D1.3 BEACON
Bentonite Mechanical Evolution

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WP1.3 Final Assessment Report

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1 Introduction

The 'Beacon' (Bentonite Mechanical Evolution) project addresses key technical issues that must be tackled in order to support the implementation of planned geological disposal projects for high-level radioactive wastes across the EU. The overall objective of the project is to evaluate the performance of an inhomogeneous bentonite barrier for the entire evolution of it i.e., from an installed engineered system to a fully functioning barrier.

An increased understanding of material properties and fundamental processes that lead to homogenization as well as improved capabilities for numerical modelling were required to achieve the project goals. The output allows for a verification of the performance of current designs for buffers, backfills, seals and plugs and an improved handling of mass losses in long-term assessments.

Part of the project activities was to develop and test the tools necessary for the assessment of the mechanical evolution of an installed bentonite barrier and the resulting performance of the barrier. For some repository designs, mainly in crystalline host rock, the results can also be used for the assessment of the consequences of mass loss from a bentonite barrier on the long term.

The driver for this project is repository safety, and the demands of waste management organizations to verify that the material selection and initial state design fulfil the long-term performance expectations. For this project, the initial state refers to the period during installation of the barrier, while long-term performance refers to the period for barrier saturation and evolution of the hydro-mechanical properties, which could range from 10's to 1'000 s of years. In current and future applications for repositories, the regulators will expect the applicants to have a sufficient predictive capability of the barrier evolution from the installed to the final state.

A part of Beacon has been focused on direct application to real assessment cases in actual repository systems. A few cases from relevant repository systems have therefore been selected as test examples. The systems to be evaluated in Beacon include three cases: 1) a tunnel plug based on the Andra design, 2) a disposal cell from the Nagra concept, 3) the KBS-3 deposition tunnel backfill. These are representative of the primary areas of uncertainty in density homogeneity. These examples cover a broad range of issues, and the results should also be applicable to other concepts and systems.

One objective of this report is the syntheses of the findings in the frame of the 3 assessment cases within the Beacon project. It reports the modelling results from the different groups assessing the HM evolution of the three assessment cases and evaluates these results in view of the respective safety case. It summarizes the lesson learned from the different work packages leading to recommendations on the implementation of bentonite-based barriers.

In the last chapter requirements are formulated on the assessment of the performance of bentonite-based barriers. Since the safety-relevant performance of the bentonite is mainly defined by its chemical, mineralogical and physical properties, comprehensive sets of requirements regarding the chemical, mineralogical and physical characteristics of bentonite have been developed by the different waste management organizations for their concepts. In most cases, these requirements assume a bentonite density as a boundary condition for the requirement to be fulfilled.

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In the framework of WP1, the needs of safety assessment regarding the evaluation of nonhomogeneous backfill properties are addressed, in particular to what extent non-homogeneous material property distributions comply with safety requirements. The outcome is a (hydro)-mechanical assessment of the case studies, given a range of uncertainties in the boundary conditions based on empirical and numerical evidence, that, based on a probabilistic approach, would ultimately result in a set of requirements under consideration of the host rock and the repository design. For this work package, three case studies were defined:

- the Andra tunnel plug
- the Nagra disposal cell
- the KBS-3 deposition tunnel backfill

Based on the outcome of the assessment cases and the evaluation method and uncertainties, the end-user may formulate design-specific requirements that can be used for the safety case in a final workshop.

The present report was compiled with the answers to a questionnaire that was distributed to the different WMOs or their representatives. The questionnaire aimed at reflecting the state-of-the-art regarding the treatment of heterogeneous bentonite density distribution and properties in the safety case.

1.1 Rationales of the Beacon project

Developing predictive capabilities of the mechanical behaviour of bentonite buffers, seals and backfills are a common need for all radioactive waste management programs that use bentonite in engineered barrier system (EBS) components. Because of the complexity of the objectives networking at European level is key for the development of an integrated system understanding, skills, training and capabilities.

Beacon aims at the development of understanding fundamental processes that lead to material homogenisation, as well as improved capabilities for numerical modelling. In earlier assessments of the long-term performance of bentonite EBS, the mechanical evolution of the installed bentonite was often neglected, and an "ideal" final state was optimistically assumed.

In order to verify the performance of current designs for bentonite barriers the following were undertaken:

1. a well-documented and communicated collection of the available knowledge prior to the project
2. re-evaluation of a large part of the existing database to extract the important information, to compile the qualitative and quantitative observations and to develop the conceptual understanding
3. enhanced, robust and practical numerical tools firmly grounded on a good conceptual understanding, which has the required predictive capabilities concerning the behaviour of engineered barriers and seals
4. a complete experimental database for the need of the assessment models
5. verified models based on experimental results from experiments in different scales
6. workshops dedicated to the mechanical issues in bentonite open to the scientific community as well as civil society

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The Beacon project is needed for the pan-European aims at building confidence amongst regulators and stakeholders regarding the performance of safety barriers in a geological repository. It is also cost- and time-effective to progress development of understanding regarding bentonite behaviour in a collaborative manner, and the sharing of precedent information enhances efficiency of overall process.

1.2 Objectives of the report

In the framework of WP1, the needs of safety assessment regarding the evaluation of nonhomogeneous backfill properties are addressed, in particular to what extent non-homogeneous material property distributions comply with safety requirements. The outcome of this work package is a (hydro)-mechanical assessment of the case studies, given a range of uncertainties in the boundary conditions based on empirical and numerical evidence, that, would ultimately result in a set of requirements under consideration of the host rock and the repository design.

The purpose of this report is to utilize all results produced in the Beacon in the context of a safety case. The key questions that should be answered are:

1. What is the probable final heterogeneity in a bentonite barrier?
2. How well can we predict this heterogeneity?
3. What are the main uncertainties regarding this prediction?
4. Will the heterogenous barrier still fulfil its assigned safety functions with acceptable margins?

1.3 Structure of the report

The structure of the report broadly follows the way the project was structured into work-packages as shown in Figure 1-1.

In Chapter 1 a short introduction is given to the Beacon project and to the objectives of the present report. Chapter 2 lists the different requirements the WMO's have regarding the bentonite homogeneity depending on its application and the repository specificities. In Chapter 3 a review of laboratory-scale up to large-scale experiments is given. In Chapter 4 the lessons learned from the development of constitutive models for the description of the mechanical, hydromechanical (HM) and, optionally, thermo-hydro-mechanical (THM) behaviour of bentonite-based materials with the aim of introducing them into numerical tools capable of analysing problems of engineering significance are being reported. Chapter 5 provided input data and parameters for the development and validation of hydro-mechanical models to describe more accurately bentonite dry density homogenization. Chapter 6 introduces the assessment cases from the three WMO's Andra, SKB and Nagra. Chapter 7 provides a synthesis of the results obtained by the different groups from the assessment of the "assessment cases". Chapter 8 provides an evaluation of the modelling results with respect to the safety relevant properties for the specific use of bentonite.

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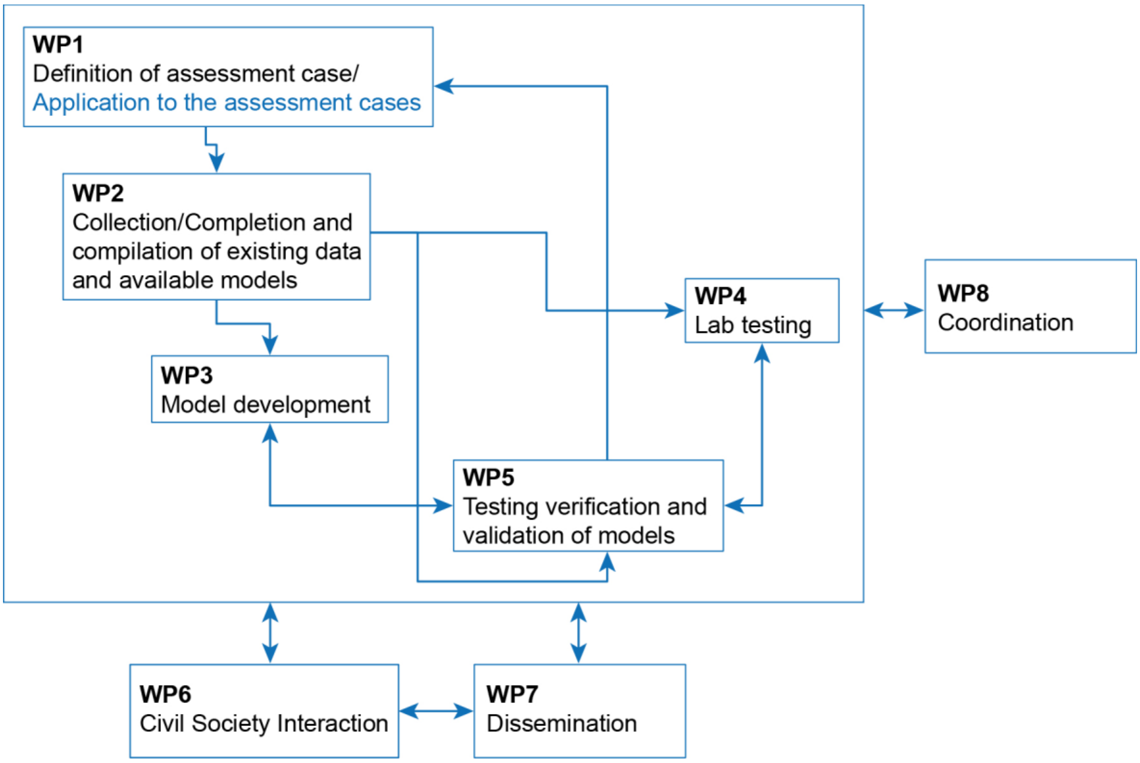

Fig. 1-1: The Interconnections between the work packages in Beacon
The present report synthesis the results obtained in WP1-5.

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2 Derivation of requirements for the assessment of heterogeneity of bentonite based buffers, backfills and seals

2.1 Introduction

The sealing ability is a crucial safety function for bentonite barriers in all geological repository concepts. Sealing is achieved by the combination of a high swelling pressure and a low hydraulic conductivity. The swelling pressure will ensure self-sealing, but may impact the other barriers in the repository as well. The low hydraulic conductivity ensures that transport of dissolved species by advection will be very limited. The hydro-mechanical properties of the installed EBS, that will consist of a combination of blocks, pellets and voids, will be completely different from the final state after full saturation. It is therefore crucial to consider:

- the mechanical evolution during the saturation phase
- the final state at equilibrium

A firm understanding of the mechanical evolution is necessary to ensure that a given design will meet the expected performance targets.

In some repository concepts there are also other safety functions that are related to the final homogeneity of the barrier. These include colloid filtration, limitation of microbial activity and mechanical support for host rock, liners and disposal containers.

2.2 Safety functions

In IAEA Safety Glossary (IAEA 2007) safety function is defined as a purpose that must be accomplished for safety. Safety refers to nuclear safety and protection and safety, whose common purpose is to protect people and the environment against harmful effects of radiation. In final repositories, radiation safety shall be maintained by a system of passive barriers.

In different national programs the term safety function may be defined and applied a little different, but in general it refers to a function that contributes to isolation from the surface environment to containment of radionuclides and/or to retention of them, and to retardation of their dispersion into the environment, either directly or indirectly by protecting the barriers in the repository. A detailed and quantitative understanding and evaluation of repository safety requires a more elaborated description of how the main safety functions of containment and retardation are maintained by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to containment and retardation can be identified. In this context, a safety function can be defined qualitatively as a role through which a repository component contributes to safety. In order to quantitatively evaluate safety, it is desirable to relate the safety functions to measurable or calculable quantities, often in the form of barrier conditions. In order to determine whether a safety function is maintained or not, it is desirable to have quantitative criteria against which the safety function indicators, or performance targets, can be evaluated over the time period covered by the safety assessment.

For bentonite barriers, buffers backfill and seals, the safety functions can often be expressed in swelling pressure and hydraulic conductivity. Swelling pressure and hydraulic conductivity can normally be expressed in terms of dry density of the bentonite material. The quantitative values that the safety function for the bentonite barrier should fulfil is strongly related to the actual application and to the environment. This may be very different between different national programs. Another key issue is the scale on which the safety function should be evaluated. Hydraulic properties are important on a local scale, at least as long as there is a continuous path.

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Microbial activity will also occur on a local scale. The self-sealing ability is, at least to some extent, local. Mechanical support for host rock and containers may on the other hand be dependent on the global properties of the bentonite barrier.

2.3 Design requirements

Design requirements are often defined as a characteristic of an engineered barrier or underground opening that shall fulfilled to be approved as a part of a repository. The design requirements must be technically achievable and possible to verify at the latest at the time of final installation, deposition or backfilling. Verification can be achieved by testing of finished parts or components, or by measuring or controlling process parameters related to the characteristics of importance for requirement compliance.

Any assessment of the post-closure safety is based on a design, which depending on the stage of development can be outlined, proposed, expected or built. The design cannot be directly determined from the main safety functions. The barrier specific safety functions together with the repository conditions and the expected evolution of the repository form the basis for the development of design requirements and a design with characteristics that are potentially capable of maintaining the safety functions in a long-term perspective. It is rather obvious that this is an iterative process. In an early stage of a repository program, a repository design needs to be assumed. A safety case will show whether this design is sufficient to fulfil the safety functions. The safety case will also identify the largest uncertainties regarding the design. A repository engineering program will investigate whether the design can be built on an actual site. This process altogether will define requirements for the individual barriers and possibly also update the actual design.

For bentonite barriers the design requirement can normally expressed in installed dry density. The dry density can be monitored during installation through measurements of the excavated volumes and installed dry mass. The installed dry mass is a function of the weight of the installed material and a knowledge of the water content. There are however many different options how the bentonite material can be installed: e.g. in-situ compacted powder, granules, pellets or blocks. There will also most likely be engineering voids in the system.

2.4 Relation between safety functions and design requirements for bentonite barriers

Safety functions for individual barriers should be maintained for very long-time scales. For bentonite barriers this is usually equal to the intended service life of the repository. Design requirements, on the other hand, are only relevant during the operation of the repository. However, the design requirements need to be defined in a way that the safety functions are fulfilled.

The safety functions for a bentonite barrier are, with few exceptions, defined for a saturated state. The technical design requirements may be defined as an average property (density) for the entire barrier or(and) as properties for each specific barrier component. It is therefore necessary to understand the evolution from the installed barrier components to the saturated barrier in order to evaluate the performance of the barrier.

2.5 Verification of safety functions

In the perspective of a repository for long lived radioactive waste, the saturation of a bentonite barrier occurs on a relatively short timescale. It may therefore be possible to verify the evolution and the performance through full scale field experiments. A number of large field test are listed

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in the WP2 deliverable D2.2 (Thatcher et al. 2017). The drawback with field test is that they are only representative for the initial and boundary conditions under which they have been performed.

The limitation of large-scale experiments makes it necessary to have predictive models that can describe the evolution of the properties of the bentonite barriers from "the installed state" to a "saturated state". The input to the models should be the design specification, including uncertainties, and the site properties, also including uncertainties. In this aspect uncertainties include variability and tolerances. The output should be the final state of the barrier, preferably expressed in distribution of dry density and evolution of stresses.

The results from the models can then be compared with the indicators/targets for the safety functions to check whether they are fulfilled. The key parameter to check is the dry density, which has a direct relation to the swelling pressure and the hydraulic conductivity. If the targets for the safety functions are fulfilled, the barrier can be assumed to perform according to specification in the safety assessment. If not, the implications of an unfulfilled safety function need to be considered in the assessment. This may be, for example, that advective transport needs to be considered in the barrier. It should be noted that a failed safety function for an individual barrier may not mean the safety of the repository is compromised. This should also lead to feedback to design and engineering in order to improve the design criteria to match the safety functions. In the case where the safety functions are fulfilled it is important to evaluate the influence of the uncertainties. Are there conditions where the safety functions can be breached? There is also the approach to margins that should be considered. The homogenization occurs relatively early in the repository evolution, while the safety functions should be fulfilled for longer timescales. Finally, there is the uncertainty regarding the modelling itself. Based on the results from the Beacon project, it is clear that the modelling of the mechanical evolution of a bentonite barrier not always is an easy and straightforward process. How much trust can be put into the modelling activity? All these aspects will be discussed further in this report.

2.6 The consequences of mass loss

Mass loss of material from an installed bentonite barrier may occur during the repository evolution. This is mainly an issue in fractured rock where bentonite may be transported away by mechanical erosion during the period with large hydraulic gradients, or by chemical erosion during periods with ingress of dilute waters. A loss of mass means that the remaining barrier needs to expand into and fill the generated cavity. The basic processes involved are the same as for the homogenization of the installed barrier components. The boundary conditions may however be slightly different: the material may be saturated to start with, and the mass loss is a continuous process. The homogenization after a mass loss has not been studied explicitly within the Beacon project and the process will not be discussed further in this report. It should however be possible to use the same type of models for this process as the ones used for the homogenization of installed barrier components.

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3 Lessons learned from WP2

3.1 Background

Prior to the Beacon project, a large number of experiments have already been carried out to study the mechanical properties of bentonite. Some of these experiments have been modelled (to a greater or lesser extent), others haven't.

A significant proportion of the experiments have been carried out at the laboratory scale and there are also quite a number of experiments conducted at a large scale in Underground Rock Laboratories (URLs). There are a smaller number of mock-up tests (i.e. larger scale lab tests). Experiments at both the laboratory and field scale have been carried out on a range of types of bentonites. There are a wide range of motivations for carrying out the reported experiments. Some recurring themes are:

- experiments that aim to characterise the bentonite e.g., by determining swelling pressure, water retention curves, looking at microstructural changes
- experiments that consider how bentonite hydrates/resaturates at a range of scales
- experiments that consider gas flow in bentonite
- experiments that consider homogenisation of bentonite properties
- experiments that demonstrate of the viability of repository concepts

Most of the experiments have some spatial heterogeneity in bentonite dry density, whether that is in the initial set-up, with mixtures of blocks and pellets or with voids into which the bentonite could swell, or in the data showing that the bentonite developed heterogeneous properties during the experiment. In particular, all the field scale tests show heterogeneous bentonite properties.

The purpose of the WP2 report was to summarise understanding of the processes affecting homogenisation of bentonite in a repository environment and to compile available information about experiments that have been carried out to date. This report has been a very valuable source of information for the selection of validation tests in WP5.

Experimental results may however also be of interest for a direct support for the safety case. This is especially true for large scale tests. Four examples of these types of tests will be discussed in this section. Three of them has been used as validation cases in Beacon (see Chapter 6).

3.2 Tunnel backfill in the Prototype repository

Summary of the test

Prototype Repository is a large-scale test installed at Äspö. The test consisted originally of six full-scale deposition holes in the TBM-tunnel, depth 450 metre. Each deposition hole is installed with full scale bentonite buffer (MX-80) and full-scale canister. The canisters are equipped with heaters to simulate heat from a canister containing spent nuclear fuel. The test is divided into two sections, in which the inner section (Section I) consists of four deposition holes and the outer section (Section II) consisting of two deposition holes all installed with buffer and canister, see Figure 3-1.

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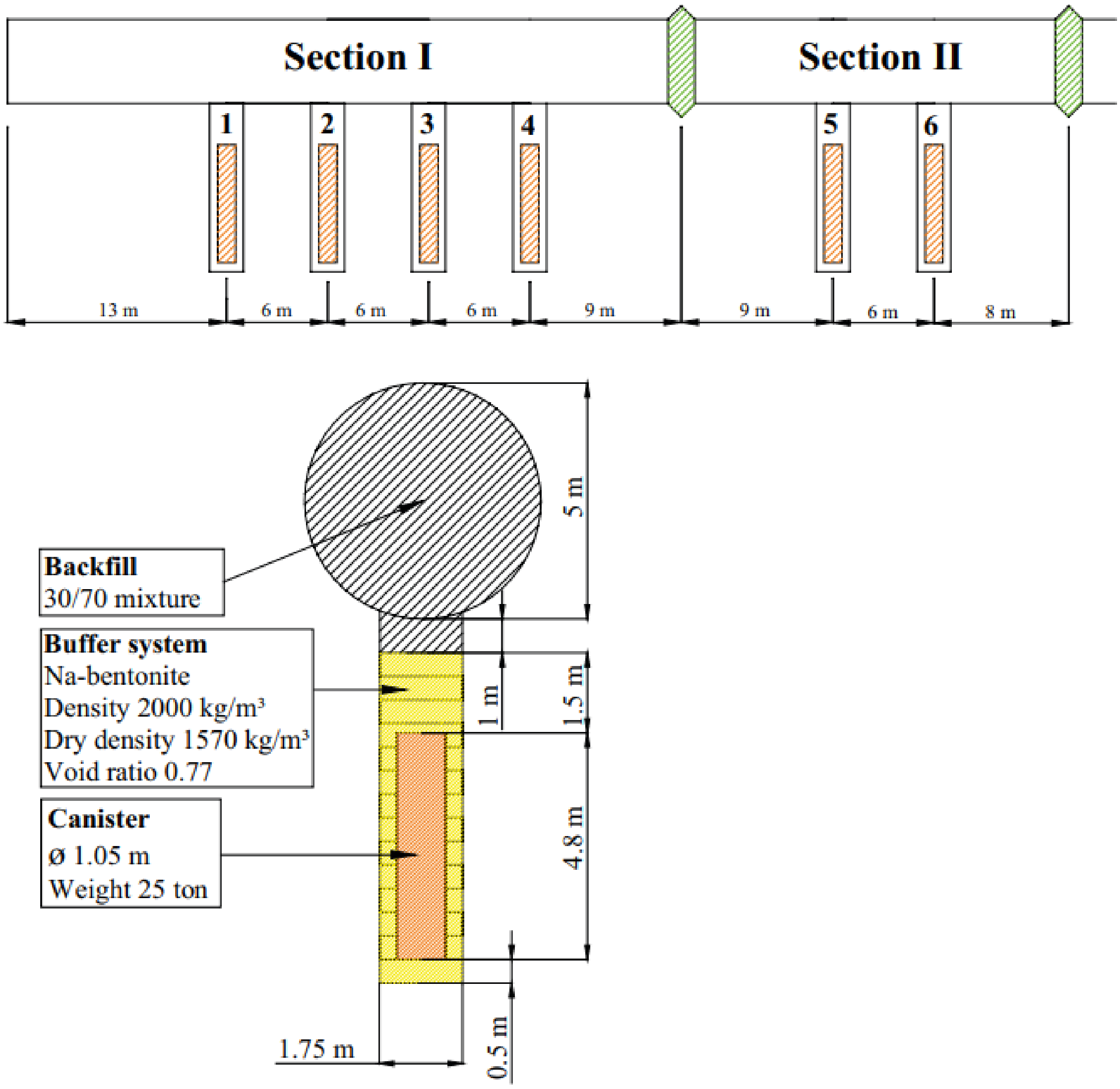

Fig. 3-1: Schematic drawing of the deposition tunnel and the deposition holes of the Prototype Repository
Johannesson (2014)

The installation of buffer, canister with heater, packing of backfill, and also the making of concrete plugs was done during the autumn of 2001 for section I. Corresponding installations for section II were made during the spring and autumn 2003. Heating of the canisters in the two sections was started successively after filling of the tunnel had reached the deposition holes. The heaters in canister 1 were activated October 3, 2001 and respective heaters in canister 6 were activated on May 23 2003. The plug in Section II was completed October 11, 2003. The buffer around canister no 6 was removed during the period April – July 2011 and the buffer around canister no 5 was removed during the period September – December 2011. The removal of the backfill was done during two periods, February – Mars and July – August 2011. At the removal of the buffer and backfill samples were taken for further analyses in the laboratory. The purpose with the investigation was to determine the distribution of the water content and density of the buffer and backfill at the retrieval of the test.

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The backfill was designed to provide a tunnel fill that would contribute to tunnel stability, hold the bentonite around the canisters in place, prevent or limit the flow of water around the canister positions, not cause deterioration of the quality of the groundwater, and remain chemically stable over a long time. It consisted of well mixed 30% by weight commercial Milos soda activated bentonite, and 70% by weight SKB-produced crushed TBM muck from the Äspö HRL ramp.

In the Prototype Repository the 30/70 mixture was compacted in situ in 10 cm thick horizontal layers in the upper parts of the deposition holes and, in 20 cm thick layers at an inclination of about 35°, in the tunnel (Johannesson et al. 2004). In the deposition holes an ordinary road construction vibrator was used for compaction, while in the tunnel specially designed vibrating compactors were used, one at the roof and one on the slope, both mounted on a boom that gave access to the whole roof and slope areas, see Figure 3-2.

Fig. 3-2: The roof compactor (left) and the slope compactor (right) during compaction
Svemar et al. (2016)

The density and water content were measured in situ in both the deposition holes and in the tunnel. Samples for determining water content were taken as well. For most of the density measurements a nuclear gauge was used. A penetrometer was used where it was not possible to use the nuclear gauges, i.e. close to the roof and walls of the tunnel. The measured average dry density was 1'830 kg/m^3 above deposition hole No. 5 and 1'770 kg/m^3 above deposition hole No. 6 (Johannesson et al. 2004).

The samples taken during removal of the backfill were sent to the Äspö Geolaboratory on the surface at the Äspö HRL with the objective to determine water content and density under known and controlled atmospheric condition. The determination of the water content and density of samples taken from the backfill was made within 48 hours after the sample had been taken from the site in order to minimize the risk of drying the sample and changing its water content and density.

Dry density and degree of saturation of the backfill in the tunnel were calculated with the data from the measurement of water content and density. About 100 determinations of water content and density were made in each of the eleven investigated sections of the tunnel. The results were plotted as contour plots, as shown in Figure 3-3 for Section No. 9. The plots indicate that the backfill had a low density and high-water content close to the rock surface, especially close to the roof. The plots of the degree of saturation indicate that there were some spots which had a divergent value compared to surrounding parts.

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The dry densities measured close to the roof were low (< 1'000 kg/m^3), see the example in Figure 3-3. This low density was not expected from the determinations made during the installation, because the density could at that time only be measured as close as about 0.5 m from the tunnel wall. It is therefore possible that the low density close to the roof also was present at the installation. No evidence of piping and erosion was observed in any part of the backfill at the retrieval. When comparing these results with the required properties in a final repository it is obvious that the Prototype Repository material, installed with in situ compaction technique, did not meet the minimum dry density criterion of 1'850 kg/m^3 for providing a sufficiently high swelling pressure and low hydraulic conductivity.

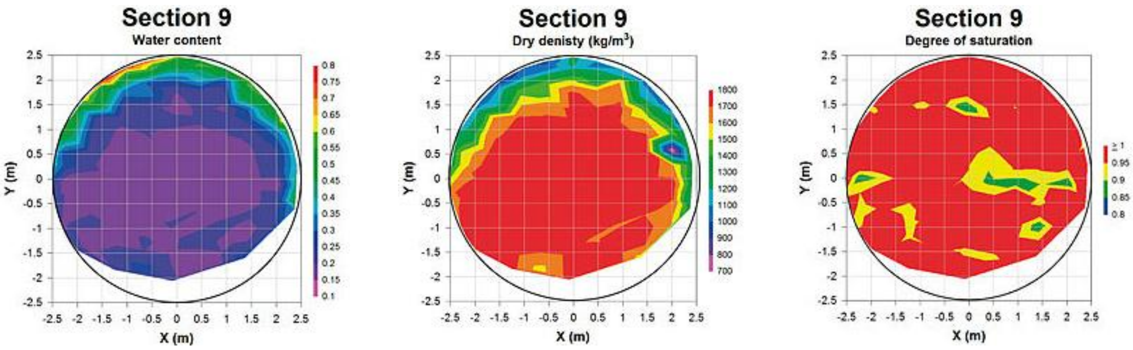

Fig. 3-3: Measured water content, dry density and degree of saturation of the backfill material in section No. 9, at approximately 5 m from the inner plug
Svemar et al. (2016)

Feedback to the safety case

At the time for the installation of the prototype repository, the requirements to fulfil the safety functions were expressed as a minimum dry density in the backfill with the following result for a 30/70 mixture of MX-80 bentonite and crushed blasted rock (Johannesson & Nilsson 2006):

- required dry density of 1'850 kg/m^3 in order to yield a hydraulic conductivity of 10 – 10 m/s
- required dry density of 1'800 kg/m^3 in order to yield a swelling pressure of 200 kPa
- required dry density of 1'700 kg/m^3 in order to yield rheological properties that limit the expanded buffer to a minimum saturated density of 1'950 kg/m^3.
- All requirements need to be fulfilled, which means that the dry density of the backfill in this particular case should have been at least 1'850 kg/m^3.

No predictive modelling of the homogenisation of the backfill material was done. At the time, it was assumed that the in-situ compaction would yield a rather homogeneous density distribution at installation and that this would be maintained after saturation.

As seen in the previous section, the installed backfill density did not fully reach this target. The density distribution after excavation shown in Figure 3-3. Clearly demonstrates that the backfill in the Prototype Repository would not fulfil the assigned safety functions. The density in the upper part of the tunnel was only around 1'000 kg/m^3 This was the case even though the achieved density at installation was assumed to be close to sufficient. The reason for the failure is either that there were density gradients present already at installation, or that the backfill material segregated during the saturation process. Whatever the reason, the results showed a non-

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conforming backfill. At the time of excavation of the outer section of the Prototype Repository the concept of in-situ compacted mixtures of bentonite and crushed rock as backfill has already been abandoned by SKB, due to the large uncertainties regarding the performance. The results from the excavation regarding dry density distributions was however even worse than what was expected.

This demonstrates the importance of field scale test to confirm the performance of a repository concept. Neither the monitoring during the installation, nor the modelling performed at the time, could detect the poor performance of the tunnel backfill.

3.3 EB - Engineered Barrier Emplacement Experiment

3.3.1 Summary of the test

The EB experiment (Engineered Barrier Emplacement Experiment) was full-scale demonstration of the use of Granular Bentonite Material as clay barrier and was dismantled after almost eleven years of operation. The experiment was carried out in a gallery excavated in the Opalinus clay of the Mont Terri Underground Research Laboratory. A dummy canister (in this case without heat production) was placed on highly compacted bentonite blocks and the remaining space was backfilled with pure granular bentonite buffer. The chosen bentonite is a predominantly divalent bentonite originated from Serrata de Nijar in Spain. To accelerate the saturation process of the buffer, an artificial hydration system was installed.

The objectives of this experiment (Mayor et al. 2007) were to

- define a buffer material and demonstrate its production at semi-industrial scale
- characterize HM properties of the buffer
- design and demonstrate the emplacement and backfilling technique
- assess the quality of the buffer after emplacement
- characterize the excavation damaged and/or disturbed zone in the rock and determine its influence on the HM behaviour of the system
- investigate the evolution of the HM parameters in the buffer and the EDZ as a function of progressing hydration
- develop a HM model of the complete system

3.3.2 Construction

A new niche was excavated for the experiment in 2001, and geophysical and hydraulic measurements were performed for EDZ characterisation. Afterwards, the bentonite blocks and the dummy canister were emplaced. A hydration system consisting of a pipe system of 37 pipes (Figure 3-4) and sensors for buffer monitoring in different cross sections were installed. Finally, the granular buffer was emplaced using an auger system which had proven to be the most suitable technique, and the experiment setup was sealed off with a concrete plug (Mayor et al. 2007). The bentonite blocks had a dry density of 1.69 g/cm^3 and an initial water content of 14%. The dry density of the granular backfill as determined from the total mass emplaced and the total available volume amounted to an average of 1.36 g/cm^3. Preceding laboratory tests had shown that at full saturation, hydraulic conductivities in the range of 10^{-12} m/s and a swelling pressure of about 1.3 MPa could be expected for such a dry density value (Mayor et al. 2007). total of about 19 m^3 were injected until June 2007. Afterwards, the buffer was only subject to further natural water

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uptake from the surrounding Opalinus Clay until October 2012, when dismantling of the experiment started. The evolution of relative humidity as an indicator for suction/saturation in the buffer was monitored in different cross sections. As an example, Figure 3-5 shows the results in cross section B1. One year after start of water injection the granular buffer can be considered almost fully saturated, in the sense that relative humidity reached 100%, which means suction has disappeared. Only one sensor (WB1/2) takes longer to reach 100% humidity

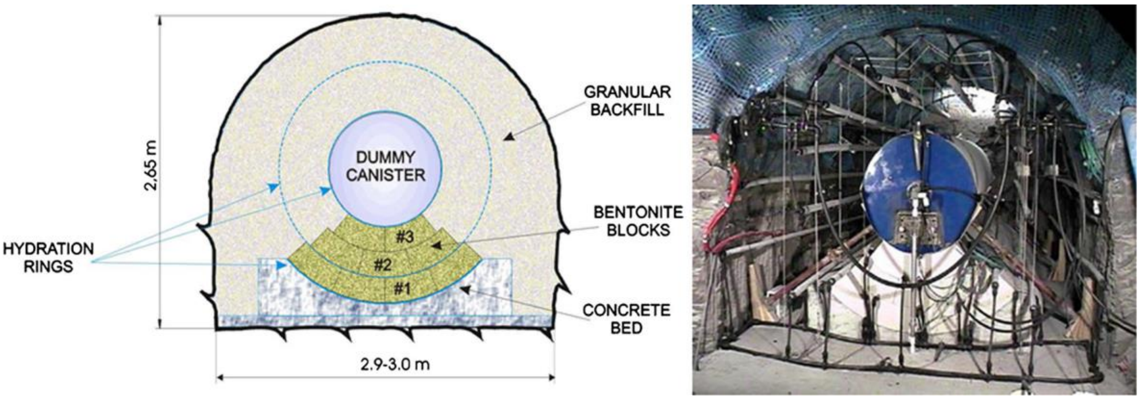

Fig. 3-4: EB experiment layout. Hydration pipes are arranged in rings around the central dummy canister

Mayor et al. (2007)

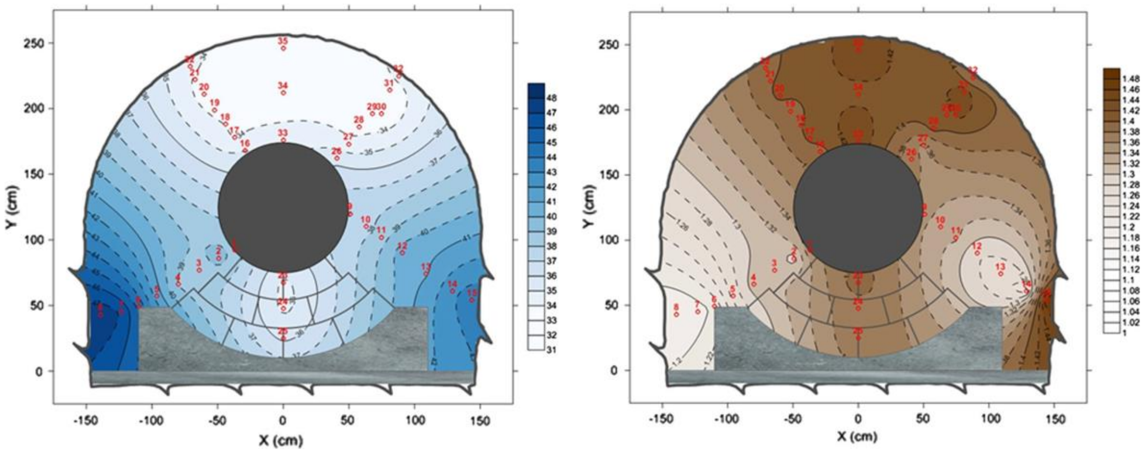

Fig. 3-5: Water content (left) and dry density (right) after dismantling in EB cross section B1. Red marks show the sampling locations

Palacios et al. (2013)

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3.3.3 Feed back to the safety case

The controlled dismantling of the EB experiment has allowed to complement and improve the previously gained knowledge (through the available monitoring data) of the isothermal saturation process of a full-scale bentonite barrier. It has been fully confirmed that the use of a granular bentonite material is a good option to construct technical barriers

- The hydraulic conductivity of the saturated granular bentonite is low enough (less than 10^{-12} m/s), even if emplaced with a relatively low average dry density (1.36 g/cm^3 in this experiment), to fall between the acceptable limits considered for this key safety indicator in the Performance Assessment of the repository concepts.
- Homogenization between the two types of bentonite emplaced (blocks and pellets) has taken place. Nevertheless, after the experiment life of more than ten years, still some heterogeneities persist through the bentonite mass: the moisture content tends to increase (and the dry density to decrease) towards the bottom of the experiment niche. This is probably due to the fact that emplacement of the granular bentonite was difficult in this case, due to the existing hydration tubes.
- The measured values of the thermal conductivity of the saturated bentonite (from 0.90 to 1.35 W/m K) are high enough to dissipate the heat generated by the waste.
- Self-sealing of the EDZ in the Opalinus Clay has been observed during the experiment, due to the swelling pressure developed in the barrier. As it could be expected, the seismic data do suggest the gradual recreation of the EDZ after dismantling.
- The dismantling has provided the opportunity to perform microbial analyses of the bentonite emplaced more than ten years before. Samples analyzed had water activities higher than 0.96; they showed relatively high culturability levels for heterotrophic aerobes and low culturable levels of sulphate reducing bacteria.
- In general, the obtained gas permeability values of the saturated bentonite are low and homogeneous (from 1×10^{-22} to 6×10^{-22} m^2).

3.4 FEBEX – Full-scale Engineered Barrier Experiment

The FEBEX project (Full-scale Engineered Barriers Experiment) studies the behaviour of components in the nearfield for a high-level radioactive waste (HLW) repository in crystalline rock. The project was based on the Spanish reference concept for disposal of radioactive waste in crystalline rock (AGP Granito): the waste canisters are placed horizontally in drifts and surrounded by a clay barrier constructed from highly-compacted bentonite blocks (ENRESA 1995). As part of this project, an "in-situ" test, under natural conditions and at full scale, was performed at the Grimsel Test Site (GTS, Switzerland), an underground laboratory managed by Nagra (ENRESA 2000, 2006a, 2006b, 2006c).

3.4.1 Summary of the test

FEBEX - Full-scale Engineered Barrier Experiment in Crystalline Host Rock, was a research and demonstration project that was initiated by ENRESA (Spain). The aim of the project was to study the behaviour of near-field components in a repository for high-level radioactive waste in granite formations.

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The FEBEX in-situ experiment was the longest-running in situ full-scale heater experiment (the laboratory-based FEBEX mock-up test was started at the same time as the in-situ test and is still running, status February 2022). Work on the project started in 1995 with the characterisation of the experimental rock volume, followed by the excavation of the FEBEX drift, further geosphere characterisation and the emplacement and instrumentation of the engineered barrier system (EBS) and plug. The initial total sealed test section comprised a total length of 14 m, which was filled with FEBEX (Serrata Clay) compacted bentonite blocks and embed two steel heaters, each 4.5 m long and 0.9 m in diameter (11 tons weight) inserted in a liner. Heating started in 1997 and continued without interruption until 2002 when Heater #1 was removed during a partial dismantling activity, while Heater #2 was maintained heating. Heater #2 was switched off in 2015 and fully dismantled and sampled. Throughout this time, the EBS and geosphere were continuously monitored, and routine sampling was performed. During the partial (2002) and final (2015) dismantling, the EBS was characterised, providing a comprehensive dataset of EBS buffer properties (mineralogy, geochemistry, dry density, water content and thermo-hydro-mechanical (THM) properties), which allowed a detailed evaluation of changes in the buffer during the early evolution of the EBS due to 18 years of heating and saturation.

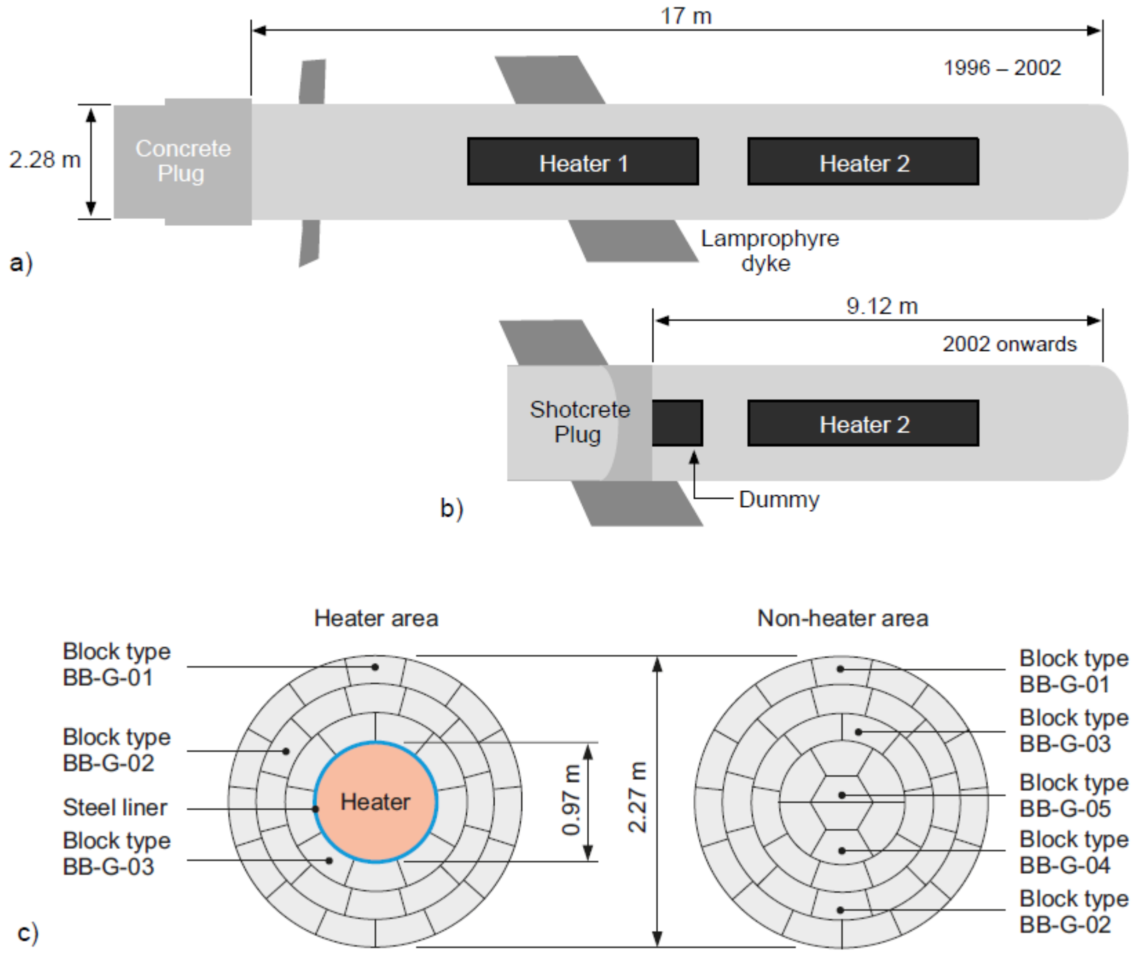

Fig. 3-6: a) FEBEX layout 1997 – 2002 prior to removal of Heater # 1, b) layout 2002 – 2015 and c) bentonite block vertical cross-sections

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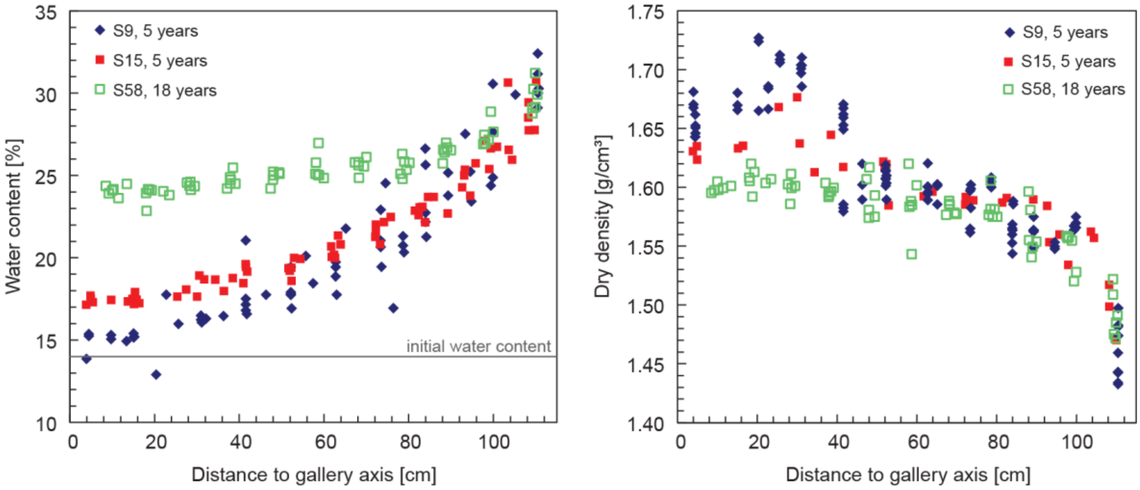

Fig. 3-7: Water content and dry density of the bentonite barrier along the gallery axis in cold sections after 5 (Daucausse & Lloret 2003) and 18 years of operation (Villar et al. 2018)

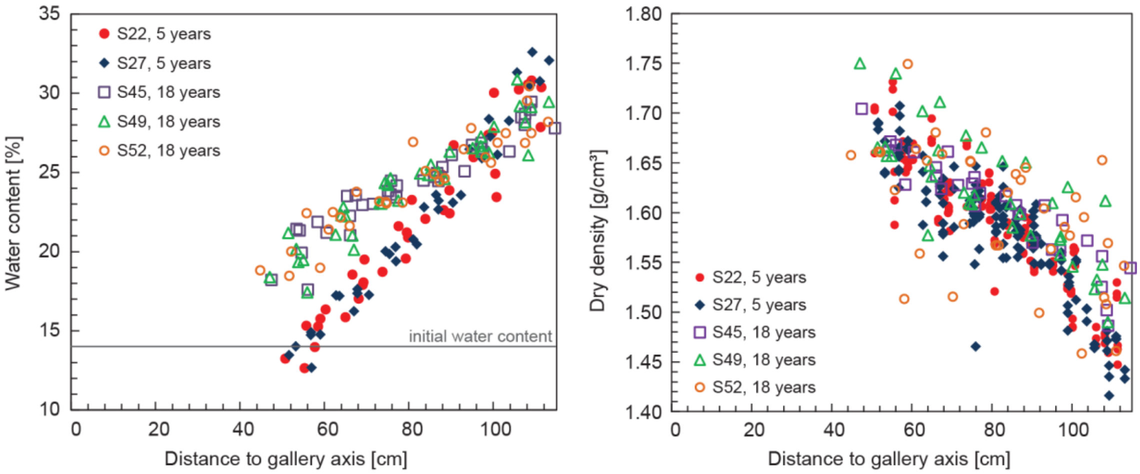

Fig. 3-8: Water content and dry density of the bentonite barrier along the gallery axis in sections around the heaters after 5 (Daucousse & Lloret 2003) and 18 years of operation (Villar et al. 2018, 2020)

The results from the decommissioning of the experiment showed that the swelling and sealing capacity of the bentonite barrier was already developed after five years of operation, since all the construction gaps in the barrier were almost entirely filled with bentonite (Villar et al. 2020) . This means that the water availability at the test site (both in the liquid and the vapour phases) was sufficient to allow quick swelling of the external part of the barrier. In turn, the quick swelling avoided preferential paths remaining open, which resulted in the water content distribution in vertical sections following a radial pattern that was largely independent of the particular features in the rock.

Although the boundaries of the blocks were clearly visible, no gap remained between them, except at the core of the barrier in the cold sections, where the water content had barely increased with respect to the original content, i.e. from 14% to values below 18%.

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The main changes during the Second Operational Phase took place in the internal part, i.e., core, of the barrier. After five years of operation, the cold and hot sections had distinctly different features, and these were also observed in the final dismantling. In particular observations included (for the locations of the sampling sections refer to Kober et al. 2017):

- The water content in the 10 cm closest to the granite of the cold sections was the same after 18 years operation as after 5 years, whereas the additional operational time allowed the saturated region to extend further towards the interior of the barrier (Figure 3-7).
- In the sections around the heater, the water content near the granite, i.e. in the outer ring of the barrier, decreased from that observed at five years after 13 additional years of operation. In contrast, the water content increased in the middle and inner rings of the barrier (Figure 3-8, left).
- The dry density distribution along the radii around the heaters did not significantly change over time (Figure 3-8, right).

Hence, the water content and dry density gradients generated as a consequence of hydration and heating have proved to be persistent, and maybe irreversible since they were already observed after five years of operation and remained stable for a further thirteen years despite the overall high degree of saturation at the end of the experiment.

The average water content (w), dry density (ρ_d) and degree of saturation (S_r) for the bentonite sections sampled in 2002 and 2015 are plotted as a function of the distance to the coordinate origin in Figure 3-9, where the sections around Heater #1 are those dismantled in 2002 after 5 years of operation and the sections around Heater #2 are those dismantled in 2015 after 18 years of operation (see Figure 3-6).

The initial installation density (Figure 3-9) is also indicated, since the section of the barrier dismantled in 2002 had an average dry density lower than that dismantled in 2015. There is no particular reason for this difference, which is simply a consequence of particularities of the installation operation. The initial water content of the bentonite was considered to be 14.4% for all the blocks (Kober et al. 2017).

A summary and interpretation of the figures below (Figure 3-10), show significant differences in dry density and water content along the axis of the tunnel (Kober et al. 2017):

- The buffer in the rearmost portion of the gallery had the highest water contents and lowest dry densities. This was most probably caused by a larger volume of construction gaps, which resulted in a lower installation density, a condition that, to some extent, remained unchanged until the end of operation. The hydration surface of the first bentonite slice (at the back of the gallery) was larger than for the subsequently installed slices, and this probably contributed to the higher water content observed at the gallery end.
- The highest dry densities were found around the rear half of the heater, where the temperatures were higher and the end-of-test water content lowest.
- Around the dummy canister, dry densities below the average of the barrier were found. This density decrease was related to the displacement of the slices towards the gallery entrance upon plug demolition and pressure release (see below). The bentonite around the dummy canister had also been subjected to a high thermal gradient during the First Operational Phase but it was cool during the Second Operational Phase, which may also have affected its condition. Also, the water from the concrete plug likely contributed to the higher water content of the bentonite slices closest to it.

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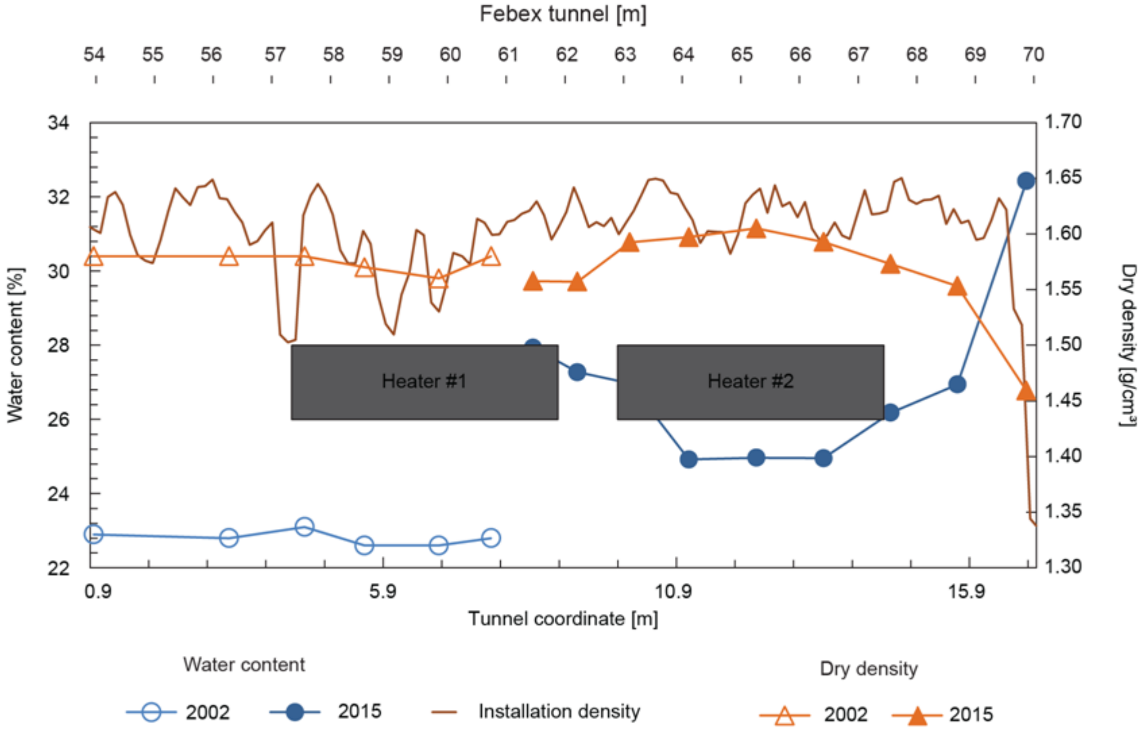

Fig. 3-9: Average water content and dry density for the sections sampled along the barrier in 2002 and 2015. Kober et al. (2017)

The best estimates for the final average water content, dry density and degree of saturation of the whole bentonite barrier are 25.5%, 1.59 g/cm^3 and 97%, respectively. The average dry density value is lower than the initial average value given during installation (1.61 g/cm^3). This change can be attributed to a combination of factors: the slight decompression suffered by the barrier on dismantling and sampling, the intrusion of bentonite into the liner and the sampling and measuring procedures.

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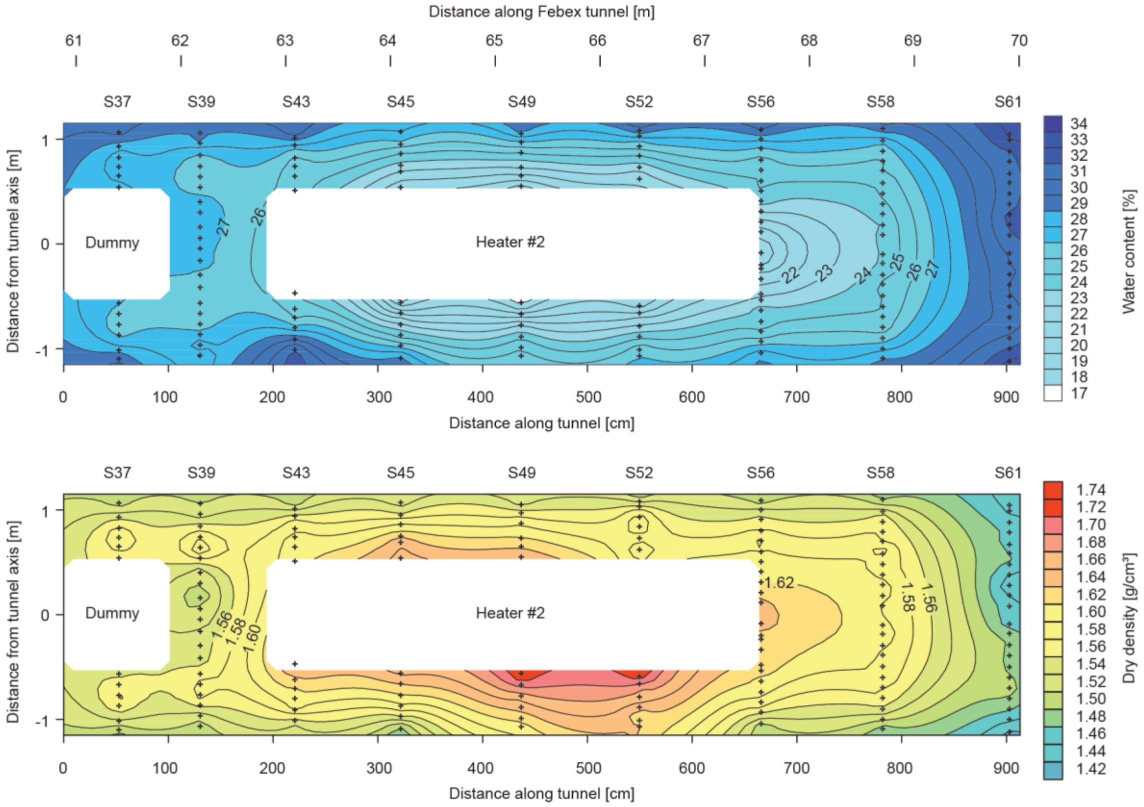

Fig. 3-10: Dry density (top) and water content (bottom); distribution in a vertical longitudinal section

Kober et al. (2017)

3.4.2 Feed back to the safety case

After five years of operation, there was a significant overall increase in the barrier water content from the initial value of 14% to an average value of 22%. This increase was homogeneous along the barrier. The effect of the heater was barely noticeable.

This suggests roughly uniform water uptake from the geosphere along the dismantled section. Within the buffer around the heater, there was a significant redistribution of moisture from the blocks nearest the heater towards the rock.

After 13 additional years of operation the average overall water content increased from 22% to 25.5%, which reflects the slowing down of the hydration rate over time. Furthermore, in this case, the hot and cold sections had very different water contents that clearly increased away from the heater towards the plug and back of the tunnel.

The barrier with an initially homogeneous dry density ended up having important inhomogeneities in terms of dry density and water content (Villar et al. 2018). This could indicate that the volume changes induced during the initial saturation were irreversible. Lloret & Villar (2003) stated that, according to laboratory tests with untreated samples interpreted using generalised plasticity models (Lloret et al. 2003) and provided that the net stresses in the barrier do not exceed the bentonite swelling pressure, these macroscopic changes would be irreversible and the density heterogeneity throughout the barrier would remain.

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These gradients have not impaired the performance of the barrier, but imply that the bentonite barrier may be inhomogeneous, depend greatly on the density and water content of the bentonite, as shown as discussed in Kober et al. (2017).

Upon final dismantling, the buffer did not achieve complete saturation, and despite experimental artefacts, the bentonite proved to perform as expected. The bulk of the bentonite reached a saturation above 97%, with only the bentonite closest to the heater remaining below 85%. The available data do not indicate any trends that bentonite cannot meet long-term target safety requirements.

3.5 CRT – Canister Retrieval Test

The Canister Retrieval Test (CRT) was primarily designed to test technique to retrieve canisters from a water saturated buffer. One such technique was tested in the lower part of the buffer in the CRT. In this test the buffer was pumped out of the borehole after having been slurred a salt solution. The upper part of the buffer was removed by mechanical means so that water and density samples could be recovered before the retrieval test was started. The data from the sampling of the buffer together with data from the installed sensors were used when comparing THM-simulations of the tests.

3.5.1 Summary of the test

A full-size canister with a bentonite buffer of Wyoming bentonite (Volclay MX-80) was installed in a full-size deposition hole in the autumn of 1999 at the Äspö Hard Rock Laboratory (Sandén & Börgesson 2000). The buffer consisted of one bottom block, ten ring shaped blocks surrounding the canister and additional three solid blocks on top of the canister, see figure 3-11. Furthermore, the outer slot between the buffer blocks and the wall of the deposition hole with a width of about 6 cm was filled with bentonite pellets. The voids between the pellets were then filled with water. The inner slot between the canister and the ring-shaped blocks with a width of 10 mm was kept open. The buffer blocks and the pellets filling had initial well-defined geometry, density and water content. A retaining concrete plug, anchored in the surrounding rock was placed on the top of the buffer.

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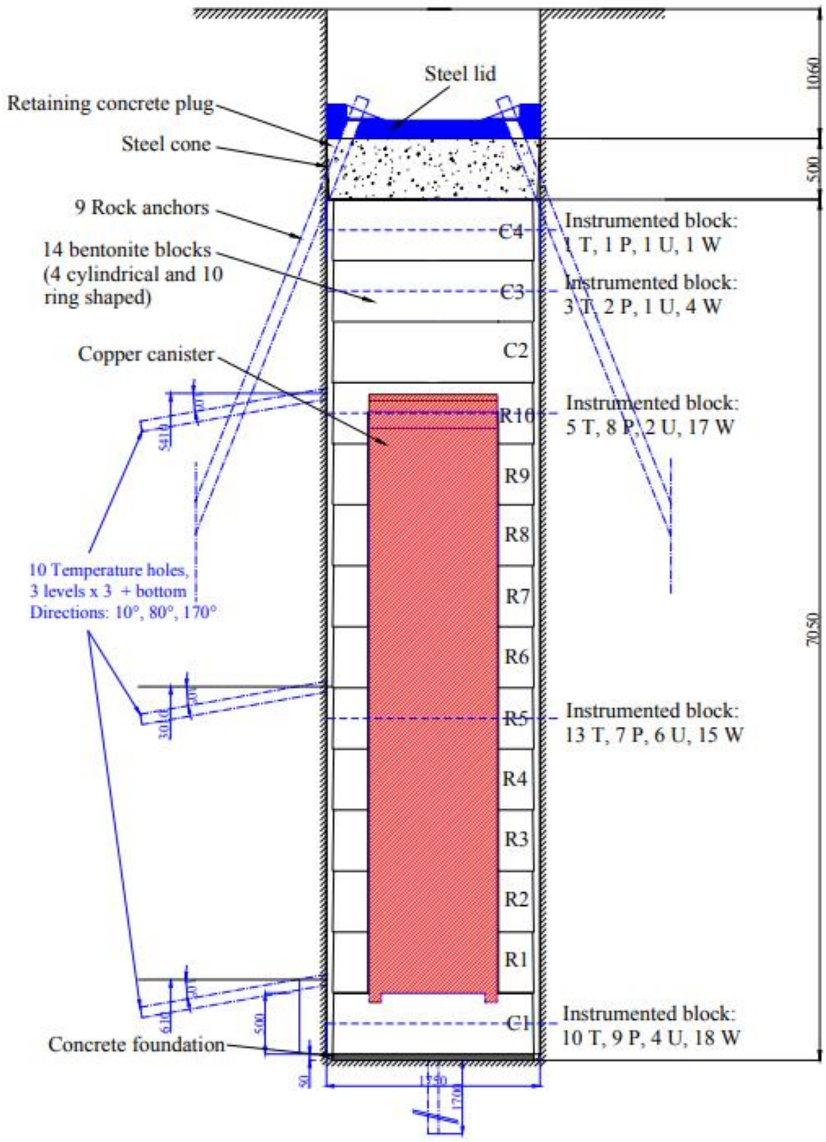

Fig. 3-11: Schematic view showing the experiment layout

Sensors have been placed in five of the bentonite blocks. For each block the number of each sensor type is described. (T = temperature, P = total pressure cell, U = pore pressure cell and W=relative humidity sensor) (Johannesson 2007).

The bentonite surrounding the canister was saturated through filters installed on the wall of the deposition hole. The water volume entering the filters and the water pressure in the filters were measured during the whole test period. This arrangement resulted in an axisymmetric and relatively fast saturation of the buffer. The canister was equipped with heaters to simulate the heating from a canister in a real repository. The power applied on the heaters was measured continuously. The temperature on the canister surface was measured with optical cables placed on the surface of the canister. Sensors to measuring temperature (T), total pressure (P), pore pressure (U) and relative humidity (W) were installed in five sections of the buffer. Furthermore, the total load acting on the concrete plug was measured together which its vertical displacement.

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After 5 years in operation the experiment was shut down and dismantled. Samples were taken on the upper most part of the buffer (Block R6-R10 and C2-C4) on which the water content and the bulk density were determined. About 1'500 samples were taken thus it was possible to get a detail picture of the of the density and water content distribution in the upper part of the test. The sampling of the buffer was made by core drilling form the floor of the tunnel, see Figure 3-12.

Fig. 3-12: Cores taken from block C3
Johannesson (2007)

An example of data from the determination of the water content and the density is shown in Figure 3-13. The analyses of the samples taken from the buffer indicate the following:

- The water content of the pellets filling in the outer slot was decreased compared to the initial water content.
- The water content of the blocks was increased.
- There was a compression of the pellets filling resulting in an increase of its dry density.
- The buffer blocks had swollen out towards the canister and compressed the pellets filling resulting in a decrease of the dry density of the blocks.
- The buffer around the canister was fully saturated while the central part of the solid blocks above the canister was not saturated.
- Although the buffer around the canister was fully saturated, the buffer was not fully homogenized after 5 years of saturation.

The data from the installed sensors and from the analyses of the buffer were used at the comparison of the modelling made of the test.

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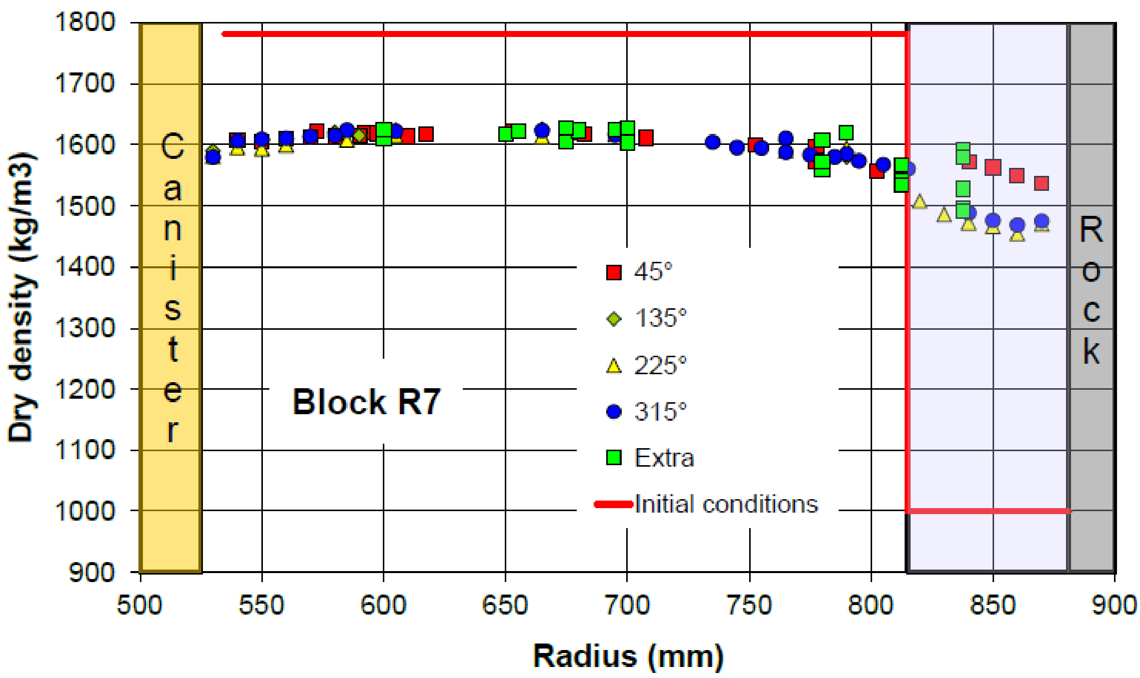

Fig. 3-13: The dry density (b) of the buffer block R7 as function of the radial distance from the center of the deposition hole
Johannesson (2007)

3.5.2 Feed back to the safety case

As we can see in Figure 3-13, the density of the installed block decreased from 1'780 kg/m^3 to around 1'600 kg/m^3 due to the expansion into the empty slot closest to the canister and into the pellets. The final density is almost constant over the entire diameter of the original block. The dry density in the initially empty slot increased from 0 to almost 1'600 kg/m^3. In the pellets, the dry density increased from 1'000 kg/m^3 to between 1'450 and 1'600 kg/m^3. A dry density of 1'450 kg/m^3 for MX-80 would give a swelling around 3 MPa in a 1 M $CaCl_2$ solution and almost 5 MPa in a dilute water. The hydraulic conductivity would be less than 10^{-13} m/s. This means that the safety functions for the bentonite buffer would be upheld in a KBS-3 type repository.

- The observations from CRT are however only valid for that particular experiment and the results cannot be directly applied to the buffer in a safety case. Some reasons for this are:
- The pellets slot was filled with water and there was artificial hydration from the rock wall. This will not be the case in a real repository.
- The measurements presented are from one single ring which was located more than a meter below the top of the canister. Expansion of the buffer in the axial direction may have an effect on the final dry density, especially close to the top and bottom of the canister.
- Figure 3-13 shows that the final dry density in the pellets fill is different in different directions. This may be an effect of the hydration history or an effect on how well the canister was centred in the deposition hole. The statistics provided by the CRT are insufficient to determine whether the variability in final dry density could be larger than the observed.

The results are still very valuable since they show that the block/pellet configuration proposed for the KBS-3 system may have the ability to yield a sufficiently low final heterogeneity.

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Summary of the findings from the large-scale tests

The four field tests presented in this chapter gives a rather mixed picture regarding the homogenisation of the installed bentonite components. In two of the tests, EB and CRT, the barrier was installed as a combination of high-density blocks and a low-density pellets filling. In both those tests the initially heterogenous barrier evolved into a rather homogenous system. FEBEX and the Prototype backfill was on the other hand installed as, at least was thought to be, an initially homogenous system. In both those cases, the final state of the barrier was actually more heterogenous than the installed state. In the FEBEX case the final heterogeneity was still within the range that can be considered as acceptable from a long-term performance point of view, while the final heterogeneity in the Prototype backfill clearly was unacceptable.

This clearly demonstrates the complexity of the homogenisation process. The process can go in both directions and this is strongly coupled to the prevailing conditions regarding hydration and heat, but also to the properties of the installed components.

It is also clear that large scale tests are of incredible value both for the direct confirmation of barrier (non) performance and for the testing and verification of numerical models. It is, however, also clear that the observation from a particular test only is representative for the conditions at that particular location.

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4 Lessons learned from WP3

The main goal of Work Package 3 was the development of constitutive models for the description of the mechanical, hydromechanical (HM) and, optionally, thermo-hydro-mechanical (THM) behaviour of bentonite-based materials with the aim of introducing them into numerical tools capable of analysing problems of engineering significance. In particular, the project Beacon is especially focused on the processes of homogenization or, conversely, the development of heterogeneity throughout the transient phase of engineered barriers and seals. The proposed scope of potential developments is wide: saturated and unsaturated materials, isothermal and non-isothermal conditions and different types of materials (e.g. compacted blocks, pellets based granular bentonite).

The work in WP3 has included not only the development and improvement of constitutive models but also tasks of model implementation into computer codes to be used in the solution of boundary value problems at different scales. A variety of codes have been used for this purpose: Code_Bright (UPC), Comsol Multiphysics (Clay Tech., LEI, Quintessa), ICFEP (ICL), Lagamine (EPFL, ULg), OpenGeoSys (BGR), QPAC (Quintessa), SIFEL (CU-CTU). This variety of codes makes evident the wide scope of the numerical implementation work performed.

1.1 Results and summary of conclusions

The development and improvement of the models by the different modelling teams have been extensive and varied. They have been driven by a variety of reasons including the widening the scope of applications, the desire to include fabric and microstructural considerations, the need to improve their performance when applied to the WP5 benchmarks and the requirement to move to non-isothermal problems. The extent of the modifications has depended strongly on the state of the model at the start of the projects; some teams have only needed to carry out minor modifications whereas other teams have had to develop a constitutive model starting from a very basic formulation. Despite the wide range of model developments and improvements, specific to each modelling team, it is possible to derive some general observations:

- It can be stated that the models developed are able to reproduce what are considered to be the key features of behaviour underlying the homogenization processes such as stress path dependency and strain irreversibility. This is confirmed by the satisfactory performance of all the models in conceptual stress path modelling and in the reproduction of Task 3.3 experiments.
- Most models are developed within an elastoplastic framework. One model adopts a hypoplastic formulation whereas another one uses a swelling nonlinear elastic model. Two models (HBM and ILM) are based on a fundamental backbone curve, experimentally determined.
- Double structure models have become dominant in WP3 developments. Sometimes both hydraulic and mechanical models are based on a double structure formulation (5 teams) and, in other cases, only one of the components includes a double structure approach (3 teams). Those double structure developments try to incorporate in the model information on the fabric and microstructure of the material. However, it has not been demonstrated that the improved model results (if identified) compensate for the added complexity and the need to determine a higher number of parameter and initial conditions.
- Most water retention curves are based on the Van Genuchten original expression or on a slightly modified form. Water retention hysteresis is largely ignored (only three teams incorporate it) whereas most teams consider some dependence on void ratio.

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- Only three teams have developed a thermo-mechanical model that include explicitly the effects of temperature on mechanical behaviour. It appears, however, that the simple inclusion of an overall thermal expansion of the material is sufficient to achieve satisfactory modelling results in non-isothermal problems at least up to the temperatures contemplated in the Beacon project. It is unknown whether the same conclusion applies to higher temperatures.
- Despite of the prevalence of the double structure models, only two teams have reported the predicted evolution of micro and macro void ratios and has compared it to experimental MIP results. Some predictions appear to be rather consistent with observations. The criterion to distinguish between the two porosity levels remains an issue, though.
- Although it has been proved that lateral friction has an important influence on some laboratory results, only three teams report explicitly the development of appropriate formulations for inclusion in the analyses.

The proper evaluation of the performance of the constitutive models developed in WP3 should be based on their applications to the WP5 benchmarks. Those benchmarks provide the information required to identify the learning points acquired from the modelling of experiments involving mechanical evolution and homogenization of the bentonite.

A source of uncertainty identified by practically all modellers is the scarcity of experimental data to determine all the parameters required by the constitutive models. This is especially valid for the modelling of granular bentonite; the situation for compacted bentonite is somewhat better. Against that observation, it must be admitted that the number of parameters in many of the models used in the project is very large. Another common remark is the scarce information on the repeatability and reliability of the experimental results in the proposed benchmarks that may underlie some of the modelling difficulties encountered by various teams.

A general observation is that the final state of the bentonite (in terms of swelling pressure and/or dry density distribution) is more robustly predicted than the transient behaviour; the comparison of the time variation of the various relevant parameters with experimental results is sometimes rather poor. This may be due to the inherent sensitivity of the transient phenomena to small changes in parameters and initial and boundary conditions but the difficulty in precisely determining the required parameters with available information may also play a role.

There is general agreement that there are still limitations in the fundamental knowledge of the basic processes underlying homogenization and other related mechanical phenomena. In this respect, the performance of simple well-designed small-scale laboratory tests addressing individual relevant phenomena is likely to be the most efficient way to advance knowledge. Large field scale tests, though useful to bring all the relevant phenomena together in a realistic setting, are less convenient for enhancing fundamental knowledge. Naturally, the relevant phenomena have to be selected based on the requirements of end-users.

The corresponding activity in terms of constitutive model development would be the performance of sensitivity analyses to establish unambiguously the role and effects of each parameter or group of parameters in relation to different basic behaviour features and phenomena. Because of the large number of cases that had to be modelled in the project (in order to increase the scope of the work), the sensitivity analyses performed have been limited.

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Another uncertainty involves the way of incorporating microstructural information in modelling and to decide in which circumstances it is advisable to resort to the unavoidable higher complexity of double structure models. In any case, experimental fabric determination should become a standard feature of laboratory testing. It is unclear at present whether the same model can be used for compacted bentonite and granular bentonite by simply changing the parameters. It is likely, however, that the variation of hydraulic parameters is quite sensitive to the evolution of fabric that is bound to be quite different in the two types of materials.

The consideration in the models of thermal effects on the mechanical behaviour of compacted and granular bentonite is also limited at present, beyond the consideration of a simple thermal expansion coefficient. It appears that this has been sufficient for a successful modelling of non-isothermal problems so far, but it is unknown whether better knowledge and enhanced models are required when moving to higher temperatures. Finally, it is imperative that friction is introduced in the simulation and interpretation of at least some laboratory experiments.

Important and substantial advances have been performed in the framework of Beacon's WP3 regarding the development and improvement of constitutive models and their implementation in computer codes. The models encompass a wide range of approaches and can deal with an extensive combination of simulation conditions. The models developed are able to reproduce what are considered to be key features of behaviour underlying the homogenization processes such as stress path dependency, strain irreversibility, and others. As a result, modelling capabilities in this area have been enhanced very significantly as a result of the project. The performance of the models when applied to the simulation of relevant problems is assessed in WP5.

In the context of these advances, several modelling teams have also identified areas of further constitutive model developments that are deemed necessary to improve simulation capabilities. In addition, outstanding uncertainties remain concerning the detailed knowledge of some of the individual phenomena underlying homogenization, the precise role of different components and parameters of specific models and the actual predictive power of the formulations developed in the project.

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5 Lessons learned from WP4

The objectives of the experimental work performed in Beacon Work Package 4 were to provide input data and parameters for the development and validation of hydro-mechanical models in order to describe more accurately bentonite dry density homogenization. Following Beacon partners BGS, CEA, CIEMAT, CTU, CU, EPFL, JYU, KIT, and GRS did carry out a wide range of experiments to provide the data needed by the models.

The following chapter aims at drawing conclusions from this work and to summarize the open questions or issues that would need to be considered.

5.1 Results summary and conclusions

The experiments performed in Beacon WP4 addressed

- the influence of **hydro-mechanical path** and aggregate size distribution for several macroscopically homogeneous bentonite materials, such as MX-80 (EPFL) and BCV (Cerny vrch bentonite, CU and CTU)
- the **gap filling potential** of swelling bentonite for different configurations and conditions, involving MX-80 (BGS), BaraKade bentonite (JYU), FEBEX bentonite (CIEMAT), BCV (CTU), and Calcigel (KIT/GRS), with instant water contact (BGS) or one-sided hydration (CIEMAT, CTU, JYU, KIT/GRS), including hydration in the vapour phase (CIEMAT)
- the **hydration-induced homogenisation** of different binary systems like block/pellet (CIEMAT) and pellet/powder as well as block/powder (CEA) systems or systems of two blocks with different initial densities (CU)
- and the **friction** at a bentonite/steel interface (EPFL)

The overall results and conclusions are summarised below.

From experiments on water uptake and stress evolution using macroscopically homogeneous bentonite following can be concluded:

1. Influence of aggregate size distribution: Under free swelling conditions EPFL found a higher volume increase for unifractional samples (MX-80 of 1 – 2 mm aggregate size) than for bifractional samples (where 20% aggregates of 0.08 – 1.25 mm were added) that started with a higher dry density. The differences in final void ratios were mainly due to different fractions of macroporosity (see 12 below). The result is in line with technical voids filling phenomena observed. This effect was not observed in confined samples.
2. Hydromechanical path dependence: EPFL used granular MX-80 bentonite with a Fuller-type aggregate size distribution to (a) hydrate under constant low stress (nearly free swelling), and subsequent stress increase, or (b) hydration at constant volume conditions, and subsequent stress increase to the same value as in (a). Despite having the same degree of saturation afterwards and being subjected to the same final value of vertical stress, a difference in void ratio of 0.13 (15% of initial void ratio) between the two samples was obtained. This path dependence (hysteresis) was also confirmed by CTU using pellet and powder materials (BCV). While having comparable microporosities, the difference is in the macroporosity of the samples undergoing different paths (see 12 below).

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3. The hysteresis effect described above disappears after several wetting-drying cycles: Samples of different initial void ratios saturated under different stress tend, however, to arrive at similar states after cycles involving high compressive load, as shown by CU for compacted bentonite and by CTU for pellets and powder (both using BCV).
4. Constant load swelling tests of CU with variable dry density (BCV, homogeneous material of 1.27, 1.6 and 1.9 g/cm^3), hydraulic path, and confining conditions showed that the water retention behaviour did not seem to be significantly influenced by the initial dry density for bentonite blocks of different densities. The final void ratio of saturated samples under the same load was independent of the initial compaction.
5. Pellet cluster stress evolution: Stress evolution in an instantaneously flooded unifractional pellet cluster (pillow-shaped MX-80 pellets of 16 – 17 by 8 mm) of GRS was rather complicated and not monotonous (compare 11). Both GRS and CTU observed that the initial stress in a pellet cluster at low density may collapse when water is introduced.

Technical void filling potential of bentonite

6. Results from the gap-filling experiments evidence the high potential of bentonite for closing voids. In CIEMAT's tests (FEBEX bentonite), voids of 17 – 24% of the sample size were filled; BGS found that even void spaces of 45% of the test cells were filled completely (MX-80). The gap filling capacity will of course depend on the dry density and the type of bentonite.
7. Swelling of bentonite into technical void does not necessarily result in a homogeneous density distribution. In those experiments that involved a progressive water supply (JYU, CIEMAT) it was found that density gradients reduced with time and increasing degree of saturation. Once full saturation was reached, however, no further homogenisation could be observed. A decrease of gradients was also observed in BGS' gap (technical voids) filling tests where water was supplied at once. These tests had a duration of 100 days, and in all of them density gradients remained. Lower gradients were obtained with lower overall dry density (due to higher saturated permeability and possibly also due to the lower swelling capacity of low-density materials, which results in less steep gradients in the beginning) and when a greater degree of swelling was allowed to occur (due to the reduction in dry density). Some evidence indicated elevated temperatures may influence the degree of residual density gradients, but more data is required to understand this. If the saturating fluid had a higher salinity higher density gradients would result.
8. A spatially inhomogeneous swelling pressure distribution tends to homogenise with progressing swelling, as shown in BGS' and KIT's experiments (both using MX-80). Remaining stress gradients in the technical voids filling tests can be widely explained by the varying local swelling pressure caused by density gradients. Friction may also play a role.
9. The rate of hydration is the dominant boundary condition that defines the final bentonite density distribution (homogenisation) – for both gap filling setups and binary systems (see 10). In the gap filling case, CIEMAT states that hydration via the gap allows the samples to saturate faster because they swell into the open void and take water very quickly, developing higher internal gradients than when they are saturated from the bentonite side, where no free space is available and a low permeability is maintained (see 10 and 12). If hydration is performed via a vapour phase, higher relative humidity (faster vapour supply) likewise results in faster hydration and larger gradients. This would mean that a lower hydration velocity results in a more homogeneous end product. Higher hydration rates on trend increase the amount of larger pores (see 12).

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Binary systems: block and granular bentonite

10. In analogy to the technical voids filling tests, homogenisation of a granular material/block system used by CIEMAT depended on the hydration direction and kinetics (see 9). CIEMAT used systems of FEBEX bentonite (block and Fuller-type granular material) and MX-80 (block and pellet/powder mixture). A (faster) hydration (via the granular material or because of higher water availability) resulted in larger final density gradients than an intrinsically slower hydration via the block or under restricted water flow. Similar results were obtained by CEA using block/block systems of different block densities. CU also investigated a block/block system and observed the same effect, although the difference due to the hydration direction was rather small. This may be due to the fact that both blocks had a rather high dry density to start with, so that the hydration was slow even when performed via the less dense block.
11. Swelling pressure evolution in binary systems is complicated and not necessarily monotonous, especially in systems with granular material or powder (CIEMAT, CEA) (compare 5).

The evolution of void ratio upon saturation

12. Many of the experiments performed involved porosimetric characterisation before and after testing, and thus enabled a view on pore size evolution. The results of (1), (2), (9) and (10) all suggest that an initial saturation at low confining stress, possibly with a high hydration rate, leads to irreversible strains that affect the macrostructure. The subsequent evolution of the system is conditioned by this early evolution. This interpretation is supported by the fact that it is the macropore volume that gets mostly modified as a result of the initial hydration and swelling. Since this effect seems to be persistent, it may be needed to be considered when modelling system evolution. Current dual-porosity models should be suited for this.

Influence of the degree of saturation on the friction at the bentonite-steel interface

13. EPFL investigated the internal friction of granular MX80 bentonite as well as the shearing at a steel-bentonite interface, for a Fuller-type (D50 = 0.8 mm) and a unifractional aggregate size (1.5 mm) distribution. For both tested granulations, the interface shearing strength of the material at hygroscopic state was lower than the internal shearing. Unifractional samples showed lower values of shear strength parameters in comparison to those prepared with a Fuller-type granulation. Samples characterized by a higher water content showed a higher peak of shearing strength when compared with samples of lower water content. The increase of strength appears to be governed by the increase of adhesion between steel-bentonite upon hydration.

New experimental methods

14. In the Beacon project, new experimental methods were developed and tested, such as particle tracking in combination with X-ray imaging. CEA used X-ray tomography and JYU used X-ray radiography. Another new method is small-scale spatially resolved stress measurement developed by KIT. These methods proved successful and can be used in future investigations. Especially with regard to stress measurement, the inhomogeneous stress distributions found in all test setups with spatially resolved measurement indicate that interpretation of conventional oedometer tests with just one axial pressure measurement needs care. A more detailed stress measurement and/or control may be advisable for future experiments. A method that is not actually new should be mentioned nevertheless: Using transparent cells provided valuable insight especially into the hydration process in setups involving granular bentonite.

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With regard to bentonite homogenization, the experimental results show that a fully homogeneous dry density distribution will not be achieved in the short term upon hydration, instead, it seems that once full saturation is reached the resulting dry density distribution is irreversible. The results of the natural analogue study performed in the frame of Beacon (Sellin & Villar 2020) do not indicate that any slower process which would lay beyond the typical small scale laboratory duration might change to this. Consequently, the question of the persistence of inhomogeneities in the long term remains difficult to answer. In any case, bentonite barriers will have to be designed in such a way that the safety functions can be fulfilled even under non-homogeneous conditions.

5.2 Remaining questions and recommendations for future work

While a comparatively high total number of experiments was performed, these could of course not cover all relevant combinations of boundary conditions: the effect of different bentonites (sodium versus bivalent), porewater chemistry, forms (Bentonite vs granular material), void ratios textures and granulations as well as hydration- and stress-paths could be investigated in more detail to achieve a more complete database. Observed phenomena, like the apparent influence of saturation rate on density distribution, should be further investigated. The effect of temperature is not established yet, there were only a few first tests performed. A question that has not been addressed in the experiments is the fate of the air initially contained in the bentonite.

Regarding the design of experimental setups, the inhomogeneous stress distributions found in all test setups with spatially resolved measurement indicate that conventional oedometer tests with just one axial pressure measurement may not be sufficient for an in-depth interpretation. Wall friction is only one of the problems that can occur. Changing from oedometer tests to triaxial stress measurement and control would provide more insight and reduce uncertainty. Sensors at different locations or spatially resolving sensors give even more information.

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6 The three assessment cases

6.1 The SKB assessment case

The objective of this task is to analyse the homogenisation of the backfill during hydration. The backfill is one of the engineered barriers in the KBS-3 repository. The backfill is the material installed in deposition tunnels to fill them. The purpose and function of the backfill in 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 KBS-3 repository to maintain the multi-barrier principle and have several barriers that individually and together contribute to maintain the barrier functions the backfill shall:

1. limit flow of water (advective transport) in deposition tunnels
2. restrict upwards buffer swelling/expansion
3. not significantly impair the barrier functions of the other barriers

For the final repository to provide protection from harmful effects of radiation as long as required regarding the radiotoxicity of the spent nuclear fuel, and to withstand events and processes that can affect the barrier system the backfill shall:

4. be long-term durable and maintain its barrier functions in the environment expected in the final repository

The acceptable dimensions and geometry of the deposition tunnels are illustrated in Figure 6-1. They are based on the license application 2011 and have been further developed today. For the Beacon WP1 assessment case the old geometry is still used, since this will enable simple comparison with earlier results.

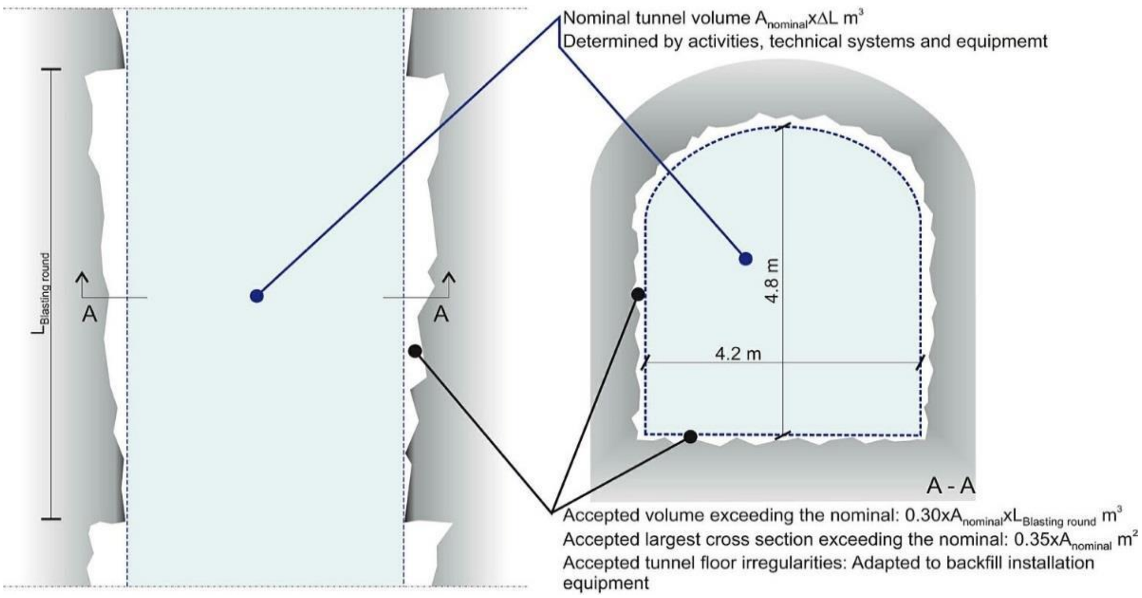

Fig. 6-1: Nominal tunnel geometry and acceptable volume of rock fall out and irregularities in the tunnel floor
SKB (2010)

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The installed backfill is planned to consist of compacted *bentonite blocks* stacked on a compacted flat bed of *bentonite pellets*, and the gap between the blocks and the rock surface will be filled with bentonite pellets. The section area of the block stack is planned to be constant throughout the deposition tunnel, while the tunnel section area is expected to vary within a certain interval for each blasting round. For the modelling work conducted for the SR-Site (Åkesson et al. 2010), this interval was represented with two tunnel sections, which for the homogenisation calculations, in turn, were represented as two 1D axisymmetric geometries, and one 2D axisymmetric geometry (Figure 6-2). The modelling teams contributing to WP5 within the Beacon project are asked to use the 2D axisymmetric geometry.

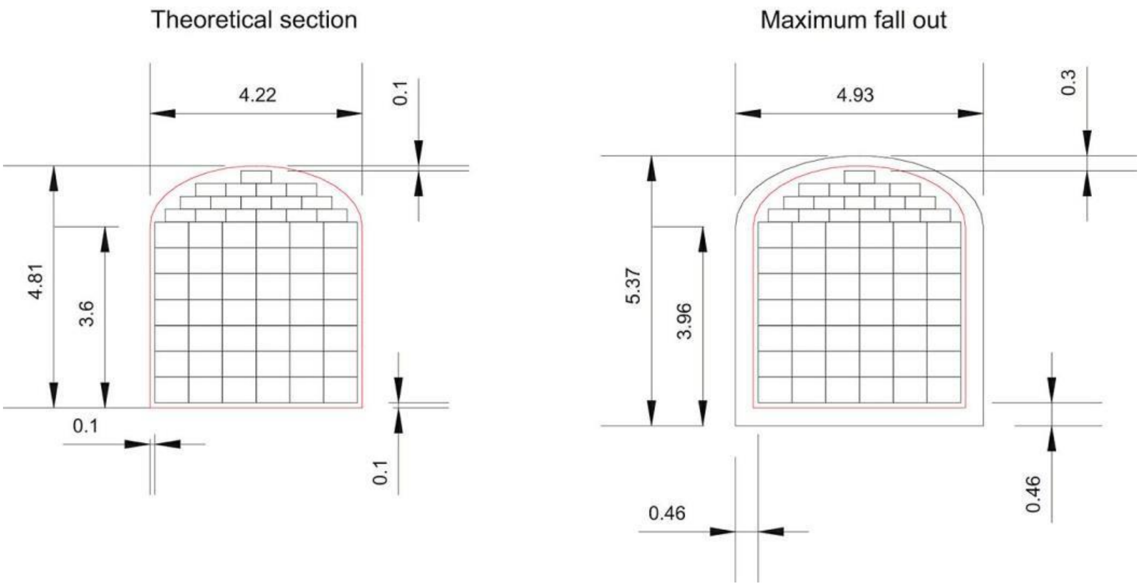

Fig. 6-2: Backfill design with arrangement of blocks and pellets filled slot
Theoretical section and maximum fallout
Åkesson et al. (2010)

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6.2 The Andra assessment case

The aim of the Andra benchmark case is to assess the hydro-mechanical evolution of a bentonite sealing of which the initial density is heterogeneous. A 2D cross-section of the sealing section was considered to simplify the assessment case. Longitudinal strains and liquid flow were neglected, and the concrete lining was not considered.

As shown in Figure 6-3 the gallery is 10 m diameter large. The bentonite core is supposed to be divided into 3 horizontal layers differentiated by their initial density. An initial 10 cm thick apical void is considered. With time, that apical and technical void is expected to be filled by swelling bentonite. The bentonite backfill is expected to homogenize with time.

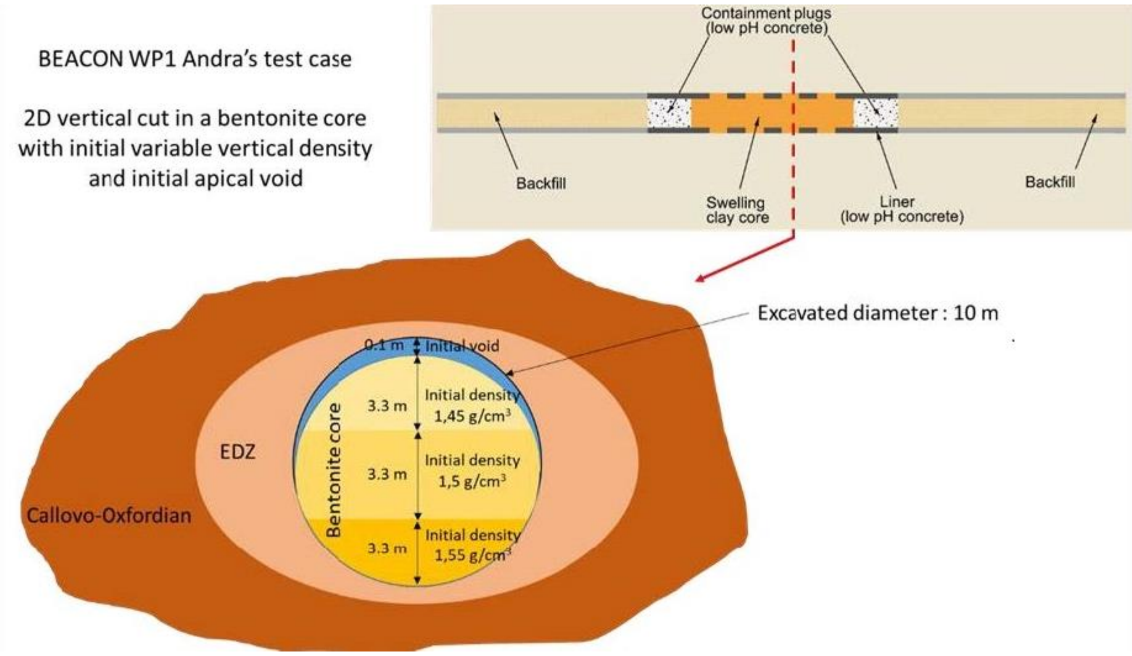

Fig. 6-3: Andra's sealing concept as a basis for the Andra assessment case

Various types of heterogeneities are expected in Andra's sealing concept:

1. Linked to the use of different types of material in the same bentonite component. For example, pure bentonite shotclay in the bottom of an off-profile in contact with a sand/bentonite pellet/powder mixture in a disposal-level drift seal.
2. Linked to variable initial density of the emplaced pellet and powder mixture. Insights from the FSS large-scale experiment show that the initial emplaced density is higher at the bottom of the core than at the top (10 m diameter galleries).
3. Linked to possible initial technological voids that could stay open after emplacement and before re-saturation of the swelling bentonite. Insights from the FSS large-scale experiment show that voids were present in off-profiles near the downstream face of the bentonite core.
4. Linked to the possible heterogeneous temporal evolution of re-saturation implying compression or expansion of some parts of the bentonite core at a given time.

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5. Linked to the chemical evolution of the bentonite core due to heterogeneous chemistry of resaturation water, part coming directly from the host rock (where direct contact exists), and part having percolated through remaining concrete liner. This heterogeneity is not so much linked to density effects as to swelling pressure differences at the same density due to chemical changes in the bentonite structure.

6.3 The Nagra assessment case

The underground facilities of the HLW repository will be constructed in Opalinus Clay at a depth of several hundred meters below ground surface roughly in the middle of the Opalinus Clay stratum or, if the confining units on either side of this stratum exhibit excellent barrier properties, in the middle of the effective containment zone, which consists of the Opalinus Clay stratum plus the confining units. To provide for optimum use of the available space at repository level (constrained by the geometric configuration of the Opalinus Clay host rock and important geological features), the current concept for the SF/HLW main facility foresees several spatially separated disposal areas, each with multiple emplacement drifts, possibly with different lengths. In this way, smaller scale unfavourable geological features can be considered in the layout of the disposal areas and the emplacement drifts.

The emplacement drifts are conceived to provide sufficient mechanical stability and suitable conditions for safe and reliable construction, operation (including possible retrieval) and backfilling/sealing. In addition, the host rock should only be affected by construction and operations of the repository to an extent that does not significantly compromise the performance of the barrier system after closure. Emplacement drifts are supported by segmental lining, i.e., tubbings (the reference design) or rock bolts and shotcrete liner (alternative support concept). In either case, the support is designed to provide stable conditions during construction and operation (to up to 100 years). Nevertheless, the use of materials with detrimental effects on barrier performance should be limited.

The emplacement drifts for SF and HLW (also termed emplacement rooms) have initial outer diameters of about 3.2 to 3.5 m. The drifts that will be supported by 0.2 m thick pre-cast concrete lining elements (tubbings) will have lengths restricted to about 1'000 m due to conventional safety and operational considerations as well as geological boundary conditions (Fig. 6-4). The annular gap between the liner and the rock is first filled with gravel and later backfilled with a low-viscosity grout. The lower part of the annular gap (between 4 and 8 o'clock position) is filled with grout only. Remaining voids in the surrounding rock may be further grouted by means of short subvertical borings through the lining.

The sequence in Figure 6-4 shows in (a) the emplacement of the tunnel support (eccentric) with prefabricated concrete elements, the annular gap backfilled with gravel and a low-viscosity grout and the expected secondary porosity in the EDZ. In (b) the canister is emplaced on a pedestal made of compacted bentonite blocks. Shortly after, as shown in (c), the tunnel is backfilled with granular bentonite material (pellets). This material forms slope angles where the granular bentonite might segregate. The bentonite blocks and pellets together form a protective mechanical and chemical buffer around the disposal canisters. Requirements on the bentonite buffer are derived and justified in Leupin (2014). They are formulated in terms of safety-relevant buffer properties and preferred values for the indicators that quantify these properties (notably the current requirement (criterion) on hydraulic conductivity after full saturation is $< 10^{-11}$ ms^{-1}). Other backfill materials remain possible; the final decision on the backfill material and its safety-relevant properties will be taken in anticipation of the construction licence.

In the current concept, shortly after an entire SF/HLW emplacement drift has been filled, a final seal consisting of highly compacted granular bentonite will be installed. Requirements regarding

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these seals are still under development and the feasibility of their construction will be demonstrated in anticipation of the construction licence in the facility for underground geological investigations.

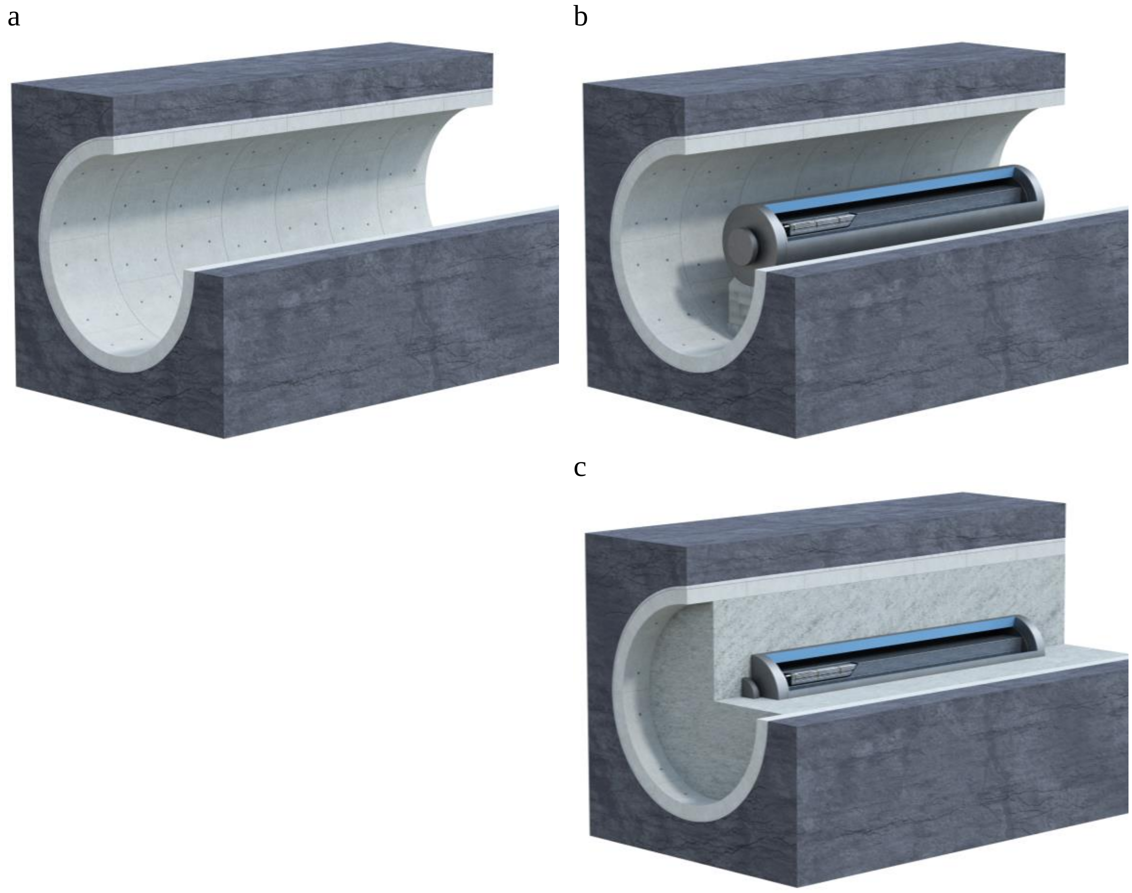

Fig. 6-4: Construction and operational phase in the HLW drift

The sequence above shows in (a) the emplacement of the tunnel support (eccentric) with prefabricated concrete elements, the annular gap backfilled with gravel and a low-viscosity grout and the expected secondary porosity in the EDZ. In (b) the canister is emplaced on a pedestal made of compacted bentonite blocks. Shortly after, as shown in (c), the tunnel is backfilled with granular bentonite material (pellets). This material forms slope angles where the granular bentonite might segregate.

Safety-relevant properties of bentonite

To safely contain the waste and to comply with the overriding safety principles, the key requirements for a buffer material in the case of high-level radioactive waste disposal independent of the host rock are: (1) a low hydraulic permeability/conductivity; (2) a self-sealing ability; and (3) durability of properties in the very long-term.

The safety-relevant properties of bentonite are:

1. swelling capacity providing mechanical stabilization of rooms and hence avoiding significant extension of the EDZ

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2. chemical retention of radionuclides by retarding transport from the buffer
3. low hydraulic conductivity ensuring diffusive transport
4. sufficiently high viscosity for mechanical support of the canister
5. sufficient gas transport capacity ensuring gas transport without compromising the hydraulic barrier
6. minimizing microbial corrosion to ensure conditions favourable to slow corrosion (of the canister)
7. resistance to mineral transformation ensuring longevity of other safety-relevant attributes of the buffer
8. suitable heat conduction ensuring favourable maximum temperature conditions

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7 Synthesis of modelling results regarding the hydromechanical evolution of the three assessment cases

The assessment cases that have been modelled in Beacon was selected already in the proposal for the project. At that time, it was not clear how much work that would be needed to handle these cases. In hindsight, it is clear that the number and complexity of the modelling tasks in Beacon, including the benchmarks in WP5, have been over-ambitious. The modelling teams have been able to produce results for all tasks, but not enough time has been assigned to the evaluation and interpretation of the results. This is especially true for the assessment cases. The Covid-19 situation also made it impossible for the teams to meet in person to discuss the issues and the results from the assessment cases. Therefore, the results presented here should be seen as "very preliminary". If more time would have been available it is very likely that the results would have been more consistent.

7.1 Synthesis of HM results for the SKB assessment case

Four modelling teams have contributed to this assessment case. An overview of the different codes and models used by these teams are shown in Table 2-1.

It can be noted that ICL was the only team that used a hydrostatic pressure level for their boundary conditions, and this has been accounted for in the evaluation below. VTT presented a sensitivity analysis with 18 different models. However, the case with restricted access of water in the task description was replaced by a test case in which water was supplied through a fracture in the mid-section of the analysed tunnel section. This is quite different from the assessment case and it may therefore not be fully relevant to compare this case with corresponding results from the other teams. Finally, CT presented models with two different mechanical boundary conditions; with roller boundary or a fixed boundary. For this comparison, the model cases with a fixed boundary were selected.

Tab. 2-1: Contributing modelling teams and used codes and material models

Partner	Code/model	Comments
LEI	Comsol/Elastic	-
ICL	ICFEP/ICDSM	Hydrostatic boundary conditions
VTT	Comsol/Double-triple porosity framework	Sensitivity analysis (model 17 and 18 in this evaluation)
CT	Comsol/HBM	Different mechanical BS's. Cases with fixed boundary in this evaluation

Final density distributions

A compilation of the final void ratio distributions for the two scan-lines (as requested in the task description, see Figure 7-1) from the different teams and different test cases is shown in Figure 7-2. The minimum dry density found along these two scan-lines has been used as a simple measure of the remaining heterogeneity of each model. A compilation of these dry density values is shown in Table 2-2.

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The results presented by LEI display a quite extensive remaining heterogeneity of the A-section, with a minimum dry density of 1'246 kg/m^3. Moreover, the results for the two cases (i.e. free and restricted access of water) are identical and this seems to be a consequence of the elastic model used by this team.

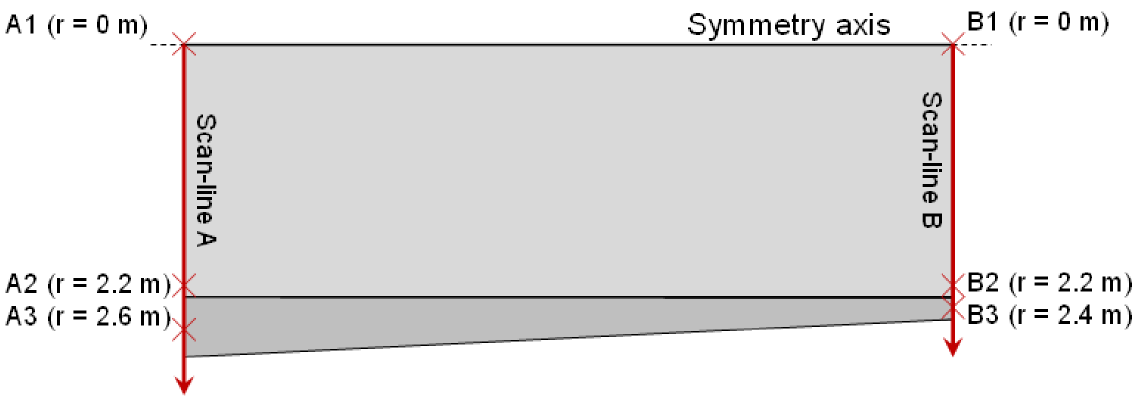

Fig. 7-1: Positions for requested modelling results: scan-lines (→) and point analyses (×)

The results for the case with free access of water presented by ICL also display a quite extensive remaining heterogeneity of the A-section, with a minimum dry density of 1'273 kg/m^3. For the case with restricted access of water, however, the final void ratio distribution is much more homogenous, and display a minimum dry density of 1'495 kg/m^3 along the tunnel axis.

The results for the case with free access of water presented by VTT display a fairly moderate remaining heterogeneity of the A-section, with a minimum dry density of 1'319 kg/m^3. For the case with restricted access of water (No. 17), however, the final void ratio distribution is much more homogenous, and display a minimum dry density of 1'469 kg/m^3.

Finally, the results for the case with free access of water presented by CT also display a fairly moderate remaining heterogeneity of the A-section, with a minimum dry density of 1'354 kg/m^3. For the case with restricted access of water, the final void ratio distribution is slightly more heterogeneous and display a minimum dry density of 1'301 kg/m^3. It can be noted that the models presented by both VTT and ICL displayed higher dry density levels in the pellets than in the blocks along the B-section in case with restricted inflow.

The final minimum dry density values for the different teams and the different cases are illustrated in Figure 7-3, and two main observations can be made from this graph:

- There is a significant variation in the minimum dry density in the cases with free access of water presented by the different teams (with values ranging from 1'246 to 1'354 kg/m^3).
- Different teams have obtained different results regarding the influence of a restricted access of water. LEI found no change, ICL found an increasing minimum dry density, whereas CT found a decreasing minimum dry density. VTT found an increasing minimum dry density, however, as mentioned above, the VTT case (No. 17) cannot readily be used for comparisons for the case with restricted water access.

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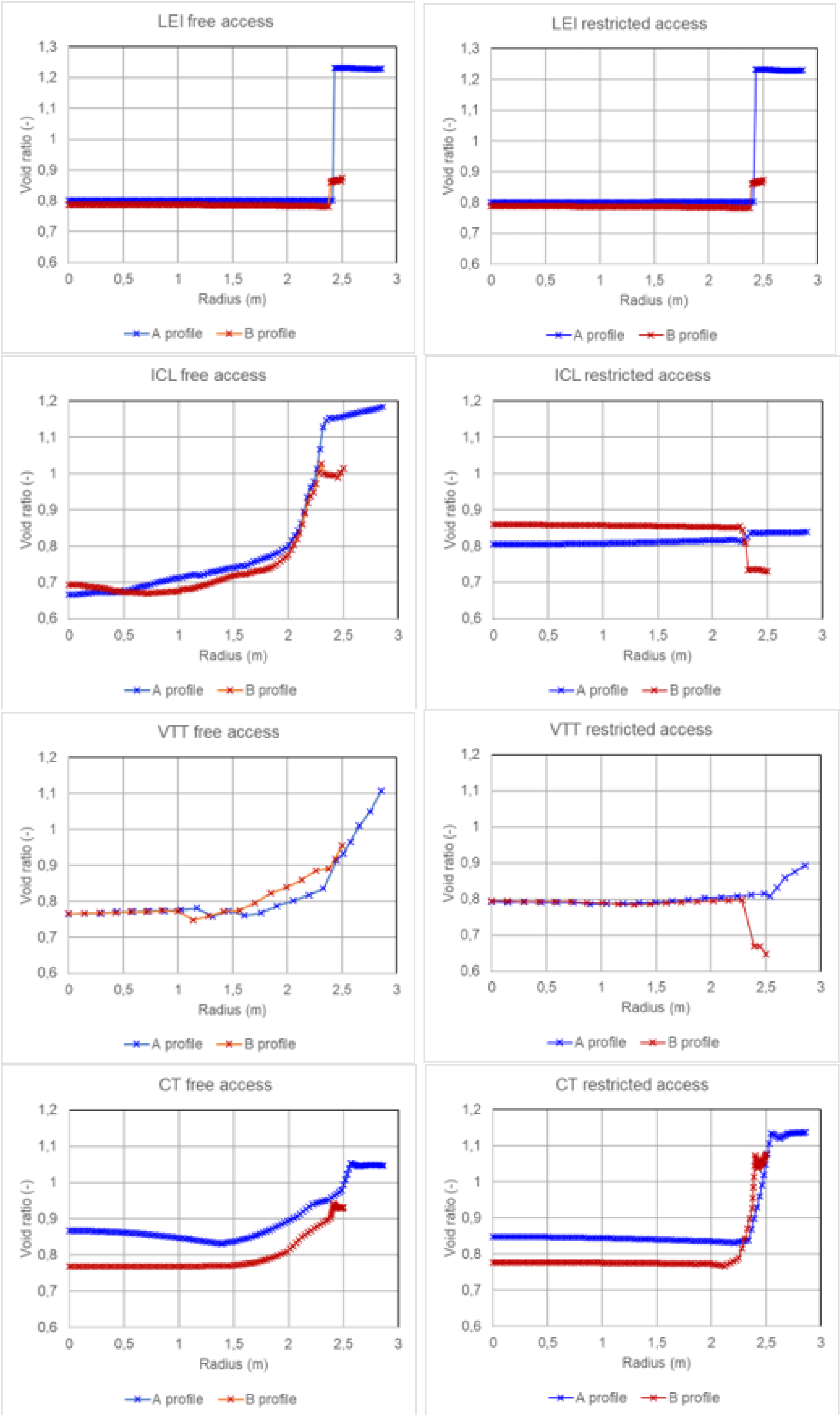

Fig. 7-2: A compilation of the final void ratio distributions for the two scan – from the different teams and different test cases

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Tab. 7-2: Final minimum dry density (kg/m^3) for different teams and different cases

Partner	Free access	Restricted access
LEI	1'246	1'246
ICL	1'273	1'495
VTT	1'319	1'469
CT	1'354	1'301

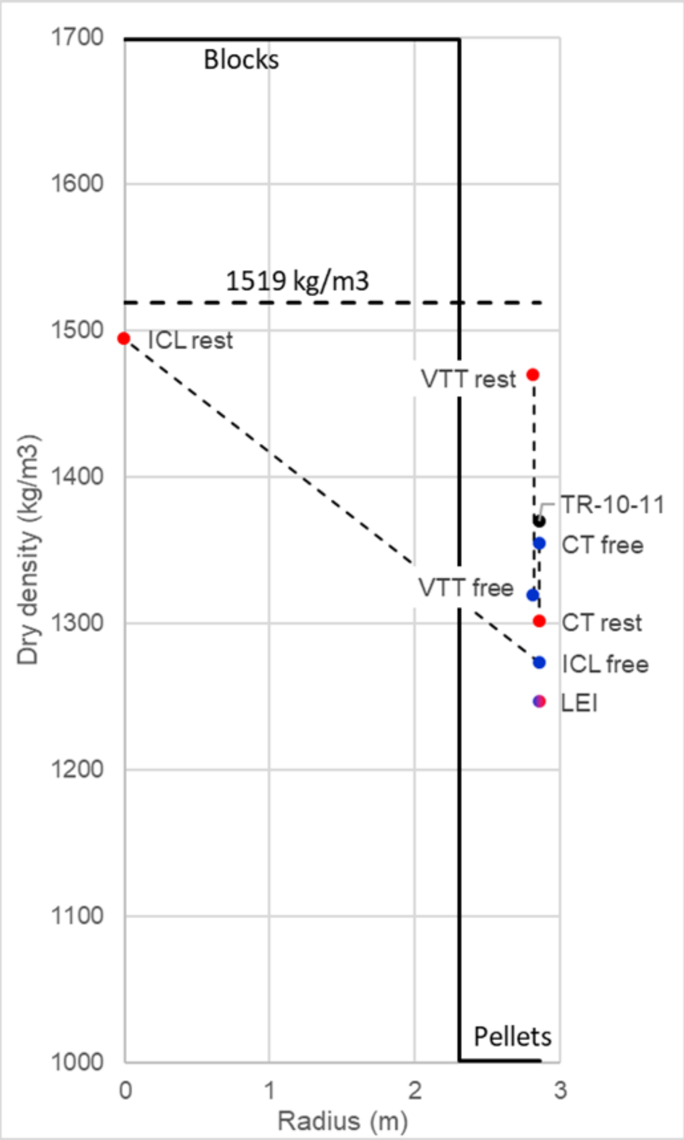

Fig. 7-3: Schematic illustration of the final minimum dry density for different teams and for different cases (free or restricted access of water)

Point marked "TR-10-11" shows the minimum dry density in the backfill homogenisation models with free access of water presented by Åkesson et al. (2010). The solid line represents

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the initial dry density profile, while the dashed line represents a completely homogenised backfill for this geometry and initial conditions.

7.2 Synthesis of HM results for the Andra assessment case

The simulations performed with three different models have been succeeded to evaluate the evolution of a bentonite seal putting in place in a tunnel. The more advanced models are able to simulate the excavation, a period of ventilation and finally the hydration of the bentonite plug. All the models predict a final state with heterogeneous distribution of dry density resulting of the initial conditions in the bentonite. Two types of heterogeneities were introduced: variable dry density distribution to represent a potential segregation when a 10-diameter tunnel is filled with pellets; technological voids on the top of the bentonite between the bentonite plug and the host rock. The simulations indicated as expected that technological gaps are closed in the early times after repository closure. It is important to note the ability of the models to simulate the closure of the voids initially present and the overall consistency of the results. This situation is close to the one encountered in one of the first lab tests used in the first task of WP5 (test1a) and this certainly highlights the progress of the teams during the project.

As shown before on the other tasks of WP5, differences between the results obtained with the 3 models (still) appear mainly during the transient phase. It should be considered that a part of the differences could be attributed to the choice made by each team in term of initial conditions, boundary conditions or parameters retained for the simulations. This highlights the needs on such complex problem to carry out sensitivity analyses with a view to comparing the weight of different parameters or modelling choices on final results in regard to the assessment indicators.

The models used to simulate the Andra case are quite different even if these used by Andra and ULG are based on the BBM model. Among the three teams, only ULG considered a double structure, and this is introduced only in the hydraulic part.

7.3 Synthesis of HM results for the Nagra assessment case

Three different models were used to simulate the Nagra assessment case. The main challenges of this assessment case are the different bentonite materials (blocks and granular bentonite), and the non-isothermal conditions. The Nagra case could be simulated by assuming an initially homogeneous distribution of granular bentonite or using the density distribution from the large-scale experiment FE.

Regarding resaturation the simulations of all three teams reach full saturation after 50 – 80 years which is comparable to results from simplified TH modelling (Senger et al., 2016). The BGR team assumed different initial conditions with an initial water saturation of 60% for the bentonite blocks. The other two teams opted for 80% as given in the assessment case description.

Differences can be found in the rate of saturation: the saturation distribution for BGR shows a rather steep gradient from the outer part towards the inner part while for UPC and EPFL the curve is more linear and less steep. In terms of consistency in simulation results, it is important to note that full saturation is reached for all the models used after about a century which coincides with the closure of the repository. The time to full saturation is in Nagra's however not safety relevant.

The simulated temperature evolution peaked between 110 and 115 °C close to the canister. Only small differences are observed between the models regarding the time of occurrence. The simulated temperature range corresponds to the range of temperatures measured in large-scale experiments such as the FE. Unfortunately, the model results do not show whether the temperature below the canister are smaller due to the higher thermal conductivity of the bentonite blocks

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(which have a higher initial water saturation) as has been observed in the Large-scale experiment FE.

At the rock interface temperatures of between 70 – 80 °C are reached. The temperatures are again in good agreement with the temperatures simulated by simplified TH models. From a safety point of view only the maximum temperature at the rock interface is of relevance which should not exceed the Opalinus Clay palaeotemperature of about 80 – 90 °C.

The final distributions of dry density in the bentonite around the canister simulated by the three different teams vary greatly. The differences are certainly related to the different initial dry density assumed (BGR) but this does not explain all the differences observed. Comparing results from UPC and EPFL (homogeneous case) differences are visible despite assuming the same initial distribution. If the final state seems in the same range for UPC and EPFL, the pathways to reach it are quite different. The results of UPC are still preliminary and the authors indicated that the model was calibrated with data that lie outside the range of swelling pressures to be simulated in the frame the Nagra assessment case.

Obviously, the distribution of dry density is the most important indicator for the homogenization process. The results obtained by BGR would suggest that the minimum requirements formulated by Nagra would not be satisfied. This is due certainly to the initial heterogeneous distribution of dry density with a large range of variation between 1.3 and 1.9 g/cm^3. Even if the bentonite became more homogeneous after full saturation, the dry density is locally still lower than the 1.45g/cm^3 expected. Their results however do not align with expected results from lab scale experiments that would suggest higher swelling pressures (e.g. Karnland et al. 2006) and further verification and/or validation of the codes used would certainly help in understanding the reasons for the observed deviation. The results from EPFL and UPC are consistent with literature data and measurements performed in large-scale experiments. These results indicate that both the degree of homogeneity and the swelling pressures comply with Nagra's safety related requirements for the bentonite buffer.

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8 Evaluation of the modelling results with respect to the safety relevant properties for the specific use of bentonite

8.1 Evaluation of the modelling results with respect to SKB safety case

The safety functions that should be upheld for the backfill in a KBS-3 type repository is to limit advective mass transfer and to keep the buffer in place (Posiva SKB 2017). The safety function: "To keep the buffer is place" is mainly affected by the compressibility of the backfill in a dry state and will not be affected by the homogenisation. For the safety function "limit advective mass transfer" the performance targets have been set to a swelling pressure of 0.1 MPa at all points in the tunnel and a hydraulic conductivity of 10-10 m/s on average over a section between two deposition holes (6 m).

In this assessment case the properties of MX-80 were assumed for the backfill material. The swelling pressure and hydraulic conductivity as a function of dry density for MX-80 can be found in Figure 8-1. As can be seen in the figures a dry density of 1'200 kg/m^3 is sufficient to reach a swelling pressure of 100 kPa in a very saline solution and 1'000 kg/m^3 would be sufficient for all relevant salinities. The hydraulic conductivity is below 10^{-11} m/s at 750 kg/m^3 for salinities up to 1 M.

The lowest calculated dry densities from all teams would still fulfil the performance targets for both hydraulic conductivity and swelling pressure with a reasonable margin. It should however be pointed out that the performance target should be evaluated against the sum of all processes that could affect the hydromechanical properties of the material. This would include, for example, mass loss from erosion and long-term alteration in addition to the homogenisation process. MX-80 bentonite is also not very likely to be used as tunnel backfill and a more relevant backfill material may have less favourable hydromechanical properties.

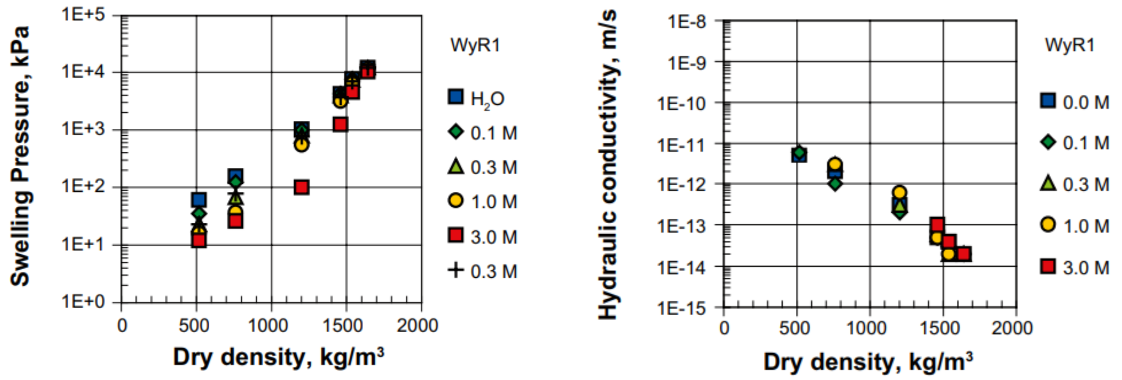

Fig. 8-1: Swelling pressure of the Wyoming MX-80 reference material (right), hydraulic conductivity of the Wyoming MX-80 reference material (left)

Right: Karnland et al. (2006)

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8.2 Evaluation of the modelling results with respect to Andra safety case

Despite the differences between the three models on some results and how they apprehend the transient phase, it is interesting to see that the final dry density distribution is in accordance with the requirements issued by Andra. The range of dry density allows to reach hydraulic conductivities below 10^{-11}m/s. The other characteristic desired by Andra is the capacity of the material to fill technological voids and to have sufficient dry densities in these zones. The models all suggest that the voids should be closed, and a sufficiently high dry density achieved.

The differences observed in the results highlight certainly that the representation of some processes should be improved to reenforce the demonstration of robustness of predictions made by the models. However, the representation of the global trend observed seems to be well captured as it was also shown before when comparing experimental data and simulations. More complex models have been used during the project introducing micro/macro coupling for both mechanical and hydraulic part indicating good directions to improve the behaviour of bentonite considering the initial presence of heterogeneities.

8.3 Evaluation of the modelling results with respect to Nagra safety case

Three teams using each a different model to simulate the Nagra assessment case. While the results obtained from two of them had some limitation due to (a) non adequate calibration of parameters (b) erroneous input data concerning the swelling pressure only one model could simulate the evolution of the bentonite dry density consistently. The results obtained by this group are well in line with experiments done at various scales over the last decades:

- The slow resaturation with water provided from the Opalinus Clay is not expected to produce irreversible distribution of dry densities and is in general favourable to a sufficiently homogeneous final density distribution.
- The salinity of the Opalinus Clay porewater is very similar to the porewater in bentonite. This is expected to have no negative effects on the evolution towards to a sufficiently homogeneous final density distribution.
- The thermal gradient between the internal and external part of the emplacement drift is expected to have no adverse effect on the evolution towards to a sufficiently homogeneous final density distribution.
- If using pre-casted tunnel liner, no technical voids are expected that must be filled with swelling bentonite. The lack of technical voids is expected to have no adverse effect on the evolution towards to a sufficiently homogeneous final density distribution.

Conclusions from the experimental work done in WP4 have indicate that:

- The Fuller curve dry density distribution of the granular bentonite chosen for the Nagra backfill can be optimized to reach higher swelling pressures.
- That it is important to ensure a slow and homogeneous resaturation of the nearfield and the tunnel support should not jeopardize this saturation pattern.
- Considering the findings in Beacon it can be concluded that with regard to the safety-relevant properties of bentonite that
- Bentonite can provide the needed mechanical stabilization of rooms and hence avoiding significant extension of the EDZ.

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- Bentonite will provide a low hydraulic conductivity to ensure diffusive transport.
- Bentonite is sufficiently high viscosity for mechanical support of the canister.
- Bentonite will ensure conditions favourable to slow corrosion of the canister.

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9 Robustness of the argumentative framework

In the frame of a project meeting in Liège (2021) general claims that are made for the assessment of the long-term safety of geological disposal of radioactive waste were discussed in terms of what arguments underly these claims and how well these arguments are supported by scientific evidence. The discussion focused on claims related to the performance of bentonite used in barriers and sealing sections.

General claims that are related to bentonite barriers are:

- saturated bentonite will limit the porewater movement
- saturated bentonite will limit microbial activity
- saturated bentonite will provide mechanical support for the host rock
- saturated bentonite will provide mechanical support for the disposal canisters

Claims are usually supported by arguments that can be formulated as design requirements. These can be related to safety functions. Fulfilment of the requirements related to Bentonite usually require that the bentonite is being resaturated which makes it difficult to check upon emplacement.

The main argument that supports the claims listed above is that saturating bentonite will swell and result in a homogenized bentonite in terms of its density distribution. The degree of bentonite homogenization that is considered to be acceptable depends on the bentonite applications safety functions and design requirements.

There are nevertheless questions that were raised during the Beacon project on how well this argument of swelling and resulting homogeneity is being supported by evidence. These questions are related to experimental observations, external factors that could impact homogenization, initial conditions, and modelling.

These questions a discussed in the following reflect consensus reached among the project partners during the Liège meeting (Liège 2021).

1.2 Questions related to experimental observations

Full homogenization of bentonite components is difficult to reach. In most cases, at the time scale of observation, dry density is not uniform despite the fact that the system seems to have reached an equilibrium state. Do we agree with this statement?

- General agreement on the statement. Homogenization is related to mass distribution; in Febex the bentonite mass distribution started homogenous but after partial saturation ended up to be more heterogeneous. However, in general saturation of bentonite leads to a higher degree of homogeneity.
- The system has to be designed such that a sufficient homogenization is reached to allow the safety related requirements can be fulfilled. Beacon provided these tools for the evaluation of this.
- Swelling is the dominant driving force for homogenization. This finding allows for conclusions to be drawn from small scale experiments.

A significant role of wall friction has been highlighted in the interpretation at of small-scale experiments. Wall friction may limit the homogenization capacity. What consequences on larger scales can be expected?

- This needs to be assessed in each single case whether a simplification can be done or not.

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- In a general way the assessment of wall friction may not be required in the description in the homogenization process for large scale experiments or in the evaluation of actual repository systems. This however is not so obvious for small scale experiments (especially for the description of stresses).
- The description of stress-path evolution may require the formulation of wall friction.

1.3 Questions related to external factors that could impact the processes of homogenisation

If present, does an initial thermal transients promote or reduce final degree of homogenization?

- The experimental results do not allow for a conclusive statement as the systems are highly coupled.

Will slow or rapid saturation have an effect on the final dry density distribution?

- Rate of saturation effects the homogenization as suction is distributing water more uniformly. In general, a slow resaturation will result in a more homogenous final state.

Will water alimentation (localized or directional flow) have an effect?

- Localized water flow has a strong effect on the homogenization as it results in irreversible changes in mass distribution. Localized water flow will affect the stress distribution. The degree of the effect will highly depend on the water inflow rate.

If swelling is the dominant process leading to homogenization does the water chemistry impact the final degree of homogenization?

- Has not been studied in detail in the frame Beacon. The salinity of the groundwater has undoubtedly an effect on the ability of smectite to swell.

1.4 Questions related to initial boundary conditions

Is an initial high degree of heterogeneity of the granular bentonite promoting or slowing down the homogenization process?

- The relative effect of homogenization is larger in a heterogeneous system to begin with. Initially homogenous systems will likely end up more homogenous. However, the CRT and FEBEX large scale tests, presented in section 3, showed that the test with a more heterogenous initial state ended up with a more homogenous final state.

What is the effect of the initial geometrical conditions on the saturation (ratio pellets/granules/ blocks/voids and geometrical configuration)?

- The effect of the geometrical conditions on the homogenization process is important as the potential for bentonite to swell/homogenize is limited.
- The tools developed to assess the evolution of the bentonite in terms of homogenization have been developed in the frame of the present project. These tools allow to assess within certain limits the homogenization process and provide feedback to repository design.

1.5 Questions related to conceptualization of processes and phenomena

Does internal/external friction need to be considered for assessing the "assessment cases"?

- Yes, wall friction needs to be considered, at least if the stress path is of interest.

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Is a porosity concept that assumes a dual porosity distribution needed in order to understand the homogenization process?

- If the transient effects (evolution of permeability) are of interest, then a more elaborated porosity model is needed. In a general sense granular bentonite justifies the use of a dual porosity approach.
- But, single porosity approached have been shown to produce good results of the final state of the barrier as well.

What are the largest aleatoric/epistemic uncertainties in homogenization experiments and process models?

- Scarcity of experimental data/physics. There are few experiments focussed on the direct determination of important material properties.
- Lack of understanding of fundamental processes
- Lack of sensitivity analyses does not allow for the identification of the most sensitive parameters/physics for modelling homogenization. Most computer codes are complex and demanding on computational power. Performing sensitivity studies on a large number of parameters is therefore very time consuming.

When modelling experimental tests, the final state is in most cases well reproduced. But major differences are almost systematics when the comparison is made on the way to reach this final state (pressure evolution, time to reach HM equilibrium…). What are the consequences on the assessment analysis?

- Comparable evolution contributes to the confidence one has in the results of the final state.

What are the relevant differences with respect to the predicted evolution of the assessment cases between TH and THM abstractions?

- Homogenization is a mechanical process – in that sense yes, a THM abstraction needed.

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10 Conclusions

The Beacon project has made a significant contribution improving our understanding of bentonite behaviour and the simulation of bentonite-based components for the disposal of radioactive waste in underground repositories. While much of the project was devoted to modelling and model development, the implementation of experimental tests using novel techniques such as imaging provided important insights and data to calibrate and feed the models specially to describe the coupling between micro and macro scales.

One of the first tasks in the frame of the Beacon project was the development of a database of experimental tests from literature. This database provided now state of the art information on the THM models used to represent the behaviour of bentonites. This database is now available and updated with the newest results obtained during the project.

The modelling teams participating in Beacon have significantly improved the capabilities of their models through the test cases proposed and simulated along the project. As a result of these developments and improvements, 10 teams are now equipped with coupled THM models that reasonably represent the behaviour of bentonite-based components in the context of an underground radioactive waste repository. Thanks to this, they were able to model test cases representative of the engineered barrier and sealing concepts proposed by SKB, Nagra and Andra in the final modelling stage. Teams are generally able to reproduce and predict the mechanical evolution of bentonite in small-scale and large in-situ experiments, particularly the final swelling pressures, dry densities and degrees of saturation of the bentonite. These are key safety indicators for bentonite used as a buffer or seal in geological disposal facilities for radioactive waste.

The progress made throughout the project is illustrated by the improved agreement between models and experiments. This is a consequence of model updates with the inclusion of friction, improved formulations of water retention curves, inclusion of thermal effects, and the development of numerical solvers. At the beginning of Beacon, there was very little experience on this type of issue, but thanks to the joint effort, there are now at least 10 teams in the European Community that can deal with the mechanical evolution of bentonite barriers. This would have never been possible to achieve without a joint project.

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