
- **Temporary plugs**. It is possible to use a plug similar to the tunnel end plug to cut off the deposition tunnel. More simple plugs could also be used to cut off water bearing fracture zones or in case of longer unforeseen stops of the installation process.

7 Installation of backfill

This chapter summarizes the further development of the installation concept described in SKB (2010b). Two important requirements on the installation are that the backfill shall be installed with high reliability and at the prescribed rate (6 meters of backfill per working day). The installation equipment as well as the geometric configuration of the backfill have been further developed compared to SKB (2010b).

In SKB (2010b) it is required that the block portion of the deposition tunnel should be > 60%. It is also stated that the maximum volume fraction of slots between backfill blocks should be ≤ 2% in average.

As described in Section 1.1 the backfill consists of pre-compacted bentonite blocks and bentonite pellets. The backfill process begins when the copper canister and buffer have been placed in the deposition holes. The backfill is installed in sections of about 6 meters at a time; each section including placement of bed pellets, installation of blocks and finally installation of pellets in the gap between the block stack and the bed rock. See Figure 7-1 for an overall process scheme of the installation.

The development of installation equipment has been focused on block installation. The equipment for installation of pellets will be integrated with the block installation equipment later on.

7.1 Installation concept

Different methods for installation of backfill were investigated by SKB in 2008, see Wimelius and Pusch (2008). Mainly two different installation strategies are discussed in the report; placement block by block and placement of units of blocks.

In SKB (2010b) it is stated that the blocks shall be installed one by one on a pre-compacted pellet bed. Individual emplacement of blocks was also a base for the further development since:

- A block stack with individually emplaced blocks can more easily be adapted to geometrical deviations than a stack consisting of block modules.
- The stability of the block stack was judged to be higher when the blocks where placed individually.
- Transportation to the installation site was considered to be simplified with individual emplacement of blocks.

In order to provide a backfill with high block filling degree in a short time, the blocks should be placed close to each other and at a high pace, which suggests that a robot should be used for the installation. The usage of a robot for block installation enables the placement of the blocks in an overlapping stacking pattern, where blocks in different layers and rows overlap each other. This is considered beneficial since a stable block stack will be obtained and the risk of longitudinal gaps will be reduced. This also means that the requirements on the pellet bed can be reduced, and a compaction of the bed is possibly not necessary.

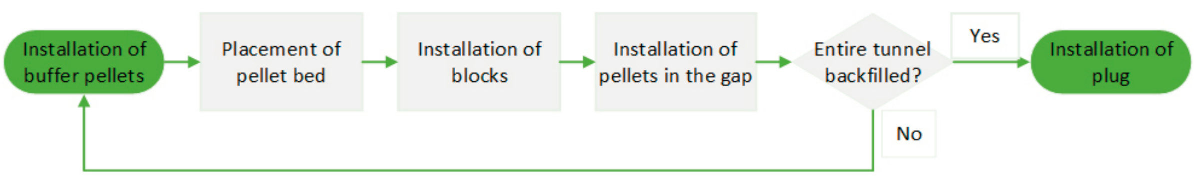

***Figure 7-1.** Overall process scheme of the backfill installation.*

The starting point in deciding block sizes and stacking pattern was to enable, if possible, use of a single block size. Uniform blocks would simplify the manufacturing, logistics and the installation process. Different block sizes and stacking patterns were evaluated against block filling degree, logistics and technical feasibility. A block size of 571×500×400 mm (LxWxH) was suggested in combination with the stacking geometry shown in Figure 7-2. The stacking geometry results in a cross section of the block stack of approximately 16.5 m^2 and a block filling degree of 66% with the maximum allowed over break (30%) in a deposition tunnel.

7.2 Selection of robot

To be able to develop and test prototype equipment for installation of backfill blocks an industrial robot was purchased. Robot reach and capacity was considered in the selection of robot type. A criterion was that the robot should be able to operate in an underground environment. Different robot types were evaluated and KUKA KR1000 L750 Titan was judged to best meet the requirements, see Figure 7-3.

After the selection of a robot a reach simulation was carried out in order to verify that the robot could carry out the backfill installation as expected. The reach simulation verified that the robot can perform backfill installation; however the cycle time for installation was longer than expected. The reach simulation gave input to the development of the platform and block feeding system.

7.3 Development of gripper

Bentonite blocks are fragile and it is therefore important to grip the blocks without subjecting them to high mechanical loads. Vacuum technology was considered a suitable method since it has previously been used for buffer blocks; the method is gentle to the material and has been industrially proven.

The vacuum surface is divided into different redundant sectors to prevent sealing problems and failure in an individual vacuum ejector. Both horizontal and vertical vacuum plates are used to maximize the grip and ensure that the blocks are properly positioned. See Figure 7-3 for a photo of the robot holding a block with the vacuum gripper.

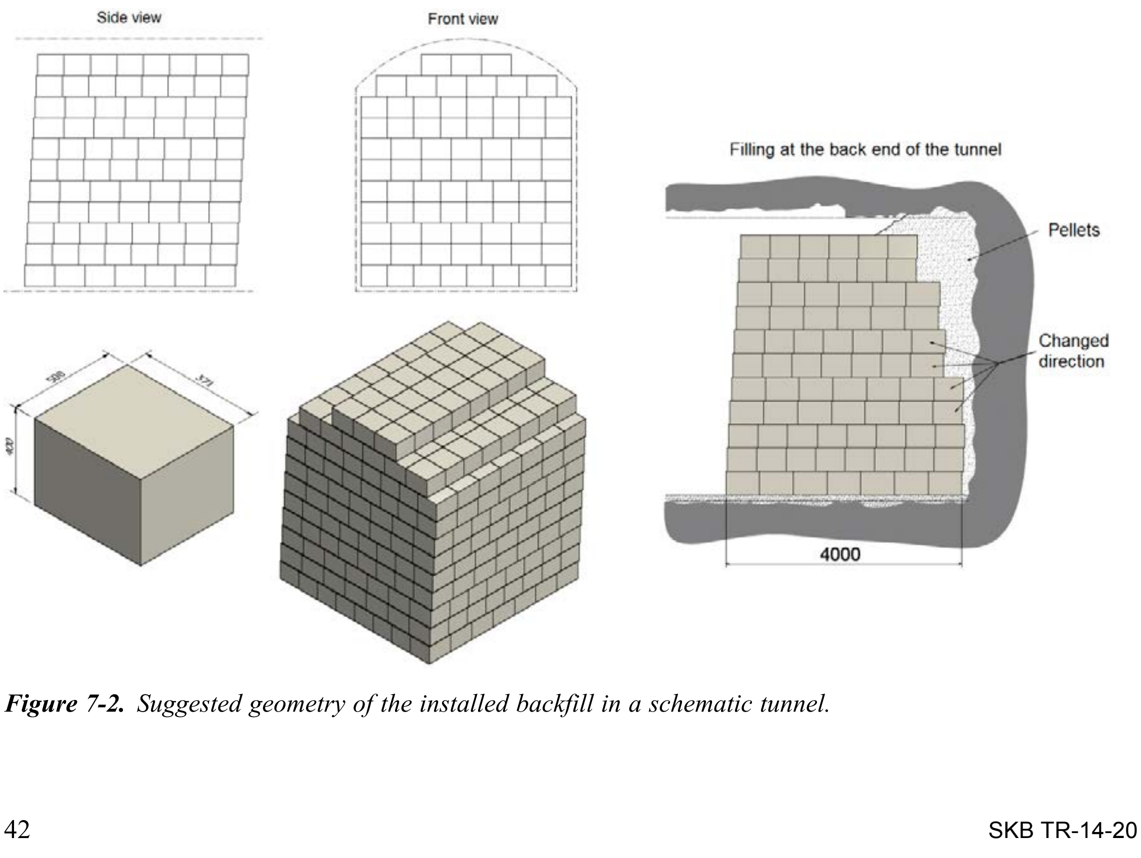

Figure 7-2. Suggested geometry of the installed backfill in a schematic tunnel.

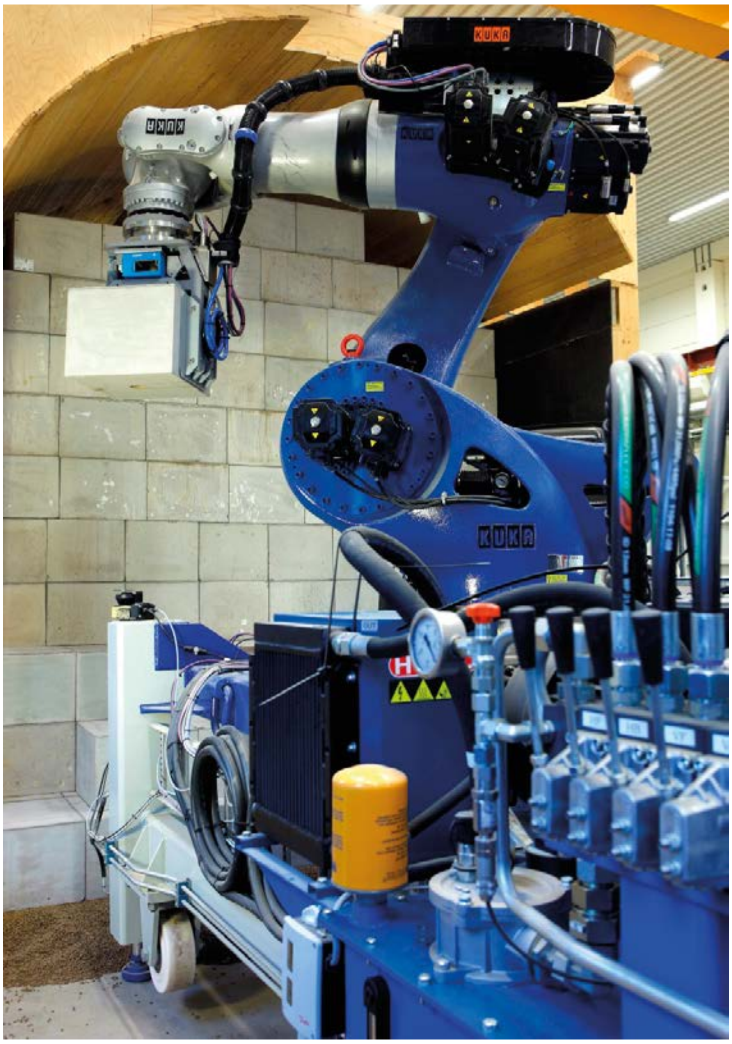

Figure 7-3. *A photo of KUKA KR 1000 L750 Titan, the prototype robot for installation of backfill.*

7.4 Platform and peripherals

A platform for the backfill robot was needed to enable movement of the robot. A prototype platform with rolling wheels and support legs for mobility and levelling was built. The backfill robot and a pallet feeding system were mounted on the platform. A safety scanner was also mounted on the platform to prevent personnel from entering the working area of the robot during stacking.

7.5 Measurement system

The achieved block stack quality is dependent on measurement information regarding:

- the backfill machine position and orientation,
- the position of the existing block stack,
- position and orientation of the blocks on the feeding pallets.

Development of the measurement system was carried out throughout the whole development phase.

A Sick LMS400 2D laser scanner was chosen for measurements of block positions on the pallet, pellet bed, tunnel walls around the stack and the stack face. The scanner was tested on different kinds of bentonite and rock surfaces and was evaluated to be acceptable. A measurement algorithm was developed to enable computer controlled moving of the scanner.

Sick LMS 511 long range scanners was chosen to measure transversal position and orientation of the platform relative to the deposition tunnel in order to keep the backfill stack aligned in the tunnel.

A long range distance meter was used to measure the position of the backfill robot and platform along the tunnel.

7.6 Development of control system

The backbone of the robot control system was developed using a small scale robot from KUKA. Development of the control system was carried out throughout the whole development phase.

The control system consists of functional sub-modules. Each sub-module takes care of a clearly defined part of the overall process. A *Backfill supervisor* was developed to control the overall process, meaning to initiate, synchronize and monitor all tasks within the process.

The sub-modules that have been integrated in the backfill machine at this stage are:

- *Backfill supervisor,*
- *Safety System* monitors the safety zone around the machine,
- *Automated Machine Control Systems (AMCS)* takes care of the low level control of the platform and interfaces to platform sensors and actuators,
- *Platform Control* handles high level control of the platform,
- *Robot Control* executes the actual robot movements,
- *Laser Measurement system,*
- *Pallet feeding system* moves the pallets,
- *Stack building* plans the stack building process and generates stack building commands.

The backfill supervisor was developed by implementing the sub-modules piece by piece. The stack building process, e.g. the positioning of the blocks and the ideal distance between the stack face and the robot was developed.

Calibration of the laser scanner was one of the biggest problems during the development. The scanner not being properly calibrated resulted in both picking and stacking problems.

7.7 Testing of the entire system in the bentonite laboratory

Full scale testing of the backfill machine was carried out at Äspö HRL. The aim of the test was to develop the overall process and especially the control system. The full scale equipment was tested in a full scale environment for the first time.

First, the overall system including the KUKA robot, gripper, platform, pallet system, measurement system and control system were built together. Development and testing of the overall system were performed in parallel and the system continuously developed.

A 5 meter high and 4.4 meter wide test tunnel made of wood was built. Concrete blocks with roughly the correct dimensions and weight were used instead of bentonite blocks, since they have higher strength and can be used several times.

The testing in the bentonite laboratory was carried out between February 2012 and December 2013.

In total about ten concrete stacks with a length of four meters was stacked on a bed of pellets.

The control system was continuously developed during the test period and lots of lessons were learned. The main conclusion and results from the testing are summarized in next section.

7.8 Conclusions and recommendations for further work

7.8.1 Assessment of requirements

The stacking tests in the bentonite laboratory show that the basic stack building solution is viable. The shape of the block stack was evaluated from the stored block position data, and it was assessed to be satisfying. The stability of the block stack was visually assessed to be satisfying. However, the overall functionality of the stacking equipment and control system are still elementary and requires further development before a completely automated process can be achieved.

One of the requirements is that the backfill shall be installed with high reliability. The tested method has potential for reliable installation, but further development is needed. Another requirement is that the installation should be performed at prescribed rate, 6 meters of backfill per working day, this is not fulfilled with the system used. Time saving measures can be performed in several functions and the requirement should be achievable after improvements of the system.

The specified maximum allowed volume fraction of slots between backfill blocks is 2%, which means that the fill percentage should be at least 98%. The fill percentage was not explicitly measured in the stacking test, but based on the stored block position data it was assessed to be close to 100%.

7.8.2 Gripping

Fast and reliable gripping of the bentonite blocks is important in order to gain high reliability and sufficient installation pace.

Many gripping related problems occurred during the tests in the bentonite laboratory. The main reasons for the gripping problems were poor surface quality of the concrete blocks and a slightly too big prototype gripper. Most of the concrete blocks suffered from poor surface quality, having lots of small holes, which led to vacuum leakage and the block could not be picked. The initial version of the gripper was slightly too big causing the gripper plate to hit the feeding pallet and making gripping of the blocks difficult. The gripper plates were however re-designed and the second generation worked better.

Another problem was that all blocks could not be picked using side grip due to limitations in the robot reach partly caused by instruments mounted on the platform which limited the robot movements. The problem was solved by moving the concerned blocks and changing the grip.

Gripping has been one of the major problem areas. Improvements of the robot calibration, accuracy in the feeding pallet measurement (today 4–5 mm), design of the gripper and design of the control system are possible, and would increase the reliability significantly.

7.8.3 Control system

The current control system is built to manage basic events in the normal process. Simplifications in data handling, control software and interfaces between subsystems should be prioritized in the further development.

All robot movements were developed and tested.

The installation of the pallet feeding system resulted in major changes in the block picking routines. Singularity point related issues were one of the biggest concerns during the development of the control system. At a singularity point, the robot control system cannot calculate an unambiguous sequence of joint angles, which might lead to one of the joints turning up to a limit resulting in stop of the robot movement. The problems were solved by re-programming, but re-design of the platform may also be effective in avoiding singularity issues.

7.8.4 Measurements

Extensive development and testing of the measurement system was performed during the test, to achieve accurate and fast measurements. The overall measurement system should however be reconsidered regarding accuracy, reliability and time consumption.

8 Large scale installation test

A large scale installation test was performed at Äspö HRL. The aim of the test was to demonstrate that installation of backfill can be carried out as intended in a realistic environment. The test was performed with a prototype installation robot and in absence of a sufficient transport system.

The work was carried out in accordance with the activity plan AP TD KBP1003-13-008. The activity plan is one of SKB´s internal control documents.

8.1 Requirements

The main requirement on the backfill installation is that the backfill shall be installed with sufficient density. The average installed density is determined by the dry density of the backfill blocks/pellets and the proportion of blocks/pellets in the deposition tunnel. These parameters can be varied to meet the density requirement. A dry density of about 1,280 kg/m^3 is required to fulfil the requirements on swelling pressure and hydraulic conductivity for Asha 2012 according to Sandén et al. (2014b).

In SKB (2010b) it is required that the block portion of the deposition tunnel should be > 60%. It is also stated that the maximum volume fraction of slots between backfill blocks should be ≤ 2% in average.

The design considerations described in Chapter 2 shall also be regarded in the design of the backfill and in the development of the methods to manufacture, install and control the backfill. The design premise that the backfill shall be possible to install at prescribed rate is further specified; a tunnel length corresponding to the average distance between deposition holes (6 m) shall be backfilled per working day.

Based on the design consideration that the backfill shall be possible to install with high reliability, the free space between the block stack and tunnel walls should be ≥ 100 mm to enable pellet installation and protect the block stack form inflowing water.

8.2 Test layout

The test was performed in the TASS-tunnel at Äspö HRL, situated at a level of –450 meters. The TASS tunnel is blasted with nominal geometries according to Figure 8-1. The average over break in the tunnel is approximately 16% with small amounts of under break (Karlzén and Johansson 2010).

The total test length was 12 meters, starting from the tunnel face.

8.2.1 Preparation of the tunnel

The tunnel floor in the reference design is blasted. TASS had a paved tunnel floor and hence the pavement and underlying gravel was removed prior to the test. Temporary guide rails were placed on the tunnel floor so that the robot platform could be moved easily during the test, see Figure 8-2. The height of the rail was 80 mm from the nominal tunnel profile. Both the guide rails and the platform were special equipment used during the test and will not be used in a future repository.

A larger water inflow (0.25 L/min) placed on the left side of the tunnel, 5 meters from the tunnel face was led away into a connecting tunnel. In the future repository a water inflow of this magnitude should be possible to handle without drainage. The inflowing water was led away to not disturb the test as the test was performed with prototype equipment and at a lower installation pace than expected in the final repository. The remaining water inflow into the 12 meter tunnel section was estimated to 0.03 L/min.

Rock reinforcements consisting of bolts and nets were installed in the tunnel roof in 2010. This type of rock reinforcements is an alternative that may be used in the KBS-3V-repository.

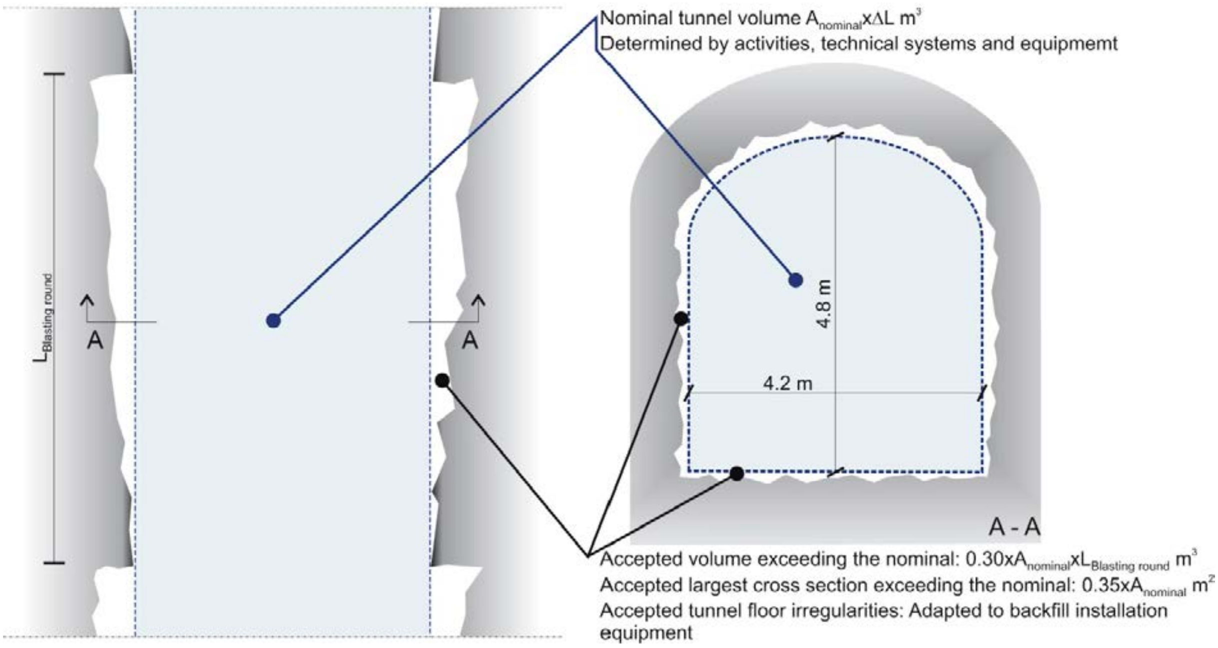

Figure 8-1. *Nominal tunnel geometry and acceptable volume of rock fall out and irregularities in the tunnel floor.*

Figure 8-2. *The robot platform was operated and moved using temporary guide rails.*

8.2.2 Material

Backfill blocks

Material: Asha 2012, for characterization, see Chapter 3

	Mean value ± Standard deviation
Mass:	225.2±1.4 kg
Height:	399.8±0.7 mm
Width:	500.3±0.4 mm
Length:	571.4±0.4 mm
Dry density:	1,641.7±10.86 kg/m^3

Pellets

Material: Cebogel
Dimensions: Extruded, Ø 6 mm
Dry density: 940 kg/m^3
Water content: 19%

Cebogel pellets was bought due to the high production costs for a small scale production of backfill pellets. Cebogel pellets were assessed to be comparable with backfill pellets out of an installation perspective.

8.2.3 Installation equipment

The backfill blocks were produced, and provided with protective plastic, at Höganäs Bjuf, and transported to Äspö on wooden pallets. A transfer system consisting of a vacuum tool connected to a small pick-up crane was used to move the backfill blocks from the wooden pallets to the transportation pallets adapted for the installation process, see Figure 8-3. In total, eight transport pallets were used in the test.

Figure 8-3. *Block transfer system.*

The backfill robot and peripherals described in Chapter 7 were used for installation of backfill blocks. The control system was operated in semi-automatic mode, in which the control system suggest next task to be run rather than running it automatically. The robot was operated and monitored from a container placed 100 meters from the installation site. A dome camera was used to give visual feedback from the installation to the operator.

The platform and pallet feeder described in Chapter 7 were used, see Figure 8-4 and Figure 8-5. A wheel loader was used to move the platform with the installation robot along the guide rails as the installation proceeded.

Logistics related to moving bentonite components was handled manually. The blocks were transported from the transfer station to the installation site with the help of a fork lift truck.

The pellet bed was placed by shovelling and thereafter levelled manually with a screed. The screed was provided with guides that fit onto the guide rails on the tunnel floor shown in Figure 8-2 and it was possible to create a flat pellet bed 100 mm over the nominal tunnel floor. The pellet bed just above the rails was however only 20 mm thick.

The pellet filling in the gap between the block stack and the tunnel wall was installed with a shot create equipment.

The major part of the installation equipment consists of solutions customized for the test, and is not representative for equipment expected to be used in the final repository. The installation robot and the feeding systems are prototypes and further developed equipment is expected to be used in the final repository. The use of a modular transporter to move the platform is also a special solution; the robot platform shall be self-propelled in the final repository. The robot platform was a prototype which will be subject for further development in order to fulfil the requirements in the underground facility in Forsmark.

***Figure 8-4.** Installation robot operating in the TASS-tunnel.*

Figure 8-5. *Robot platform with block feeding system and installation robot.*

8.3 Pre-test

A pre-test with concrete blocks was carried out prior to the real installation test. The aim of the pre-test was to verify that the equipment and installation process worked as intended after transportation of the equipment to the TASS-tunnel.

A 100 mm thick pellet bed was installed on the tunnel floor as described in Section 8.2.

The tunnel scanning equipment was tested and worked as intended. Communication between the backfill machine (backfill robot, platform and peripherals) and the operator room was tested. Some software problems occurred, but were fixed.

The platform was moved into the tunnel and placed on the rails. Problems occurred with the automatic levelling of the platform, since the support legs did not have a solid base due to the uneven tunnel floor. The levelling was finally performed manually.

Stacking of concrete blocks on the pellet bed was carried out. In total 257 concrete blocks were stacked. Stacking of the lower layers was done successfully. However, when building the upper layers it was noticed that the space between the robot and the tunnel roof was limited. Cables attached to the robot gripper got stuck in the support bolts and nets in the tunnel roof and had to be released manually, see Figure 8-6. The bolts were cut as short as possible and the net was fastened better to the tunnel roof after the pre-test to avoid problems in the installation test.

All planned installations and preparations were performed, and the pre-test showed that the equipment worked as intended on an overall level, after the adjustments performed.

The concrete blocks and pellets were removed and the TASS-tunnel cleaned prior to the installation test.

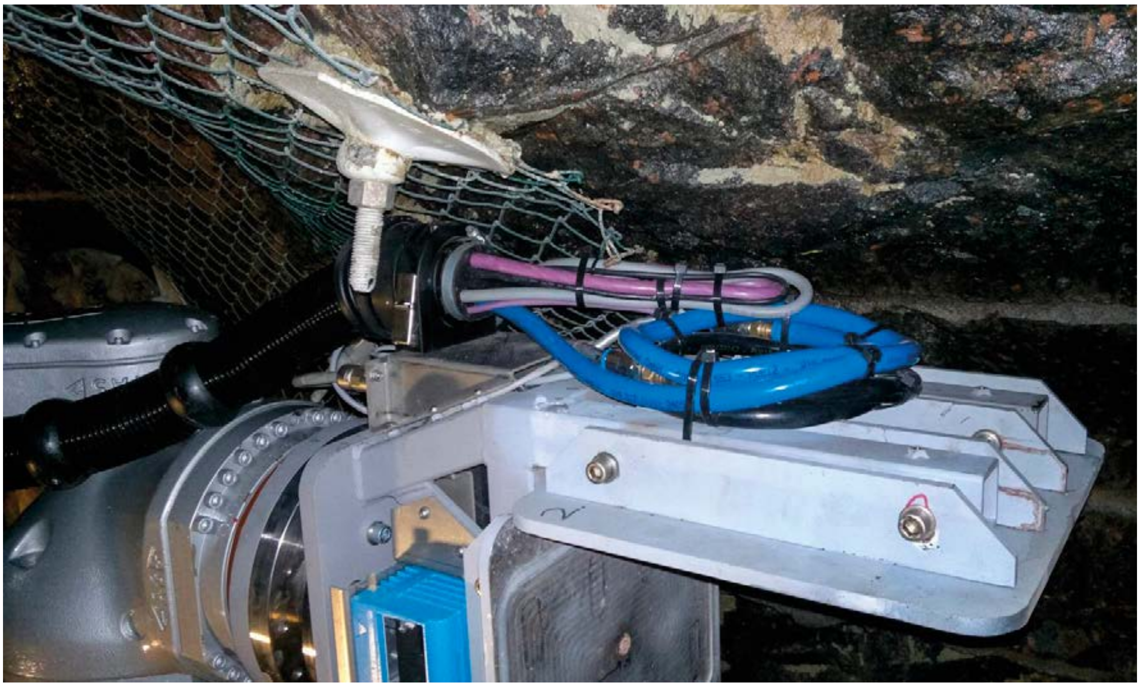

Figure 8-6. Robot gripper with cables that got stuck in support bolts and nets.

8.4 Installation test

The test was performed around the clock for nine days. Six people worked at each shift, one team leader, one robot operator, one machine operator and three people working with the transfer of blocks from the wooden pallets to the transport pallets and on to the pallet feeder.

A 100 mm thick pellet bed was installed on the tunnel floor as described in Section 8.2. The pellet bed was manually spread when the work position of the platform was changed. In total 12,513 kg of pellets were installed.

The robot platform was placed on the rails and the stacking of backfill blocks began. The robot platform was moved outwards of the tunnel as the backfill blocks were stacked. The working position of the platform was changed about 20 times in total. In total 1,684 blocks were installed.

The first part of the stack was built so that there was a gap between the tunnel face and the block stack of 100 mm minimum. A sufficiently large gap is needed to enable the installation of the pellets. The block stack was built one stacking layer at a time. The position of the first block in each stacking layer was determined by the measurement system. The sideways position of each stacking layer was decided based on the local tunnel profile. The stack built follows the shape of the tunnel, see Figure 8-7.

Pellets were installed in the gap between the tunnel walls and the block stack when the entire 12 meter stack was built. The pellets were blown into place using shot create equipment. In total 72,000 kg pellets were installed in the gap. In order to end the installation as a vertical standing wall made of pellets, water was added during the last part of the pellet installation.

8.5 Results

The aim of the test was to demonstrate that installation of backfill can be carried out as intended in a realistic environment. The test is regarded successful from that perspective.

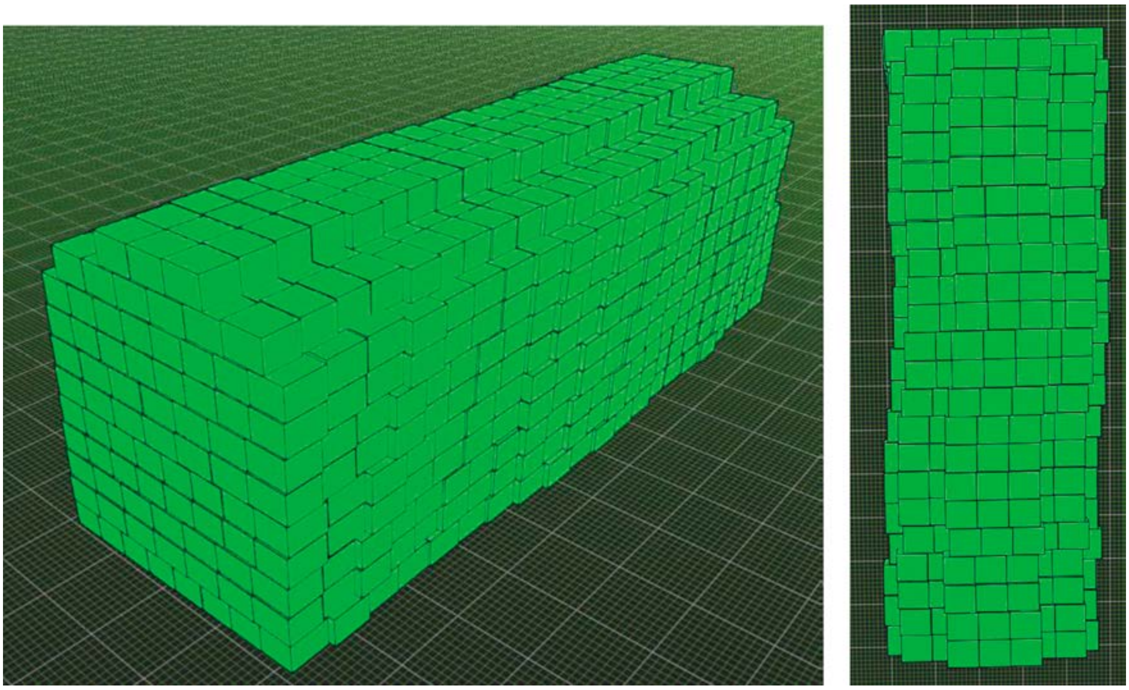

Figure 8-7. *Installed block stack reconstructed from logged process data.*

8.5.1 Block stack quality

The quality of the block stack is affected by many factors; accuracy of measurements, pellet bed quality, variation in size of backfill blocks and backfill block quality.

The specified maximum allowed volume fraction of slots between backfill blocks is 2% in average which means that the fill percentage should be at least 98% of the ideal stacking pattern. The fill percentage was evaluated based on the stored block position data from the backfill machine control system. The transversal fill percentage was estimated to be close to 100%. Due to angle differences between layers unacceptable large gaps were formed along the tunnel. The average gap between the blocks along the tunnel was about 15 mm and the largest gap 75 mm. The main parts of the gaps were smaller than 10 mm. The longitudinal fill percentage was evaluated to be about 97.5%. The gaps were a result of a combination of platform orientation measurement error and selected method for fixing the orientation deviation between the platform and the tunnel.

In the prerequisite it is stated that the free space between the block stack and tunnel walls should be ≥ 100 mm to enable pellet installation and protect the block stack form inflowing water. The transversal fill percentage was close to 100%, the gaps between the blocks varied from zero to a few millimetre due to uneven block surfaces and small settlings in the pellet bed. The prerequisite that the free space between the block stack and tunnel walls should be ≥ 100 mm was due to the gaps not fulfilled at all locations. No problems did however occur in the pellet installation.

8.5.2 Installed density

The average installed density was determined to 1,420 kg/m^3 based on the parameters in Table 8-1.

The achieved block filling degree was 71% calculated from the average block volume given in Section 8.2.2 and the average tunnel volume calculated from the amount of over break and stack length given above.

Table 8-1. Parameters used to calculate the average installed density.

Parameter	Value
Nominal tunnel area	19 m^2
Average amount of over break	16%
Stack length from the tunnel face	12.3 m
No of blocks	1,684
Average block dry mass	187.6 kg
Total mass of pellets	84,500 kg
Average pellet dry density	940 kg/m^3

8.5.3 Time used

The total time for installation of the backfill blocks was 89 hours including 10 hours for breaks, shift changes etcetera and 9 hours down-time caused by different problems, which are listed below:

- Problems gripping the block.
- Various software problems occurred, among others; failure in pallet measurements, software crash of the laser measurement program, stacking position problems and singularity point related problems.
- Operator caused errors.

In addition performance degradation was caused by the fact that the distance between the tunnel roof and backfill machine was smaller than required for the building of the upper layers, therefore many upper block layers were built with reduced speed.

After the actual stack building, the pallet change was the most time consuming operation, which consumed 10 seconds per block.

8.5.4 Block quality

As described in Section 5.4 manufacturing problems occurred due to larger stones and inhomogeneities in the bentonite material. This led to blocks with a larger variation in geometry and poorer quality, regarding cracks and inhomogeneities, than expected.

70 blocks were rejected at the block transfer station due to cracks or other visual quality problems; see Figure 8-8 for an example of rejected blocks. A few blocks were rejected since they were affected by water inflow in the storage tunnel.

The robot had problems at the gripping of 40 of the blocks due to cracks, inhomogeneities and larger pores. A wet sponge was used to wet the block surface of these blocks, which enabled the robot to install 30 of the blocks. The remaining blocks were rejected.

One block was dropped by the robot during the installation. This was caused by cracks or inhomogeneities in the block that made the vacuum gripper lose its grip. The block fell between the pallet and the robot and did not cause any further problems.

The standard deviation of the block height was 0.7 mm and the maximum accepted height deviation was ±2.5 mm. This variation in block height was regarded to be acceptable for stacking, causing no extra gaps in the stack.

8.5.5 Pellet bed quality

The inclination angles and the evenness of the pellet bed affect the quality of the block stack. The thickness of the pellet bed varied due to the blasted tunnel floor and due to the guide rails placed on the tunnel floor. The compressibility of the pellet bed was lower above the rails than at the side of the rails due to the different bed thickness. This led to that the outermost blocks tilted slightly against the tunnel wall and lower block stack stability was feared. This was not seen in the bed tests (presented in Section 4.5), probably since the thinnest pellet bed tested was 100 mm thick, compared

Figure 8-8. Examples of backfill blocks rejected due to cracks and missing pieces.

to 20 mm above the rails. To counteract the tilting of the block, the pellet bed was made with a slight U-shape, with a bed thickness of 110–120 mm above the nominal tunnel floor between the guide rails and the tunnel wall. However the U-shape of the pellet bed caused extra gaps between blocks and slowed down the stacking.

The inclination of the pellet bed along the tunnel axis changed stepwise as the platform was moved which resulted in extra gaps.

8.5.6 Pallet feeder

The pallet feeder worked almost without problems during the installation test. Once the pallet moved approximately 50 mm forward though, while the robot was building the block stack, despite the fact that a motor brake was installed to prevent this kind of incident. This resulted in the gripper colliding with the next block to be picked.

8.5.7 Measurement equipment

The block stack face was measured twice using a tachometry. The first measurement occasion was in the middle of the stacking procedure and the other after finishing the building of the stack. The tachometry measurements were compared to the logged process data from the robot measurement system. Overall the measurements corresponded very well, but there was a detectable angle difference in the final stack face indicating an error in the measurement of the platform angle.

8.5.8 Control system

The control system functioned well, handling many common problems. However the control system needed operator intervention and some trouble-shooting during the installation.

The levelling of the platform is based on levelling of the deposition machine for the KBS-3V system. Problems occurred in the control logic, caused by different types of hydraulic problems and the uneven tunnel floor.

8.6 Conclusions and recommendations for further work

The underground installation test showed that the prototype backfill robot is capable of building backfill as intended. The stack quality was good and the requirements should be achievable with modest improvements in the control system.

8.6.1 Assessment of requirements

Block stack quality

The longitudinal fill percentage was evaluated to be about 97.5% which means that the volume fraction of slots between backfill blocks is more than 2% in average. The gaps were a result of a combination of platform orientation measurement error and the selected method for fixing the orientation deviation between the platform and the tunnel. Improvements can be done and the fill percentage is assessed to be achievable with the current system.

The measurement errors of the platform orientation could be explained by misalignment of the laser scanner, erroneous codes or that the tunnel did not fully correspond to the CAD model used. The explanation to why the errors were not detected until after the test is inadequate underground preparations due to lack of time.

In the prerequisite it is stated that the free space between the block stack and tunnel walls should be ≥ 100 mm to enable pellet installation and protect the block stack form inflowing water. This was not fulfilled at all locations since small transversal gaps were formed between the blocks. This did not lead to any problems during the installation of pellets which can be explained by the gaps being at maximum in the lowest layer and decreasing for each layer. It is therefore suggested that this requirement should be revised.

Installed density

There are no numerical requirements specified for the density since the density required is dependent on the bentonite material. For Asha 2012 a dry density of about 1,280 kg/m^3 is required to fulfil the requirements on swelling pressure and hydraulic conductivity, see Figure 3-2 and Figure 3-3. The average installed density was 1,420 kg/m^3, the required density was thereby achieved with a margin in the installation test.

The required block portion of the deposition tunnel was > 60%, and the achieved block filling degree was 71%. If the over break in the tunnel had been 30% (maximum allowed over breakage) instead of 16% the installed density would have been 1,270 kg/m^3 and the achieved block filling degree 63%. The block filling degree still fulfils the requirement. The density requirement would not have been fulfilled, which is explained by the blocks having lower density than expected. The average block density is however expected to be higher for Asha in the final repository when the production process is further developed.

Time used

It is difficult to draw conclusions regarding the installation time for backfill installation in the final repository based on this installation test since prototype equipment and temporary solutions were used. In addition, manual intervention was needed and a sufficient transport system was lacking which also makes the installation time longer than in the real case. It is, however, assumed that the capacity requirement will be met when a fully developed installation system is available.

Deposition tunnel geometry

During the underground pre-test it was noted that cables belonging to the robot gripper got stuck in reinforcement bolts and nets, causing high risk for the equipment to suffer damage. This shows the importance of the requirement on the deposition tunnel geometry. It also shows that the gripper needs to be further developed and slimmed down.

8.6.2 Equipment

The platform used in the tests is a prototype built for testing the backfill technology and methods. In the further development of the platform avoidance of unnecessary robot movements should be considered. Easy access to the most critical parts of the equipment, among others to be able to change fuses and perform robot rebooting, should also be considered.

Pellets between the block stack and tunnel wall was placed using shot create equipment and dust occurred during the process. Alternative installation methods should be considered to avoid dust, since it will affect the performance and lifespan of the equipment for installation and measurement.

8.6.3 Tunnel floor

The test showed that it is important that the pellet bed is flat and have an even compressibility to achieve a high block filling degree. This is achievable with the design and equipment used today, but a flatter tunnel floor would make the thickness of the pellet bed more even and as a result the settling in the pellet bed will be smaller.

The prototype platform could not be run on the uneven floor in the TASS tunnel and therefore rails for the machine were mounted. The equipment used in the final repository will be mounted on a self-propelled base and rails will not be used.

8.6.4 Blocks

The bentonite material being inhomogeneous and containing larger stones led to poor block quality which led to problems in the installation process, this is undesirable. The material requirements have to be strengthened and the quality system further developed prior to commissioning of the final repository. Backfill blocks of considerably higher quality is expected in the final repository and these kinds of problems should be possible to avoid.

9 Backfill production system

This chapter describes the production of backfill components from the bentonite delivery to finished backfill blocks and pellets. Development of the backfill process description has been accomplished and the equipment needed for production of the backfill has been specified, and this is presented in *Basic engineering of backfill production* (Eriksson 2014).

9.1 Requirements

Following requirements have been identified for the production system:

- The production system should be able to produce the backfilling components needed for 200 deposition holes per year, which equals to approximately 200 tons of backfill blocks and 40 tons pellets per working day. (SKB 2010b).
- The material should be possible to transport pneumatically into the production building.
- The production system should be able to produce components according to the specification.
- The blocks should be protected from the variation in relative humidity that can occur in storage buildings and during transport.

9.2 Production process

The bentonite clay used in the backfill production process is mined in open pit mines. The bentonite is thereafter crushed and dried before it is transported by bulk ships to the harbour of *Hargshamn*. At *Hargshamn* the material is unloaded into storage buildings and delivery control is performed. Next the bentonite is crushed, and if needed, dried, before being placed in silos.

The bentonite is transported to the production site using bulk trucks which are unloaded into storage silos within the production facility. In the production building the bentonite is mixed with water to achieve suitable water content for block and backfill compaction. Finally blocks and pellets are produced and further transported to the repository. For an overview of the production process, see Figure 9-1.

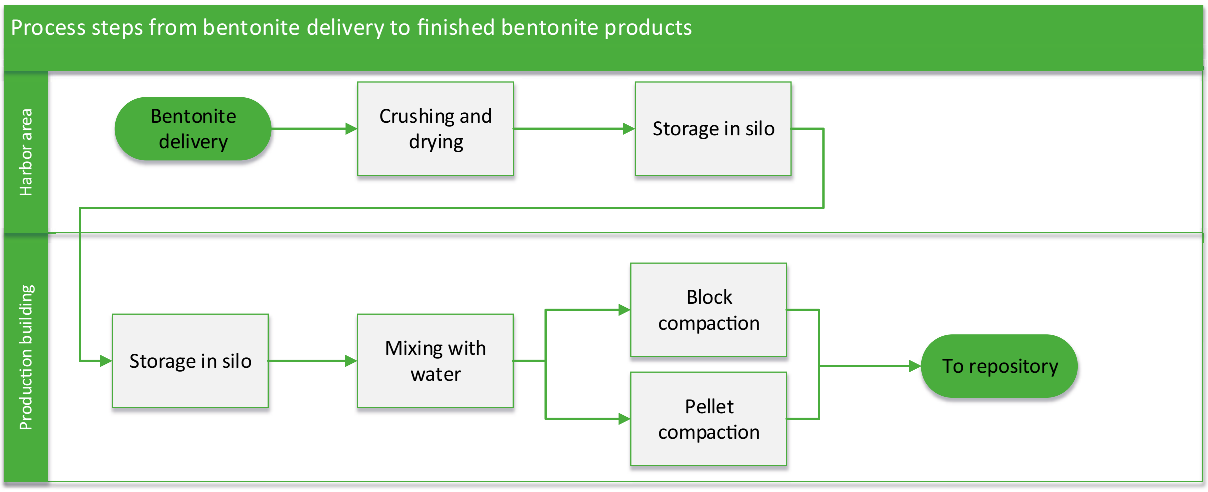

Figure 9-1. *Overwiew of the process steps from bentonite delivery to finished bentonite products.*

9.2.1 Storage

The bentonite will be stored in a storage building before being fed into the process. The capacity of the storage building should be dimensioned after the size of the ships that will be used for the bentonite transport.

9.2.2 Crushing and drying

The bentonite will be crushed into a granule size distribution suitable for block and pellet production. If the material has a water content higher than 12% it needs to be dried before placement in silos to enable transporting the material pneumatically.

Suitable equipment for drying and milling the material is a pendulum mill, also known as a Raymond mill. With this type of mill it is possible to blow hot air through the milled bentonite and thereby drying it at the same time. An example of equipment that could be used is MO-12 from Molars, which has a minimum capacity of 12 tonnes per hour.

9.2.3 Silos

The bentonite will be stored in silos both before transport to the production facility and within the production facility. The silos should be possible to load and unload pneumatically.

9.2.4 Mixing

Water is added to the material before production of blocks and pellets. This is done in a mixer where the bentonite and water are mixed to achieve a water content of approximately 20%. The exact figure is dependent on the material used.

An intensive mixer from Eirich has been proved to work well for mixing bentonite during test production at Äspö HRL. A suitable model is RV-24, with a capacity of 1.6 tonnes per batch, which equals to approximately 240 tons in 16 hours.

9.2.5 Block compaction

A hydraulic double pressure press has been used during test production of backfill blocks. This is a single-sided pressure system with an active mould, which makes it possible to produce compact and homogenous blocks.

The manufacturing of blocks with Asha-2012 material, described in Section 5.4, was associated with problems and the main part of the achieved blocks did not fulfil the required density. This is not expected to be a problem in the future production where the material will be better pre-processed. From a production perspective, the production worked well and indicated that the method is suitable for producing blocks with a high capacity.

The compaction cycle starts with filling the mould with bentonite to a predefined height and then vacuum is applied. The pressing cylinder (upper tool) is pushed down and the block is compacted.

The filling factor is defined as the ratio between the height before and after compaction. The filling factor has been determined for different types of bentonite and is between 1.42 and 1.78 (Sandén et al. 2014a). This means that a press with a stroke of at least 710 mm is needed for production of blocks with a height of 400 mm.

A suitable block press is Laeis HPF 1600 which can be bought with a stroke of 800 mm and equipment for applying vacuum. The press has enough force to compact blocks with a pressure of 56 MPa. The estimated cycle time for production of one block in the future production facility is < 2 min. This means that two block presses are required to produce 200 tons of backfill blocks in 16 hours.

The blocks need to be protected from the difference in moisture content between the blocks and their surroundings. This can be done either by wrapping the blocks in plastic, place them in airtight containers or by controlling the surrounding atmosphere.

9.2.6 Pellet production

Pellets can be produced either by extrusion or through roller compaction. Based on laboratory tests and installation tests extruded pellets are chosen to be the preferred pellet type for the backfill, see Chapter 4 for further details.

Extruded pellets have been produced at Äspö HRL using a pellet press from Amandus Kahl. The pellet press worked well after tuning of the production process. A suitable pellet press is therefore the one tested, Amandus Kahl Flat Die Pelleting Press 33-390, with a capacity to produce 40 tons pellets per day.

9.3 Conclusions

Time estimations of each process steps have been made in order to analyse the total capacity. The conclusion is that the required amount of backfill components can be produced with the equipment described above if two block presses are used and the process is running 16 hours/day (2 shifts).

Blocks and pellets that fulfil the specifications have been produced with prototype equipment. All equipment described in this chapter is standard equipment, hence a production system for backfill components can be built based on standard equipment and there is no need to develop special equipment.

The bentonite needs to be dried to enable pneumatic transportation. The pendulum mill is assessed to be able to dry the bentonite sufficiently.

10 Quality assurance and control

The main purpose of quality assurance and control is to control and verify that the backfill meets the requirements and hence function as intended in the final repository. It is important to control the quality in the entire backfill production chain to make sure that the production is reliable and that rejection of prepared backfill material and components is very low.

An overall quality management system for the KBS-3 repository is under development, with common principles for classification and quality assurance for all the systems in the KBS-3 repository. The development of a quality management system is an iterative process; the quality system will be detailed and updated several times before the commissioning of the repository.

A product mapping was carried out during the project "System design of backfill". Key parameters needed to verify that the requirements are met were identified in the product mapping. The product mapping was followed by a process mapping, in which activities, quality assurance measures and decisions that affect the quality of the backfill were identified. The most important activities, quality assurance measures and decisions are the ones that are related to requirements regarding the barrier function of the backfill, see Chapter 2. A summarized process mapping of the backfill installation is shown in Figure 10-1.

The product- and process mapping provides a basis for further development of a quality plan for the backfill. The quality plan is an important part of the quality management system and specify which processes and procedures that will be applied, by whom and when, to meet the requirements.

A large part of the quality management system is method descriptions for production and control and specifications for production and control equipment. Method descriptions are under development and will be detailed gradually.

To be able to further develop the quality plan the following is required:

- Detailed requirements and design criteria of the backfill.
- A bentonite supply strategy.
- A defined installation sequence and logistics for the canister, buffer and backfill installation.

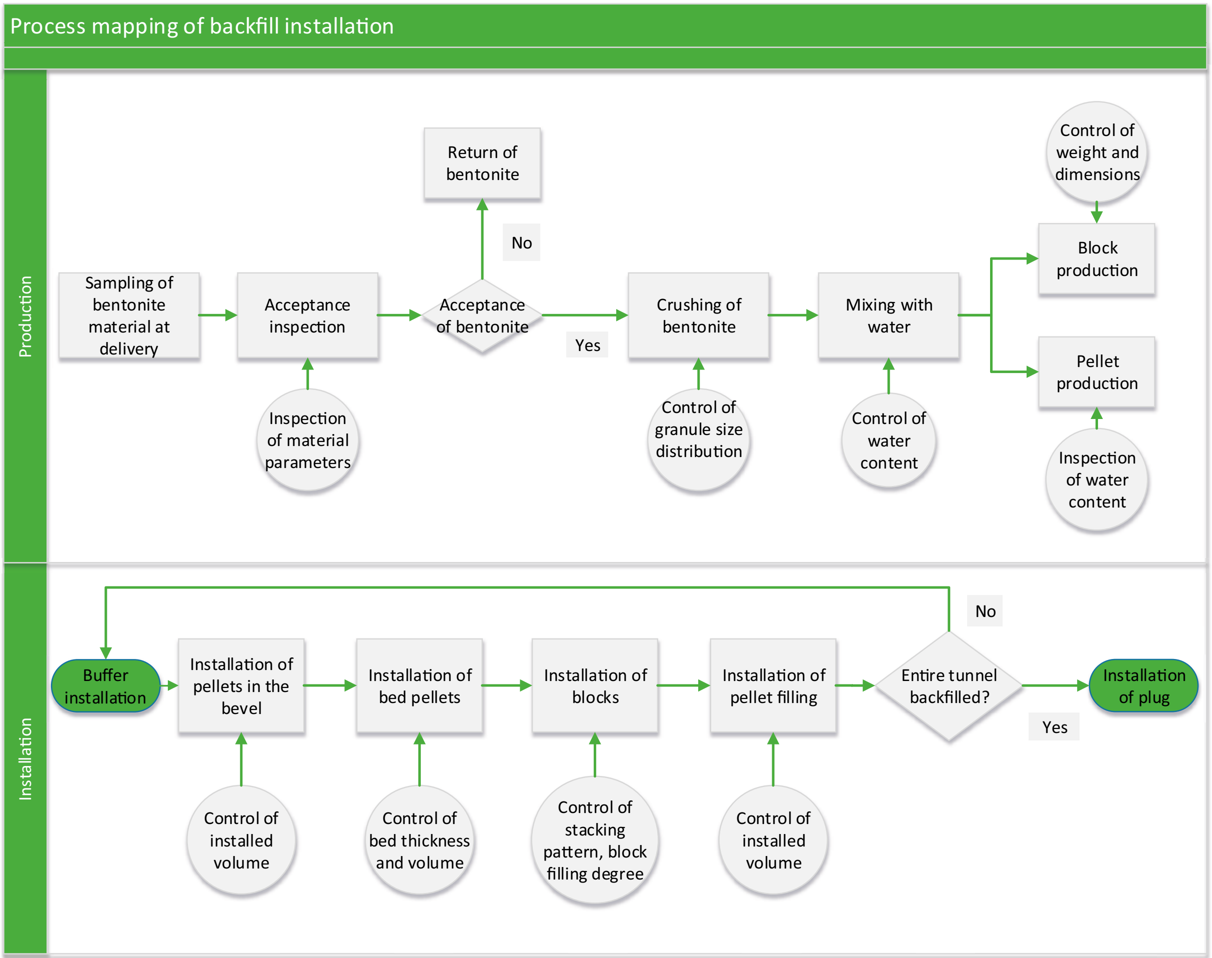

Figure 10-1. *A simplified process mapping of the backfill installation illustrating the most important activities (boxes), quality assurance measures (circles) and decisions (diamonds).*

11 Overall conclusions and recommendations for further work

Bentonite material

In SKB (2010b) the reference design for the bentonite material is specified using montmorillonite content; the montmorillonite content should be between 50 and 60% with an accepted range of 45 to 90%. This requirement was fulfilled for all the bentonites delivered. However, the hydro-mechanical tests indicate that the montmorillonite content alone is not enough to predict the hydro-mechanical behaviour of the bentonite. SKB needs to overlook the way the reference design is specified, to be able to predict the behaviour of the backfill in the KBS-3V repository.

Block quality

Brick size and full scale blocks were produced and laboratory investigations were carried out on the blocks. The requirements of high strength and smooth block surfaces free of cracks were fulfilled for the main part of the blocks. An overall conclusion from the block production test is that blocks with required density and dimensions can be produced and that a hydraulic double press is considered an applicable method for production of backfill blocks.

The tests showed that the water content, granule size distribution and material composition affect the strength of the blocks and the quality of the block surfaces. The production problems that arose, when pressing blocks with the Asha-material, highlight the need of well defined material specifications and the necessity to perform quality assurance. Laboratory tests are also necessary in order to fine tune the block production process. In a future production plant it will be necessary to have the possibility to adjust the water content (large mixers) and the granule size distribution (crushing equipment) of the delivered materials.

One main conclusion from the relative humidity tests is that, independent of the relative humidity (18 to 94%), the blocks will be possible to handle and install (lifting with vacuum tool) within 48 hours of exposure to this environment. In case of longer exposure, the manageability of the blocks can be affected, and hence it might not be possible to handle and install the blocks.

Pellets

Based on large scale tests and laboratory tests the 6 mm extruded pellets was assessed to be the one of the investigated pellet types that best meets the requirements regarding erosion, water storing capacity and durability during installation.

Pellet pressing tests have been performed and the overall conclusion is that pellet extrusion is considered an applicable and sufficiently robust method for production of bentonite pellets for the backfilling of the deposition tunnels. Tuning of the production process, especially identifying the optimal water content, must be performed for every new material.

Bed tests were performed and a conclusion from the bed tests is that a non-compacted pellet bed is applicable as foundation for the stacking of backfill blocks. A non-compacted pellet bed would simplify the installation process and should be considered. The ability of ta non-compacted pellet bed to restrict buffer expansion must however be further investigated before a new pellet bed design could be suggested.

Handling of water inflows

Different methods for handling water inflows into the deposition tunnels have been investigated. Pellets and geotextiles have been tested and are recommended for use in tunnels with a total water inflow less than 5 L/min and with a maximum water inflow rate to one 6 meter section of less than 1 L/min.

For higher inflow rates; > 5 L/min in 300 m tunnels or inflow rates of > 1 L/min in one 6 m section, it will be necessary to use other methods in addition to pellets and geotextiles. Different methods have been theoretically developed; macadam filled water storing sections, drainage through a bore-hole to an adjacent tunnel, local freezing and temporary plugs are assessed to be the methods with high potential that should be further studied.

Installation

The large scale installation test carried out in the TASS-tunnel at Äspö HRL showed that installation of backfill can be carried out as intended in a realistic environment. The shape and stability of the stack were satisfying. The requirement on installed density and fill percentage was fulfilled. The requirements on installation time should be achievable after further development of the system.

The shotcrete equipment used for installation of pellets has a relatively low capacity and bentonite dust from the pellets arose during installation. Alternative installation methods should be considered to increase the capacity and to avoid dust, since it will affect the performance and lifespan of the installation and measurement equipment.

Both the stacking tests in the laboratory and the full scale test showed that the basic stack building solution is viable. However, the overall functionality of the stacking equipment and control system are still elementary and require further development before a completely automated process can be achieved. One of the requirements is that the backfill shall be installed with high reliability and the tested method has potential for reliable installation. Another requirement is that the installation should be performed at prescribed rate, 6 meters of backfill per working day, this was not fulfilled with the system used during the large scale installation test. A fully developed and automated installation process would probably fulfil the requirement. One possibility that should be investigated to further reduce the installation time is the possibility to use larger backfill blocks.

According to the relative humidity tests, the blocks should not be exposed to the surrounding atmosphere for longer than 48 hours. The blocks can be protected for example by wrapping them in plastic, place them in airtight containers or by controlling the surrounding atmosphere. How the protection should be designed must be further investigated.

Suggestions on updated backfill design

The stacking pattern suggested in Chapter 7 has been tested and is assessed to give a stable block stack with sufficient block filling degree. It is suggested that the stacking geometry and block geometry in SKB (2010b) is updated with the stacking pattern and block geometry suggested in Chapter 7. It is also suggested that the backfill design is updated with the recommended pellet type; extruded pellets with a diameter of 6 mm.

The design of the bottom bed needs to be further investigated before an updated design could be suggested.

Further work with requirements and specifications

In SKB (2010b) the reference design for the bentonite material is specified using montmorillonite content only. SKB need to overlook the way the reference design is specified, to be able to predict the behaviour of the backfill in the KBS-3V repository.

In SKB (2010b) it is stated that the amount of potentially harmful substances sulphide, sulphur and organic carbon should be determined. No threshold values have however yet been defined regarding the content of these substances.

The specification of bentonite material ready for manufacturing of blocks and pellets needs to be further detailed in order to obtain a reliable production process.

In SKB (2010b) it is stated that the free space between the block stack and tunnel walls should be ≥ 100 mm to enable pellet installation. Based on the installation tests it is suggested that this requirement is revised.

The requirement on the deposition tunnels imposed by the backfill must be further investigated. A flatter tunnel floor would make a more uniform height of the pellet bed and result in smaller settlings in the pellet bed.

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